Strategic Niche Management for Biomass

A comparative study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark

Rob Raven
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Proefschrift

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Rob Raven,
Eindhoven, July 22nd, 2004
# Contents

## Chapter 1. Introduction

1.1 Introduction .............................. 1
1.2 Bioenergy in the Netherlands and Denmark: a brief introduction .......................... 3
1.3 Experimental introduction of technologies ............................................................. 8
1.4 Research questions, case-studies and data collection ............................................ 12
1.4.1 Research questions ..................... 12
1.4.2 Case study justification ................. 13
1.4.3 Manure digestion plants ................. 14
1.4.4 Co-firing .................................. 16
1.4.5 Data collection ........................... 19
1.5 Outline of the thesis ........................ 21

Appendix 1.1 ........................................ 23

## Chapter 2. Conceptual framework

2.1 Introduction ................................ 25
2.2 A review of the relevant literature ................................................................. 25
2.2.1 Evolutionary theories on technological change ............................................. 25
2.2.2 Constructive Technology Assessment ......................................................... 35
2.3 SNM: the research model ...................................... 37
2.3.1 Voicing and shaping of expectations ......................................................... 39
2.3.2 Network formation .................................. 39
2.3.3 Learning processes ................................. 41
2.3.4 Dynamic interaction between three processes .............................................. 43
2.4 Additions to the SNM research model ............................................................ 45
2.4.1 From technological niche to market niche ................................................. 45
2.4.2 Dynamics in actor expectations and visions ................................................. 49
2.4.3 Niche-regime interaction ....................................................... 51
2.5 SMM: the policy tool .................................. 53
2.6 Research protocol ............................. 56

## Chapter 3. Manure digestion in the Netherlands

3.1 Historical overview ............................................................. 59
3.1.1 Farm-scale plants (1973-1985) ................................................................. 59
3.1.2 Centralised plants (1986-1995) ................................................................. 61
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.3</td>
<td>Reintroduction of biogas plants (1996-2003)</td>
<td>65</td>
</tr>
<tr>
<td>3.2</td>
<td>Analysis of niche dynamics</td>
<td>69</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Visions and expectations</td>
<td>69</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Network formation</td>
<td>74</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Learning processes</td>
<td>80</td>
</tr>
<tr>
<td>3.3</td>
<td>Interaction between internal niche processes</td>
<td>84</td>
</tr>
<tr>
<td>3.4</td>
<td>Dutch regime dynamics</td>
<td>86</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Natural gas, energy crises and nuclear power (1973-1985)</td>
<td>86</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Energy prices, competition and environmental considerations (1986-1995)</td>
<td>90</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Competition and sustainability (1996-2003)</td>
<td>95</td>
</tr>
<tr>
<td>3.5</td>
<td>Conclusions</td>
<td>100</td>
</tr>
<tr>
<td>Appendix 3.1</td>
<td></td>
<td>105</td>
</tr>
</tbody>
</table>

**Chapter 4. Co-firing in the Netherlands** ......................................................... 107

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Historical overview</td>
<td>107</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Initial explorations in co-firing (1993-1995)</td>
<td>107</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Commercial application (1996-1999)</td>
<td>109</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Towards wider diffusion (2000-2003)</td>
<td>112</td>
</tr>
<tr>
<td>4.2</td>
<td>Analysis of niche dynamics</td>
<td>116</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Visions and expectations</td>
<td>116</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Network formation</td>
<td>119</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Learning processes</td>
<td>129</td>
</tr>
<tr>
<td>4.3</td>
<td>Interaction between niche processes</td>
<td>134</td>
</tr>
<tr>
<td>4.4</td>
<td>Dutch regime dynamics</td>
<td>137</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Competition and environmental considerations (1993-1995)</td>
<td>137</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Full competition and increasing overlap between energy and waste (1996-2000)</td>
<td>140</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Uncertainty in innovation and biomass definitions (2001-2003)</td>
<td>142</td>
</tr>
<tr>
<td>4.5</td>
<td>Conclusions</td>
<td>145</td>
</tr>
<tr>
<td>Appendix 4.1</td>
<td></td>
<td>150</td>
</tr>
</tbody>
</table>

**Chapter 5. Manure digestion in Denmark** ..................................................... 153

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Historical overview</td>
<td>153</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Farm-scale plants (1973-1983)</td>
<td>153</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Centralised plants (1984-1994)</td>
<td>155</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Organic household waste and farmscale plants (1995-2003)</td>
<td>158</td>
</tr>
<tr>
<td>5.2</td>
<td>Analysis of niche dynamics</td>
<td>163</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Visions and expectations</td>
<td>163</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Network formation</td>
<td>166</td>
</tr>
<tr>
<td>Contents</td>
<td>ix</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>5.2.3 Learning processes</td>
<td>173</td>
<td></td>
</tr>
<tr>
<td>5.3 Interaction between niche processes</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>5.4 Danish Regime dynamics</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>5.4.1 Reducing oil dependencies (1973-1983)</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>5.4.2 Decentralised CHP and agro-environmental regulations (1984-1994)</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>5.4.3 Increasing competition, climate change policy and waste policy (1995-2003)</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>5.5 Conclusions</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Appendix 5.1</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>Appendix 5.2</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Appendix 5.3</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>Chapter 6. Co-firing in Denmark</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>6.1 Historical overview</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>6.1.1 Decentralised CHP units (1990-1992)</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>6.1.2 Centralised co-firing (1993-2000)</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>6.2 Analysis of niche dynamics</td>
<td>218</td>
<td></td>
</tr>
<tr>
<td>6.2.1 Visions and expectations</td>
<td>218</td>
<td></td>
</tr>
<tr>
<td>6.2.2 Network formation</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>6.2.3 Learning processes</td>
<td>227</td>
<td></td>
</tr>
<tr>
<td>6.3 Interaction between niche processes</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>6.4 Danish regime dynamics</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>6.4.1 Natural gas and decentralised CHP (1990-1992)</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>6.4.2 Banning coal and introducing competition (1993-2000)</td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>6.4.3 Implementing competition (2001-2003)</td>
<td>237</td>
<td></td>
</tr>
<tr>
<td>6.5 Conclusions</td>
<td>239</td>
<td></td>
</tr>
<tr>
<td>Chapter 7. Analysis and conclusions</td>
<td>243</td>
<td></td>
</tr>
<tr>
<td>7.1 Introduction</td>
<td>243</td>
<td></td>
</tr>
<tr>
<td>7.2 Comparing the cases</td>
<td>243</td>
<td></td>
</tr>
<tr>
<td>7.2.1 Manure digestion (NL) versus manure digestion (DK)</td>
<td>244</td>
<td></td>
</tr>
<tr>
<td>7.2.2 Co-firing (NL) versus co-firing (DK)</td>
<td>247</td>
<td></td>
</tr>
<tr>
<td>7.3 Crucial factors for the emergence of market niches</td>
<td>251</td>
<td></td>
</tr>
<tr>
<td>7.3.1 Niche development patterns in the four cases</td>
<td>252</td>
<td></td>
</tr>
<tr>
<td>7.3.2 Characteristics of emerging market niches</td>
<td>253</td>
<td></td>
</tr>
<tr>
<td>7.3.3 The role of internal niche processes in emerging market niches</td>
<td>254</td>
<td></td>
</tr>
<tr>
<td>7.4 Niche-regime interaction</td>
<td>259</td>
<td></td>
</tr>
<tr>
<td>7.4.1 Relation between regime stability and niche size</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>7.4.2 Effect of experimentation in niches on regime dynamics</td>
<td>263</td>
<td></td>
</tr>
</tbody>
</table>
7.4.3 Multiple regimes ................................................................. 264
7.4.4 Sources of regime instability ................................................. 264
7.5 The role of public authorities in niche development ...................... 265
7.6 Future research agenda .............................................................. 269

Epilogue ................................................................................................. 273

References .............................................................................................. 277

Samenvatting (Dutch) ................................................................................. 299

Short summary (English) ............................................................................ 319

Curriculum Vitae ....................................................................................... 323
Chapter 1.
Introduction

1.1 Introduction

Bioenergy is energy (electricity, heat) produced from organic sources like wood, energy crops or manure. These sources are called biomass. Biomass is the most important energy source in the world after fossil fuels. In Europe, biomass conversion is considered a renewable, environmentally-sound way to produce energy. In the Netherlands, biomass is the main source for renewable energy generation (over three-quarters of total source in 2001). Moreover, in the third White Paper on energy (1995), the Dutch government set the target of increasing bioenergy generation from 17.1 PetaJoule (PJ) in 1995 to 54 PJ in 2000, 85 PJ in 2007 and 120 PJ in 2020 (Ministry of Economic Affairs, 1995:51).

Introducing bioenergy into society is complicated, however. In a 1997 action programme for renewable energy, the Dutch government recognised several bottlenecks for bioenergy. First, the price of bioenergy was high compared to energy from fossil fuels. Second, there was no market for biomass, resulting in uncertainties about biomass price, quality and security of supply. Finally, there were barriers related to regulatory frameworks and policies, in particular related to emission standards for biomass combustion (Ministry of Economic Affairs, 1997). Six years later, in 2003, the government published another plan of action, now

---

1 Estimates in 2000 indicated a bioenergy share of about 14% (55 EJ annually) of total global energy supply. This share is much larger in developing countries, than in industrialised countries, 35% and 3%, respectively (Broek, 2000:2).

2 These figures are the amounts of avoided primary energy, which is the standard method for measuring renewable energy generation in the Netherlands. Most European countries (including Denmark) and international institutions often use a different calculation. They calculate the primary energy content of the first usable energy form. The difference between the two is best explained with an example. Let us assume that wind turbines produce 10 PJ electricity in a certain year. The primary energy content is then 10 PJ. In the case of avoided primary energy, however, the amount of electricity is calculated on the basis of the average efficiency of electricity production in a country (43.5% in 2000 in the Netherlands). The avoided primary energy, as used in the Netherlands, is thus 10/0.435 = 23 PJ. The avoided primary energy of wind energy is then larger than the primary energy content. The problem with this calculation is that it makes international comparisons impossible, because it depends on country-specific conversion efficiencies.

In the case of biomass combustion, the difference is smaller. The primary energy content is in this case defined as the energy content of the biomass fuel. Let us assume that this is 10 PJ and that the biomass is converted to electricity with an efficiency of 38%. The avoided primary energy content, as used in the Netherlands, is then (10 x 0.38)/0.435 = 8.7 PJ. The avoided primary energy of biomass combustion is smaller than the primary energy content (Novem, 1999; Beek and Benner, 1998).

When comparing countries, I will use as much international data as possible. However, for more detailed figures (on the level of fuels or technologies) often only data are available that are calculated according to national methods. In these cases I recalculate data as much as possible, depending on the availability of data.
for biomass exclusively. Additional bottlenecks were recognised: a lack of public acceptance and ambiguity about the sustainability of biomass, the problem of choice related to the number of biomass technologies and a lack of a level European playing field. Despite an increased use of biomass, from 17.1 PJ in 1995 to 32.1 PJ in 2003, the contribution of biomass remained substantially short of the goals of the third White Paper (Joosen, Jager and Ruijgrok, 2002; Ministry of Economic Affairs, 2003).³

Compared to other European countries, the share of biomass in total primary energy supply (TPES) in the Netherlands is small (see Figure 1.1).⁴ Biomass contributes the largest share in Finland: biomass accounts for 19% of TPES; in the UK biomass accounts for 0.9% in TPES. In between are countries like Norway and Switzerland (both with a large share of hydro, therefore the peaks in total renewables) and the Netherlands (with a small, but dominant contribution of biomass). The graph is in particular interesting because of the figures for Finland, Sweden, Austria and Denmark. The first three countries are characterised by large wood resources from forestry or wood industries (see also Table 1.2, Appendix 1.1). Denmark, however, lacks large amounts of by-products from forestry and wood industry; only a limited part of the country is forested. As in the Netherlands, a large part of the biomass is household waste and by-products from agriculture (straw, manure). Nevertheless, the share of biomass in TPES in Denmark (8.4%) is much larger than in the Netherlands (1.3%). Moreover, Denmark was able to meet interim policy goals: in Energy 21 (the 1996 Danish White Paper on energy), the goals were set at 69.3 PJ in 1996, 73.4 PJ in 2000, 84.9 PJ in 2005, 95.9 PJ in 2010 and 145.7 PJ in 2030, respectively; in 2002, total use of biomass was equivalent to 81 PJ (Odegaard, 2000:18; Ministry of the Environment and Energy, 1996; Energyistyrelsen, 2003).⁵ Denmark and the Netherlands are thus – to some degree – similar in terms of biomass availability, but the role of biomass in energy generation is much larger in Denmark than it is in the Netherlands.

The main theme of this book is to understand the difference between the two countries. In the following sections I will present a general introduction to bioenergy systems, give a more elaborate view of current biomass and bioenergy use in the Netherlands and Denmark, and pick two bioenergy technologies for further investigation.

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³ Avoided primary energy.
⁴ TPES is the total primary energy content supplied to a country, including import and export.
⁵ These figures are the primary energy content of renewables. See also footnote 2.
Figure 1.1. Share of total renewable sources and of biomass and organic waste in primary energy supply in several European countries in 2001. Total renewable sources include hydro, wind, solar, tide, geothermal and biomass and organic waste. Biomass and organic waste is divided into solid biomass, liquid biomass, renewable municipal waste and biogas (IEA, 2003).

1.2 Bioenergy in the Netherlands and Denmark: a brief introduction

Biomass and bioenergy represent a large number of fuels, conversion technologies and end-products (see Figure 1.2). Biomass can be produced with energy crops (e.g. wood, rapeseed or sugar beets), but the current sources in most European countries are mainly by-products from the agricultural or forestry sector or waste streams from industrial sectors (e.g. demolition wood, paper sludge, sewage sludge) or households (municipal waste). The conversion methods include thermal processes (especially combustion), biochemical processes (especially digestion) and mechanical processing (extraction of oil for liquid fuels). Thermal conversion and anaerobic digestion are currently the most widely employed methods for bioenergy generation in the Netherlands and Denmark.
Introduction

Biomass is a diverse fuel and involves many conversion technologies and end-products. On the supply side, the fuels can be specially produced energy crops (e.g. wood, rapeseed or sugar beets), or they can come from the agricultural or forestry sector (e.g. thinning wood, straw, manure), from industrial sectors or households (e.g. demolition wood, paper sludge, organic household waste) or from abroad (import). Biomass can also come in mixed forms (e.g. specially produced biomass pallets from various sources) or can be mixed with non-organic sources (e.g. in the case of domestic household waste). Biomass can be thermally, biochemically or mechanically converted into bioenergy. Thermal conversion includes combustion, gasification and pyrolysis. Combustion is widely used to various extents and is mainly applied to convert dry biomass sources into electricity and heat. In a gasification process, biomass is heated with limited amounts of oxygen. The end-product is syngas, which can for example be used in a gas turbine for the generation of heat and power, or for the production of methanol or hydrogen (liquid fuels). Pyrolysis converts biomass into liquid (bio-oil or bio-crude), solid and gaseous components by heating the biomass in the absence of air. The components can be used in gas turbines, in combustion units or for the production of bio-diesel. Biochemical processes include digestion and fermentation. In the digestion process, microbes produce a mixture of methane and carbon dioxide (biogas) in the absence of oxygen. The biogas can be used in thermal processes for power and heat production or it can be upgraded as a replacement for natural gas. Digestion is mainly applied for wet biomass streams (e.g. manure, organic household waste), and is used in many countries on a commercial scale, in particular in developing countries. Fermentation, also a biochemical process, is used commercially on a large scale in various countries (e.g. Brazil) and it produces ethanol from sugar crops (sugar cane, beet) and starch crops (maize, wheat). Enzymes convert the biomass into sugars and yeast converts the sugars into ethanol. Ethanol can be used as a liquid fuel, particularly in the transport sector. Extraction, finally, is mainly a mechanical process that produces rapeseed oil from rapeseed. Rapeseed oil can be further processes into bio-diesel and used in the transport sector (Faaij, 1997).

Figure 1.2. Biomass and bioenergy: sources, conversion and products
The Netherlands

Dutch development of bioenergy began after global oil prices increased in 1973. In the Netherlands, the short-term focus was on increasing energy recovery from waste. The first experiments concentrated on improving technologies for anaerobically digesting industrial wastewater. The biogas produced in these plants could be used for energy generation. This research resulted in experiments with manure digestion. In the early 1980s, there were many experiments with manure digestion; about twenty-five small digesters were constructed. The Dutch government supported research, development and implementation, but diffusion did not take off; most plants were abandoned after 1985. In the 1990s, manure digestion was investigated at some locations, but this did not result in a significant contribution to energy generation.

Oil prices again declined after 1985, complicating the further development and diffusion of bioenergy technologies. In the same period, environmental problems played a more important role in Dutch energy policies. This resulted in the further optimisation of energy recovery from waste. In 1984, the Dutch government implemented a national research programme to stimulate waste prevention and waste recycling; recovery of energy from waste incineration was one of the main research lines. In subsequent years, most of the existing waste incinerators were optimised and a few new incinerators were constructed. Energy generation increased from 6.5 PJ in 1990 to 16.2 PJ in 2002. About 50% of the waste was organic, equivalent to 8.6 PJ in 2002.

Another technology that emerged in the late 1980s was the extraction of biogas from landfill sites (the result of spontaneous digestion of organic waste in a landfill). In 1987, four landfill sites were equipped with gas extraction systems. The number of sites increased rapidly after the government implemented the obligation to cover landfill sites. The number of plants increased to twenty-two in 1993 and sixty-four in 2000. Together, the landfill sites produced 3.1 PJ biogas in 2002. Digestion technologies were also diffused in other sectors in the 1990s. Digestion of industrial waste waters was increasingly applied in food processing industries; biogas production increased from 0.5 PJ in 1989 to 1 PJ in 2002. Digestion was also used in stabilising the sludge that remained in sewage treatment plants after purification. In the 1980s there were about 250 sewage treatment plants in the Netherlands. After 1985, these plants began to use biogas for energy generation. Total biogas production increased

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6 Data on the Netherlands are from Joosen et al. (2003), Raven and Verbong (2001) and the International Energy Agency website (http://www.iea.org/statist/renew.htm).
7 The first experiment with anaerobic digestion of industrial wastewater in the Netherlands already took place in 1914, but broad diffusion only took off in the 1970s.
8 Nationaal Onderzoeksprogramma Hergroei van afvalstoffen (NOH).
9 Equivalent to 12.3 PJ avoided primary energy.
10 The landfill sites were covered with vegetation. Vegetation would die if the biogas was not extracted from the landfill.
11 The biogas was used for the production of 0.5 PJ electricity and 0.15 PJ heat and another 16 million m3 gas was supplied without conversion (e.g. in industrial processes).
12 The biogas was converted to 0.07 PJ electricity, 0.6 PJ heat and another 7 million m3 gas was supplied without conversion.
from 1.6 PJ in 1989 to 2 PJ in 2002. Finally, anaerobic digestion was applied in a few plants that processed organic household waste, but biogas production remained limited (0.07 PJ in 2001).

In the 1990s, combustion technology became more important, with wood combustion in household stoves playing a major role. In 2002, energy generation in household stoves was 4.6 PJ heat. In addition, two wood-processing industries applied wood combustion. The plants began operating in 1997 and 1998. Two energy companies experimented with wood combustion for power production. One company (Essent) constructed a 25 MWe plant, fuelled by wood (1999), while another company (NUON) constructed a small power plant (wood) with a capacity of 1.3 MW in 2000. Jointly, all plants (industrial combustion and power plants) produced 3 PJ heat and electricity in 2002. Finally, a major increase of biomass combustion occurred in large centralised power plants. Almost all power companies started combining biomass and coal combustion in these plants (co-firing) in the early 1990s. In addition, one energy company (EPZ) constructed a wood gasifier with a capacity of 30 MW and connected it to an existing power plant in 2000. Total energy generation increased from 0.03 PJ in 1995 to 9.7 PJ in 2002; total installed capacity increased to 177 MWe in 2002. In 2002, co-firing was the largest contributor to bioenergy generation, after waste incineration.

**Denmark**

In Denmark, experiments with bioenergy also began after the first oil crisis in 1973. Denmark is characterised by a more widely distributed energy system than is the case in the Netherlands, in particular with regard to heating. There was not yet a natural gas infrastructure in Denmark in the 1970s; most towns and villages relied on district heating systems or individual heating systems. Until the 1960s, these had been fuelled with coal, coke and wood, but later a switch was made to inexpensive oil. When oil prices increased in the 1970s, some of these plants turned back to biomass, in particular straw and wood. Wood was also used in small wood stoves in households and the number increased in the 1970s and 1980s. In 1980, more than half of the primary renewable energy sources were either wood (41.1%) or straw (17.6%). Waste (including the non-organic part) was also strongly represented (38.7%).

Denmark also experimented with digestion technology in the 1970s, in particular with manure digestion. Several farmers, Folke High Schools and local communities participated in energy projects, including manure digestion. The number of experiments with biogas was

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13 The biogas was converted to 0.4 PJ electricity and 0.8 PJ heat and another 13 million m3 gas was supplied without conversion.
14 Equivalent to 4.8 PJ avoided primary fuels.
15 Equivalent to 4.2 PJ avoided primary fuels.
16 Avoided primary energy.
17 Data on Denmark are from Energistyrelsen (2003) and the International Energy Agency website (http://www.iea.org/statist/renew.htm)
18 Primary energy content of wood, straw and waste was 11.3 PJ, 4.8 PJ and 10.6 PJ, respectively.
similar to the number in the Netherlands. The plants were small and total energy generation remained limited.

In the late 1980s, global oil prices dropped and new notions about environmental problems emerged. In the following years, energy recovery from waste incineration increased from 12.2 PJ in 1990 to 22 PJ in 2002 (17.8 PJ from organic waste). Most plants produced heat for district heating systems or industrial processes; some also produced power. The diffusion of decentralised wood and straw combustion also continued. The Danish policy for decentralised biomass systems was established in two agreements between the Danish government and its parliamentary opponents, both aiming at the construction of decentralised combined heating and power plants (CHP) and at the increased use of biomass in district heating plants. The number of district heating plants using wood increased from three in 1984 to about fifty plants in 1999 (Centre of Biomass Technology, 1999). Another fifty-eight district heating plants combusted straw. Seven CHP plants also combusted straw in 1998 (Centre of Biomass Technology, 1998).

In the 1990s, biomass was increasingly used in large, centralised Danish power plants. An agreement between government and opposition (1993) instructed the Danish energy companies to combust large amounts of straw and wood. Several centralised power plants were equipped with biomass processing and combustion equipment. In 2002, these plants were equipped to combust 590,000 tons of straw and 530,000 tons of wood, equivalent to 9 PJ straw and 8.5 PJ wood and a capacity of 173 MWe.\(^{19}\)

The combustion of wood and straw was the dominant route for bioenergy generation, but Denmark also implemented digestion technology. In several action programmes, the government stimulated centralised biogas plants for the digestion of animal manure and organic waste from food processing industries. The first plant was constructed in 1984 and the number increased to twenty in 2002, while the number of farm-scale plants also rose. In 2002, thirty-seven farm-scale plants were installed. Total biogas production was 3.4 PJ in 2002, of which about half was produced in manure digestion plants (the remaining portion was produced at landfill sites, in sewage treatment plants and in industrial waste water systems).

**Conclusion**

In this section I have briefly described the development of bioenergy systems in the Netherlands and Denmark. Both countries began experimenting with several bioenergy technologies in the 1970s, but the outcomes varied greatly. After thirty years, digestion and combustion have emerged as dominant conversion routes in both countries. Two cases are especially interesting, i.e. manure digestion and co-firing. The Netherlands and Denmark experimented with manure digestion in the 1970s, 1980s and 1990s, but only Denmark was able to implement a significant number of plants. The case of co-firing is interesting, because\(^{19}\)

\(^{19}\) Figures for co-firing in Denmark are based on how much straw and wood the power plants are physically capable of combusting, and are not the actual use of straw and wood (see also Chapter 6). The actual use is probably lower, because of discontinuities in daily operation. Average energy content of straw is 15.2 MJ/kg and for wood 16 MJ/kg. Total biomass used for energy generation was equivalent to 81 PJ (primary energy content) in 2002.
it is one of the few cases in which the Netherlands was able to implement a bioenergy technology rapidly. Denmark, too, was able to develop this option. Manure digestion was thus developed successfully in one country and less successfully in another, while co-firing was developed successfully in both countries. In this thesis, I will focus on these two technologies, manure digestion and co-firing.

1.3 Experimental introduction of technologies

To investigate the differences between co-firing and manure digestion in the Netherlands and Denmark, I will use the Strategic Niche Management (SNM) approach. SNM has been used by various researchers to investigate the experimental introduction of sustainable technologies and is part of a research direction that focuses on the role of societal experiments (e.g. pilot plants, demonstration plants) in technology introduction. The SNM approach originally emerged from the observation that, in particular in the transport sector, many innovations with (potentially) improved environmental characteristics fail to become commercially successful. The car industry, for example, has investigated and experimented with several options in the past (in particular, battery-powered vehicles), but never achieved large commercial exploitation (Hoogma et al., 2002). SNM was built upon insights from evolutionary theories on technological change (economic, historical and sociological theory) and on constructive technology assessment (CTA) (see Chapter 2). Ideas about variation and selection of technologies and the concepts of technological niches and technological regimes were introduced by evolutionary theories, while CTA provided insight into how the evolutionary process could be steered or managed. In this section I briefly introduce some of the main concepts, while a more detailed discussion of the main concepts and conceptual framework follows in Chapter 2. The aim is to articulate (additional) research questions that can contribute to SNM, which I will do in section 1.4.

Evolutionary theories often emphasise that technological change has a structured nature; technological development occurs along certain trajectories or paths. Electricity generation, for example, is organised in many European countries around large-scale, centralised production units that combust fossil fuels. After this system had emerged, research and development for decades has focussed on improving efficiency, building larger plants, and expanding supply and distribution networks. Turning back or radically changing this system once it has been established is difficult. Most technological variation is incremental in nature – it aims to optimise the established technology or system. Radically different technologies are simply not considered at all or actors expect that viability will be too limited to legitimise large investments. Evolutionary theories have introduced several concepts for understanding and investigating the structured nature of technological development. In SNM, the concept of technological regime is used, as originally introduced by Nelson and Winter (1982). A

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A technological regime is a set of ‘rules’ that structures actors’ behaviour and guides them into specific directions. Rip and Kemp (1998) have defined a technological regime as follows:

A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems – all of them embedded in institutions and infrastructures.

A technological regime helps one understand why most technical change is incremental rather than radical. Variations in technology are mainly incremental, and established selection mechanisms (user preferences, regulations, etc.) favour the adoption of incremental innovations. Then how is it possible that radical innovation still takes place? Levinthal (1998) has argued that radical innovation occurs in specific application domains, or market niches, where specific, local conditions result in a preference for a new technology over the established technology. SNM literature adds that niches are also often created, that they do not just exist out there. For environmental technologies in particular, existing market niches are often absent. Schot et al. (1996) has called these niches technological niches. Technological niches are special application domains that are protected from (some of the) rules in the regime, e.g. price/performance ratio, user preferences or regulatory requirements. Protection – for instance, subsidies or regulatory exemptions – from the technological regime can create a proto (temporary) market that provides a testing ground for novel technologies. A technological niche facilitates learning and improves societal embedding; technologies may improve or new functionalities may emerge. In SNM, technological niches are the breeding place for radical innovation.

SNM proposes societal experiments like pilot plants for creating technological niches. In an experiment, actors can try out the innovation in a real-life context and learn about its desirability. A technological niche emerges when the number of experiments increases – when more actors are attracted and they start sharing ideas, expectations, lessons, etc. In an iterative process of learning from individual experiments, sharing experiences among experiments and designing new experiments, stability in the technological niche may increase. Schot et al. (1996) identified three issues important to this process, i.e. voicing and shaping of expectations, network formation and learning and articulation. These processes are important in understanding the direction and outcome of niche development. They can be used to comprehend emerging strategies of niche development. Emerging strategies are patterns that are realized despite, or in the absence of, intentions (Mintzberg & Waters, 1985, quoted in Hoogma, 2000:19). On the basis of two dimensions (‘technological choice and design’ and ‘use environment’), Hoogma (2000:21) distinguished between four possible emergent strategies in niche development, depending on the level that the niche differs from a regime on the two dimensions (Table 1.1). SNM research has shown that differences in the iterative process of designing experiments (fit versus stretch) and the dynamics in expectations, network formation and learning, resulted in different emerging strategies.
Table 1.1. Typology of emergent introduction strategies\textsuperscript{21}

<table>
<thead>
<tr>
<th>Use environment</th>
<th>Technology choice and design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit</td>
<td>Selective substitution</td>
</tr>
<tr>
<td>Stretch</td>
<td>Leapfrog design for substitution</td>
</tr>
<tr>
<td>Stretch</td>
<td>Market differentiation</td>
</tr>
<tr>
<td></td>
<td>Exploration of a new regime</td>
</tr>
</tbody>
</table>

Technological niche creation through the protection of an innovation from the incumbent technological regime may eventually result in the emergence of a market niche. Market niches are application domains in which a new technology has some specific advantages over the established technology, with both producers and users of the technology acknowledging this fact. Further development and diffusion (e.g. through application of the technology in new niches) can eventually result in a transition, or in a regime shift: the previous basic set of rules has changed into a new basic set of rules.

Finally, Figure 1.3 shows the locus of technological niches in the total innovation process, from the emergence of a new idea (the invention) to widespread diffusion in society. The figure also emphasises that niches are not the only step in the innovation process. SNM, however, claims that they are a crucial step towards a regime shift.

\textsuperscript{21} A technological niche implies a misfit with, or stretch from, the technological regime on the two dimensions. In time, niches can for example develop from a fit-fit strategy to a stretch-stretch strategy. In the case of selective substitution, both the chosen technology and targeted use environment remain close to the existing regime. In market differentiations, the chosen technology remains close to the regime, whereas the targeted use environment departs substantially from the regime. In a leap-frog design for substitution, the targeted use environment remains close to the regime, whereas the chosen technology differs dramatically. Finally, in the case of exploring a possible new regime, both technology choice and targeted use environment differ considerably from the technological regime.
### 1. New options
- **Science:** Promising findings
- **Technology:** Identification of technological opportunities
- **Regulation, Market, Society:** Users’ ideas

### 2. Building a protected space for ‘hopeful monstrosities’
- **Science:** Re-orientation of R&D agendas
- **Technology:** Promises & mobilization of resources
- **Regulation, Market, Society:** Articulation of functionality, of demand, diffuse scenarios

### 3. Development in a protected space
- **Science:** Problem-solving
- **Technology:** Ongoing developmental work
- **Regulation, Market, Society:** Limited checks on patents, regulation, markets

### 4. Prototype
- **Science:** Trouble-shooting
- **Technology:** First implementation & tests
- **Regulation, Market, Society:** Identification of lead users, of first-round markets

### 5. Market introduction
- **Science:** Socio-technical demonstrators
- **Technology:** Tentative introduction

### 6. Adoption, diffusion
- **Science:** Rationalisation
- **Technology:** Service, adaptation, emerging standards
- **Regulation, Market, Society:** Market niches, branching out, linkages to other sectors

### 7. Wider changes
- **Science:** New questions, incl. impact monitoring
- **Technology:** Sectoral changes
- **Regulation, Market, Society:** (possibly) regime shift

![Figure 1.3](image-url)

This brief introduction to SNM has described the main concepts used in SNM. I conclude that SNM offers an appropriate theory for analysing bioenergy in the Netherlands and Denmark for the following two reasons. First, experiments with bioenergy have been conducted in the Netherlands and Denmark since the 1970s, but with different results. SNM offers a conceptual perspective to analyse the developments and offers possible explanations for these differences. It offers a framework for investigating the differences on the level of innovative practices, or niches. Second, investigating two different countries requires taking into account different country characteristics. The Netherlands and Denmark may differ in dominant technologies, regulations, firm strategies, user practices, etc., which may effect the possible outcome of niche development. The focus on niches against the backdrop of regimes offers the possibility of researching these differences by investigating the influence of the technological regime in each country.

Nevertheless, two considerations are important to take into account. First, the development and implementation of bioenergy technologies is at a different stage than electric vehicles were in previous SNM research. Large commercial diffusion never took off in any of
the electric vehicle cases, while the application of bioenergy technologies shows much more progress in this direction, especially in Denmark. Research on niche development of bioenergy technologies therefore offers a chance to investigate what happens further down the line, when technological niches evolve into market niches – or even contribute to regime changes. What enables the diffusion of sustainable technologies?

Second, electric vehicles were investigated against the backdrop of the transport regime. The transport regime is generally considered to be a very stable and strong regime that offers little room for developing alternatives. Bioenergy technologies, however, develop against the backdrop of different regimes, i.e. the electricity and/or heating regimes. These regimes, both in the Netherlands and Denmark, are characterised by having undergone major changes since the 1970s: the role of public authorities and environmental considerations became more important and a process of liberalisation and internationalisation set in. Both regimes changed and are still changing; much more than the transport regime, these regimes are in flux (Hofman and Marquart, 2001). What is the effect of this fundamental difference in the way niches and regimes are related or interact? Niche-regime interaction and stability in regimes therefore requires special attention in this thesis.

I will also discuss SNM as a policy strategy. SNM claims to be a tool for policy makers in introducing sustainable innovations. The case studies in this thesis can result in new insights into the way SNM can be used as a policy tool. However, I will not deal with this issue systematically; I only discuss what kinds of strategies are distinguished in SNM literature (Chapter 2), and speculate about possible strategies and outcomes on the basis of SNM insights and my case studies (Chapter 7).

1.4 Research questions, case studies and data collection

1.4.1 Research questions

I started this chapter with the main research theme of this thesis, i.e. the difference between the Danish and Dutch situations regarding bioenergy. I also introduced two technologies that are in particular interesting, i.e. manure digestion and co-firing. The main research question addressed in this thesis can now be formulated as follows:

1. How and why does the Danish development of bioenergy from manure digestion and co-firing differ from the Dutch development?

I address this question through a specific conceptual lens, i.e. the SNM approach. Insights and concepts from SNM guide the process of answering the question. However, as discussed above, SNM literature remains unclear about two issues, i.e. the emergence of market niches and the interaction between niches and regimes. Both issues are crucially important in understanding the differences between Denmark and the Netherlands. Consequently I will focus on these issues in my case study. By doing this I will not only provide an answer to my
research question, but also make a more theoretical contribution to the SNM approach. Since I focus on both issues, my thesis addresses the following two sub-questions:

a. What are the crucial factors for the emergence of market niches?
b. How does niche development interact with regimes?

Answering these questions has both scientific and societal relevance; it can contribute to further enhancing theories using the concepts of niches and regimes. In Chapter 2 I will review the literature in order to more thoroughly investigate possible theoretical implications. I will also design my cases such that I am able to derive theoretical implications from the cases (see below). This research also has societal relevance because it contributes insight into how niches develop, and this insight can contribute to improving or developing strategies for introducing bioenergy technologies.

1.4.2 Case study justification

In this thesis I follow the case study approach. Case studies are useful when investigating how and why questions, when there is no control over behavioural events and when there is a focus on contemporary events (Yin, 1994:6). Yin argues that for making generalisations, case study choice is important. The biggest advantage of a multiple case study design is that it allows ‘replication logic’. By contrasting carefully selected cases a researcher can strengthen his or her argument. If the cases are well chosen, a researcher can also derive theoretical implications from the case studies. In this thesis I investigate the experimental introduction of two bioenergy technologies, both in the Netherlands and Denmark, in the period after the first oil crisis in 1973, i.e. manure digestion and co-firing. Manure digestion in the Netherlands and Denmark represents a contrasting storyline. The Netherlands experimented with manure digestion, but failed to develop a substantial number of plants. In Denmark, manure digestion was developed more successfully in terms of numbers of plants. The co-firing case is interesting because the two countries show a similar outcome. In addition, the cases are interesting because they employ different types of application. Co-firing is a large-scale technology, mainly applied by traditional energy companies in centralised, large energy plants. Manure digestion, on the other hand, is a small-scale, decentralised option for energy generation, mainly applied by farmers. Or, in terms of the previously introduced concepts, co-firing represents a niche that is potentially much closer to the technological regime (fit-fit), than manure digestion (stretch-stretch).

In the next section I briefly present the basic technological configurations of manure digestion and co-firing. The aim of this section is to present a short introduction to the type of technologies that I will research in the case studies, not to give an elaborate overview of all technological configurations.
1.4.3 Manure digestion plants

In a manure digestion plant or ‘biogas plant’, animal manure is partly converted into a mixture of methane and carbon dioxide called biogas. In a biogas plant, manure from the farm (or farms) is stored and sometimes pre-treated (see Figure 1.4). In some biogas plants, additional organic sources (e.g. waste from food industries) are added. The most important part of a biogas plant is the anaerobic digester, in which part of the manure is converted into biogas. After cleaning and storage, the biogas can be used in the production of energy. The manure leaving the digester can be processed further and stored or used directly as a fertilizer on farming land.

The heart of a biogas plants is the anaerobic digester. Inside the reactor, the manure is stored in the absence of oxygen for a period of ten to thirty-six days, depending on the type of manure. Microbes and enzymes convert the manure in three steps (hydrolysis, fermentation and methane formation) into biogas. The biogas yield depends on many parameters, with one of the most important being the process temperature. Generally, three types of temperature ranges are distinguished: psychophilic temperature (10°C to 25°C), mesophilic temperature (25°C to 35°C) and thermophilic temperature (49°C to 60°C). Most current biogas plants operate at mesophilic or thermophilic temperatures.

There are many different types of anaerobic reactors, each designed for specific types of organic matter. Generally, these reactors can be divided on the basis of different modes of feeding. In batch-systems, fresh manure is added together with a small amount of digested manure to the reactor. After three to four weeks, the entire reactor is emptied and a new amount of fresh manure is added. These systems are often used for the digestion of straw-rich material. In continuous-flow (ADF) systems, the reactor is also the manure pit. As it is produced, fresh manure flows into the digester. The digested manure is removed occasionally, when it is needed for fertilising, or it overflows into a holding tank, from which it can be used for further purposes. The most used system is the continuous-flow tank reactor (or completely mixed reactor). The manure is pumped into the digester one or two times a day, displacing an equal volume of digested material into a storage tank. Old and new manure is completely mixed in the reactor and the volume in the reactor remains constant.

In addition to these three basic designs, there are numerous variations in reactors (size, horizontal or vertical, building material, isolation material, etc.). Wide variation is also possible among additional components like mixing systems inside the reactor (for maintaining a homogeneous mixture and preventing the formation of scum layers), heating systems (for keeping the manure at a steady temperature) and pumping systems (for supplying and removing manure).

On the supply side of the digester, there are two steps in the process. First, a special tank is often used for manure storage, in particular when manure from more than one farm is

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22 Biogas plant is a common term for referring to anaerobic digestion plants that process organic matter and not just manure. In this thesis, however, I will only use the term to refer to manure digestion plants. The description of manure digestion plants is based entirely on Wellinger (1999) and Nes, Diemen and Schomaker (1990).
digested. If the digester is located on a farm, the manure can be stored in existing storage systems, e.g. under the stable. If the manure comes from different farms, there may also be loading and unloading equipment and special transportation equipment. Moreover, some biogas plants add organic waste to the process (codigestion), because it increases biogas yields. This requires special storage facilities and unloading equipment for the organic waste. Second, some biogas plants are equipped with pre-processing equipment, in particular when the plant employs codigestion. The processing equipment is used for the removal of undesired particles, size reduction or for blending different waste streams. It can also include a special hygienic (or sanitation) step to kill pathogens. Sometimes, the storage equipment and pre-processing steps are combined.

Figure 1.4. Basic layout of a biogas plant

After the manure leaves the digester, several more steps are important. Most biogas plants are equipped with a manure storage tank for digested manure. These tanks do not differ much from traditional storage equipment in agriculture, although some are equipped with integrated gas storage systems. The manure can also be further processed in post-treatment equipment, which may include a hygienic step at a high temperature to further reduce the risk of pathogens spreading. Other post-treatment equipment includes separation technologies like mechanical separation or reversed osmosis, and volume reduction technologies like drying. Post-treatment technologies are usually installed when the manure has to be transported over long distances or when the plant is designed to produce fertilizer products. Other steps after digestion are biogas cleaning, storage and utilisation. Biogas often contains small amounts of pollutants, the most important of which is hydrogen sulphide (H$_2$S), which can seriously damage the utilisation equipment. Cleaning the biogas can be done by absorbing the H$_2$S with liquid or solid substances, in particular substances that contain iron oxide. The most applied technology nowadays is biological cleaning, which adds a little air to the biogas, while microbes break down the H$_2$S. After cleaning, the biogas can be stored in gasbags and used in different applications, the most important being gas appliances for generating heat (e.g. for household or stable heating), combustion engines for generating electricity (either for home use or for supplying it to the grid), combined heat and power units or technologies for upgrading the biogas and injecting it into a natural gas grid.
Manure digestion plants can be divided into farm-scale plants and community plants (or centralised plants). In a farm-scale plant a single farmer digests manure, while in a centralised plant groups of farmers supply manure to a single plant. Centralised biogas plants tend to be larger, are more complex (e.g. loading and unloading and transport equipment at central plant, logistics) and have different organisational structures (e.g. limited firms or cooperatives). Furthermore, such plants produce for different markets: farm-scale plants mainly produce energy and fertilizer for home use (although they often sell power to energy companies), while centralised plants often sell products (fertilizer, heat, power) commercially.

1.4.4 Co-firing

In co-firing plants, biomass and fossil fuels (in particular coal) are combusted together.\textsuperscript{23} Almost all current co-firing plants are extensions to an existing coal-based combustion plant. A general coal plant operates as depicted in Figure 1.5: Coal is delivered and stored on location. Before it is supplied to the boiler, a milling and grinding system reduces the coal to the size required for the combustion process. Most large, coal-fired power plants in the Netherlands and Denmark are \textit{pulverised coal plants} (PC plants). In PC plants, coal particles of sizes smaller than 1 mm (pulverised), are blown with part of the combustion air into the boiler through a series of burner nozzles. Secondary and tertiary air may also be added in different parts of the boiler. PC plant technology is well developed worldwide and accounts for 90\% of all coal combustion technologies. Generally, PC plants are large (over 300 MW) and have high efficiencies. Other types of coal plants are \textit{stoker boilers} (or grate-fired plants) and \textit{fluidised bed plants}. Most stoker boilers are equipped with a moving grate or chain, with coal lumps continuously fed on the grate or chain. Air is blown through the grate and through the coal bed on top of the grate. The chain or grate moves the coal slowly into the region where ignition is executed. The coal gradually burns off, leaving ash that drops off at the end in a receptacle, from which it is removed for disposal. Stoker boilers come in small sizes ranging from 10-25 MW. In fluidised bed plants, the air velocity is higher, resulting in a bubbling bed of burning coal parts and air (bubbling fluidised bed, BFB). With a very high air velocity, the air and coal parts circulate through the boiler (circulating fluidised bed, CFB plant). CFB plants are the most commonly used power plants in the market for smaller sized boilers. They have capacities up to 300 MW; efficiencies are generally a little lower than for PC plants of similar sizes. In all plants (PC, stoker boilers, CFB), the hot gasses from the combustion process heat water to steam with a high temperature and pressure. The steam is led through a steam turbine, which drives a generator. The generator produces electricity, while the steam (at a lower pressure) is led to a condenser. The condenser cools the steam and supplies the water which goes back into the boiler. Inside the condenser, the heat is transferred to cooling water, which can be used for heating purposes (e.g. a district heating system). In the boiler, ashes are removed and can be recycled for concrete or asphalt.

\textsuperscript{23} This description is based on data from Ree et al. (2000) and the website of the IEA Clean Coal Centre (http://www.iea-coa.co.uk).
production. The flue gasses leaving the boiler are first cleaned from unburned particles and dust, often followed by desulphurisation systems. Fly ashes are also recycled, e.g. in cement production. Finally, the gasses leave the plant through a chimney.

There are many options for co-firing biomass in a coal-fired power plant. The first and least complex is direct co-firing (I in Figure 1.5). In this case, the biomass is supplied to the plant location and stored on site. From that point, the biomass is directly introduced into the conventional coal plant, without any treatment. The biomass is reduced to smaller sizes in the same pre-treatment equipment that mills and grinds the coal. The small coal and biomass particles are combusted together inside the boiler in the same burners or on the same grate. In the second case, indirect co-firing with mechanical pre-treatment (II), biomass is also supplied and stored on location, but the biomass undergoes a separate mechanical pre-treatment step before it is supplied to the boiler. Mechanical pre-treatment depends on the type of biomass used, but can include steps like size reduction and contamination removal. After pre-treatment, the biomass is supplied to the boiler and combusted in separate biomass burners. In the case of indirect co-firing with thermal pre-treatment (III), biomass is pre-treated both mechanically and thermally. The two most important options for thermal pre-treatment are gasification and pyrolysis, but other technologies for thermal pre-treatment are also investigated (e.g. hydrothermal upgrading). The syngas, bio-oil and/or char produced in these processes can be decontaminated first or directly supplied to the coal boiler and combusted in separate burners. Finally, in the case of parallel co-firing (V), the biomass is combusted in a separate boiler, but the steam cycle of the biomass boiler is integrated into the coal plant’s steam cycle.

The level of adjustments to the coal plant varies, depending on the chosen system. In all cases, the introduction of biomass into the combustion process requires adjusting the process conditions to reflect the different combustion characteristics of biomass and coal. The huge variety in biomass sources makes switching between biomass fuels difficult. In the case of direct co-firing, limited construction or investment is required; only supply equipment (e.g. for unloading) and storage equipment is necessary. However, direct co-firing can have far-reaching consequences for the fuel supply network or for the efficiency of a power plant. In the case of mechanical pre-treatment, more adjustments are needed (for example, the construction of wood mills or separation technologies), but still the changes made to the existing plant are limited. In the cases of thermal pre-treatment and parallel co-firing, however, a new biomass facility is needed. This can be conventional biomass combustion technology, but also more advanced options like gasification or pyrolysis. Generally, the more a biomass system is integrated into the coal system, the more construction work and investment is required. However, more advanced integration has the advantage of enabling higher biomass/coal ratios and more variety in biomass fuels. Another advantage is that the bottom ashes from biomass and coal combustion are kept separate. This can be an advantage when reusing the bottom ashes in industries like road construction and concrete production. Finally, the efficiency of the overall process can be higher, because the combustion or gasification processes are specifically designed for biomass. Currently, the most applied method for co-firing is indirect co-firing with mechanical pre-treatment.
Figure 1.5. Representation of different types of co-firing plants: I is a standard coal-fired plant; II is a direct co-firing plant; III is an indirect co-firing plant with mechanical pre-treatment; IV is an indirect co-firing plant with thermal pre-treatment; V is an indirect co-firing plant with a separate biomass boiler and integrated steam cycles.
1.4.5 Data collection

Using case studies as a research strategy is often considered to be open to the researcher’s subjective interpretation, especially if the boundaries of the research are not strictly defined or known. Yin (1994:78) argues that the advocacy of an argument should come from multiple sources of evidence. He distinguishes between six sources: documents, archival records, interviews, direct observation, participant-observation, and physical artefacts. Although each source has its strength and weaknesses, combining the findings from several sources helps build the evidence. A researcher should strive to “converge multiple sources of evidence into a fact”.

Most of the data I collected came from printed documents (including internet sources) and interviews, and to a lesser extent from physical artefacts and direct observation. Documents, both primary and secondary sources, have the advantage that they can be reviewed by others and can contain exact information on dates, names and other facts. The disadvantage is that they may be biased, due to an author’s personal interpretation or due to selectivity (important documents are missing). It is important to read critically and pay attention to possible biases. Comparison of documents from different sources can also be used to become aware of biases. I have included the following documents for data collection:

- official policy documents at the national and European levels (e.g. White Papers on energy)
- reports from research institutes, universities, consultancy firms, etc.
- articles from scientific journals
- articles from popular journals and newspapers
- conference proceedings
- minutes and slides from meetings
- books on (bio-) energy, (bio-) energy policy
- informative internet sites on (bio-) energy
- governmental and semi-governmental internet sites
- internet sites of energy companies
- internet sites of interests groups
- statistics from national and European statistics offices

Interviews were conducted as a second source of evidence. Interviews offer the opportunity to collect much information in a limited amount of time, to acquire information that might be difficult to find elsewhere, to acquire information about recent developments that have not yet been documented, and to access new actors (snowball effect). The major drawback of interviews, however, is that the information is often biased or selective. Again, I have tried to combine the information from different sources (interviews, documents) as much as possible. All interviews were conducted following an open-ended interview strategy. I prepared all interviews with open questions or themes that I wanted to discuss or wanted the respondents’
opinions about. Afterwards, I drew up interview reports and sent the reports back to the respondent for verification. The following people were interviewed:

**The Netherlands**

<table>
<thead>
<tr>
<th>Name</th>
<th>Position and Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andre de Boer</td>
<td>Employee of The Netherlands Agency for Energy and the Environment (Novem). Responsible for stimulating research and experiments for biogas plants in the Netherlands</td>
</tr>
<tr>
<td>Hans Smulders</td>
<td>Manager of manure distribution company Mestac and responsible for the Biorek Agro biogas plant in Elsendorp, the Netherlands</td>
</tr>
<tr>
<td>Harm Kruijdenberg</td>
<td>Responsible for the Dutch National Programme on Reuse of Waste (NOH)</td>
</tr>
<tr>
<td>Hendrik Jan van Doorn</td>
<td>Researcher at the Dutch Animal Sciences Group (Praktijkonderzoek Rundveehouderij); this institute implemented three biogas plants in the Netherlands after 2000</td>
</tr>
<tr>
<td>Henk Kasper</td>
<td>Manager of the Scharlebelt biogas plant in Nijverdal, the Netherlands</td>
</tr>
<tr>
<td>Marc Buiter</td>
<td>Research employee of the Dutch consultancy agency ETC and involved in several biogas research projects</td>
</tr>
<tr>
<td>Rob Remmers</td>
<td>Employee of the Dutch energy company Essent and concerned with different kinds of bioenergy projects in the Netherlands including co-firing and biogas plants</td>
</tr>
<tr>
<td>Theo Bijman</td>
<td>Manager of Thecogas (previously Ecogas), a Dutch biogas company</td>
</tr>
<tr>
<td>Lood van Velsen</td>
<td>Employee of the Dutch engineering company Haskoning and involved in biogas research and experiments in the 1970s and 1980s in the Netherlands</td>
</tr>
<tr>
<td>Wim van der Hulst</td>
<td>Employee of the province of Noord-Brabant (the Netherlands) and concerned with biogas projects in this region</td>
</tr>
</tbody>
</table>

**Denmark**

<table>
<thead>
<tr>
<th>Name</th>
<th>Position and Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morten Tony Hansen</td>
<td>Employee of the Danish consultancy company Dk-Teknik, participant in the Danish Centre for Biomass Technology</td>
</tr>
<tr>
<td>Sigurd Lange Pedersen</td>
<td>Senior advisor at the Danish Energy Agency</td>
</tr>
<tr>
<td>Hakon Mosbech</td>
<td>Head of R&amp;D at the Danish utility Energi E2 and concerned with the co-firing plant Avedore 2</td>
</tr>
<tr>
<td>Peter Overgaard</td>
<td>Head of the Biomass division at Elsam Engineering (previously Tech-Wise), part of the Danish Utility Elsam, and concerned with the co-firing plants Studstrup 4 and Enstedvaerket</td>
</tr>
<tr>
<td>Claus Friborg</td>
<td>Co-firing specialist at Elsam Engineering and concerned with the co-firing plants Studstrup 4 and Enstedvaerket</td>
</tr>
<tr>
<td>Kurt Gregersen</td>
<td>Employee of the Bioenergy Department, Southern University, Esbjerg</td>
</tr>
<tr>
<td>Jens Bo Holm-Nielsen</td>
<td>Employee of the Bioenergy Department, Southern University, Esbjerg</td>
</tr>
<tr>
<td>Teodorita Al Seadi</td>
<td>Employee of the Bioenergy Department, Southern University, Esbjerg</td>
</tr>
<tr>
<td>Lars Nielsen</td>
<td>Employee of the Danish Risø Laboratory</td>
</tr>
<tr>
<td>Johannes Christensen</td>
<td>Head of the Farm Management and Production Systems Division of the Danish Research Institute of Food Economics (FOI) and chairman of the Biogas Action Programme</td>
</tr>
<tr>
<td>Niels Meyer</td>
<td>Professor Emeritus of the Department of Civil Engineering of the Technical University of Denmark; researcher in the field of renewable energy in Denmark and participant of the Committee for Renewable Energy (1982-1991)</td>
</tr>
<tr>
<td>Ejvin Beuse</td>
<td>Employee of the Danish Organisation for Renewable Energy (OVE)</td>
</tr>
</tbody>
</table>
In addition to document analysis and interviews, I also visited several (experimental) plants. This was of course dependent on whether the experiments still existed, and if they were accessible. Often the visits were combined with an interview. Although the visits did not contribute directly to data collection, I was often able to get a more accurate impression of the research phenomenon, as well as improved insight into the technological operation, scale or complexity of the experiment. I visited the following plants:

<table>
<thead>
<tr>
<th>The Netherlands</th>
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<tbody>
<tr>
<td>Amer-9</td>
</tr>
<tr>
<td>Gasifier and co-firing plant in Geertruijdenberg</td>
</tr>
<tr>
<td>Praktijkcentrum Sterksel</td>
</tr>
<tr>
<td>Farm-scale biogas plant in Sterksel</td>
</tr>
<tr>
<td>Scharlebelt</td>
</tr>
<tr>
<td>Centralised biogas plant in Nijverdal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thørso biogas plant</td>
</tr>
<tr>
<td>Centralised biogas plant in Thørso</td>
</tr>
<tr>
<td>Green Farm Energy</td>
</tr>
<tr>
<td>Farm-scale biogas plant in Hadsten</td>
</tr>
</tbody>
</table>

Finally, direct observation was possible during a visit to Denmark. I participated in two meetings of the Danish biogas community (which included biogas plant operators, researchers, and public authorities). This helped me gain insight into the knowledge exchange between different participants and provided me with a better understanding of the daily operation of the Danish Biogas Action plan.

1.5 Outline of the thesis

In the following chapter I discuss SNM and some background literature. In doing so, I focus especially on evolutionary theories and on Constructive Technology Assessment. I do not discuss all potentially usable theories, as this thesis has other objectives. Instead, I discuss in detail the theoretical insights used in SNM and identify shortcomings and puzzling aspects. I will then discuss additional literature that can be helpful in dealing with SNM’s shortcomings. Based on the discussions, I formulate a research protocol for the four experimental chapters. Chapter 3 is the first empirical chapter and discusses the manure digestion case in the Netherlands. This case is interesting because it gives explanations for the failed introduction of manure digestion in the Netherlands. In Chapter 4 I discuss the Dutch co-firing case. I will show that the use of biomass in centralised power stations increased rapidly between 1993 and 2003. However, the case study also illustrates that in particular the societal embedding of co-firing is still problematic, endangering the further expansion of this renewable energy technology in the Netherlands. In Chapter 5, I continue with the manure digestion case in Denmark. In contrast to the Dutch, the Danes were able to implement many centralised and farm-scale biogas plants. However, also in this case further expansion is uncertain, in particular because of the liberalisation process in the Danish electricity sector. Chapter 6 discusses the Danish co-firing case. The development of co-firing plants in Denmark was stimulated through political agreements between the Danish government and the Danish
parliamentary opposition, and resulted in several co-firing plants in Denmark. Despite numerous technical problems, the Danish utilities continued to develop co-firing, especially after 2000, installing several permanent co-firing plants. Chapter 7, the last chapter of this thesis, brings together the insights from the empirical chapters. I compare the four cases and answer my research questions. Finally, I discuss a future research agenda for SNM.
## Appendix 1.1

Table 1.2. Some issues regarding biomass sources, availability and use in Finland, Sweden, Austria, Denmark and the Netherlands

<table>
<thead>
<tr>
<th>Country</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Finland</strong></td>
<td>Wood is the main source for bioenergy in Finland. In 2000, the percentage of energy from wood was about 20% of the total energy consumption. About half of the energy from wood is produced from black liquor, a by-product of the wood processing industry (Alakangas and Vesterinen, 2003).</td>
</tr>
<tr>
<td><strong>Sweden</strong></td>
<td>In 1997, biomass contributed 284 PJ/yr to the primary energy demand in Sweden. In 1994 the main share of the biomass energy (170 PJ) was used in industry. The rest was used in district heating plants and households. Only a small part of the wood fuels is sold on the market. In 1995 approx. 284 PJ or approx. 17% of the total energy supply was supplied from biomass. The largest share originated from digester liquors, a by-product of the wood processing industry (108 PJ), and from by-products of wood industries like sawdust and bark (58 PJ). The residential use of wood was about 43 PJ/yr. In the district heating sector (consisting of about 100 biofuel-fired plants) approx. 35.3 PJ heat and 0.7 PJ electricity was produced from wood fuels during 1996 (Rijpkema, van den Berg and Haren, 1997:128-132).</td>
</tr>
<tr>
<td><strong>Austria</strong></td>
<td>A relatively large part of the country is covered with forest (39% of the 92700 km²). Biomass is especially well established for heating: 19% of the buildings use biomass for heating, typically in small-scale stoves. These small stoves are used in 35% of the houses, whereas 56% is equipped with a central heating system and 10% is connected to a district heating system. The biomass used for heating mainly originates from forestry: fuel wood and scrap wood account for 98.4% of the energy from biomass. Around 1987 Austria also started developing district-heating networks fired with biomass. In 1997 over 200 plants existed. There is little cogeneration of heat and power due to the large amount of electricity available from hydropower, which covers a large part of the demand in summer. Due to the extensive forests and active forestry, large, cultivated wood reserves are available in Austria (Rijpkema, van den Berg and Haren, 1997:11-16).</td>
</tr>
<tr>
<td><strong>Denmark</strong></td>
<td>In Denmark about 8% of TPES came from biomass in 2000, of which the greater part was municipal solid waste (46%). Other biomass fuels are straw (20%), firewood (16%), wood waste (10%) and wood pallets and chips (7%). The major part of the wood is harvested from a forest area of about 460,000 ha, but in order to increase the contribution of wood to renewable energy production, wood resources have to increase, either through forestation or importation (Frandsen, 2002).</td>
</tr>
<tr>
<td><strong>Netherlands</strong></td>
<td>In the Netherlands, 80% of the renewable energy is generated by biomass. Within biomass, the major contribution is energy from household waste in 12 waste incinerators with energy recovery. In general, a large number of biomass flows are found in the waste, agricultural, and forestry sectors. The major increase in contribution after 2000 is in the field of biomass co-firing in five existing coal-fired power plants. Biomass is mainly used for electricity generation in municipal waste incineration plants, energy production from landfill gas, biomass co-firing in coal-fired plants, combustion of wood in households and wood processing industries by four combined heat and power plants and through digestion of organic waste (Kwant, 2002).</td>
</tr>
</tbody>
</table>
Chapter 2.
Conceptual framework

2.1 Introduction

In this chapter I discuss the conceptual framework I use to answer my research question. I discuss several puzzles and problems of Strategic Niche Management (SNM) and suggest several improvements based on the literature. I begin, however, with positioning SNM in the literature. SNM emerged from two bodies of literature, evolutionary theories on technical change and constructive technology assessment (CTA). The former aims to understand and explain the process of technological change, while the latter aims to provide insights into steering or managing this process. SNM can be used for both aims (as research model or policy tool). I will discuss evolutionary theories and CTA in section 2.2; section 2.3 continues with discussing the research model SNM; section 2.4 deals with puzzles and problems related to this model and explores new insights; then, in section 2.5, I discuss the policy tool SNM, referring to SNM as a tool for steering and managing technological change. The chapter ends (2.6) with a research protocol for doing my case studies.

2.2 A review of the relevant literature

2.2.1 Evolutionary theories on technological change

Evolutionary theories originally emerged as a reaction to neo-classical economic theories. The main criticism on neo-classical theories was threefold. First, evolutionary economists criticised the neo-classical literature because of the simple characterisation of firms and the way these firms used information. Second, they criticised the literature because neo-classical theories were much too static to do justice to the dynamic nature of economic processes. The third criticism focused on the exogenous treatment of technological change in the theories (Duysters, 1995:19). Evolutionary theorists built upon the Darwinian concepts of variation and selection, in particular to understand and explain economic growth; technology was only relevant because it affected the firms’ profitability (Geels, 2002a:47). Historians and sociologists have also used evolutionary concepts, but for understanding and explaining the rate and direction of technological rather than economic change. In this section, I will focus on evolutionary approaches to technological change.

Basic evolutionary concepts

The economist Schumpeter was the first to mention evolutionary aspects in economic processes and technological change. In his view, technical change was a process of unfolding, or creating new combinations and he emphasised the evolutionary character of change...
(Schumpeter, 1934:66, from Geels, 2002:1258). In the late 1970s and early 1980s, Nelson and Winter (1977, 1982) and Dosi (1982) elaborated on the evolutionary characteristics of economic and technological change. In the 1990s, various strands of evolutionary theories were developed, including theories on routines and trajectories, on the population of firms, on path dependencies and on systems of innovations (Lente and Rip, 1992:4).

The fundamental mechanisms in evolutionary theory are variation, selection and retention (Duysters, 1995:20). Technological variation refers to the creation of technological designs by engineers and scientists in R&D laboratories or research institutes, on the basis of trial and error. Variation is the equivalent of random mutations in biological evolution, while selection refers to users choosing the design they prefer. In other words, variations are judged in a selection environment. A design is successful if it is (repeatedly) selected in the selection environment; unsuccessful designs are abandoned – this is the equivalent of the ‘survival of the fittest’ in biological selection. Finally, retention refers to the mechanisms that retain successful variations. In evolutionary theories, routines are often considered an important retention mechanism. Engineers and designers develop routines on the basis of designs picked in the selection environment; they learn what characteristics the selection environment prefers. Routines are equivalent to genes in biological systems.

When a design emerges as successful, engineers and designers direct most efforts towards improving the design. They develop routines such as heuristics or rules of thumb, resulting in a decreased variety of technological designs. A dominant design emerges when the firm that introduced the innovation grows or when other engineers and firms imitate the design. Routines become shared among the engineering community and across firms. The shared routines can result in a specific pattern of technological change. Dosi (1982:152) called the set of shared routines (or “normal problem solving activity”) a ‘technological paradigm’. He called the emerging pattern a ‘technological trajectory’. Nelson and Winter (1982:258) introduced the concept of ‘technological regime’: technicians’ beliefs about what is feasible or at least worth attempting. They referred to the emerging pattern as ‘natural trajectories’. Once established, technological paradigms or regimes direct technological progress along trajectories, and improvements along certain lines. A technological variation is no longer completely random. Certain variations (close to the dominant design) are preferred above others, in line with prevailing routines and beliefs. This has two consequences. First, it reduces uncertainty: engineers are able to anticipate the selection environment; they have specific ideas about what works and what the user prefers. Second, most variation that occurs is of an incremental nature.

**Broad regime definition**

This basic evolutionary model, as outlined above, has two fundamental problems. First, too much emphasis is placed on the embedding of retention (routines) in the minds of engineers.

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1 In research on firm population, variation and selection refer to the organisational structures and strategies of firms rather than technological designs. See for example Duysters (1995:20).

2 The analogy with biological ideas of variation, selection and retention is used only for clarification. I do not intend to use these concepts strictly the same as they are used in biological sciences.
Second, the model provides no explanation for the emergence of radical innovations once a technological regime has been established. I will discuss these problems subsequently.

In the basic evolutionary model it is argued that retention is a cognitive mechanism (routines, rules of thumb), embedded in the minds of engineers. The model fails to address mechanisms outside the minds of engineers. Rip and Kemp (1998) use insights from historical, sociological and actor-network studies to argue that a technological regime is also embedded in production technologies, infrastructures, institutions, etc.\(^3\) They introduce the concept of ‘rules’ to define a technological regime as follows:

A technological regime is the grammar or rule-set embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems – all of them embedded in institutions and infrastructures.

Rip and Kemp broaden the technological regime concept. The notion of rules emphasises that technological trajectories emerge not only from routines, but also from a broader set of retention mechanisms. Rules, a concept used in sociology, refer to some sort of shared structure (e.g. routines, norms, protocols etc.) that guide local behaviour. Scott (1995) distinguishes three dimensions of rules: regulative, normative and cognitive rules. Geels (2004) uses these dimensions to illustrate how rules coordinate and structure actors’ behaviours in technological development (Table 2.1). The regulative dimension refers to explicit formal rules which constrain behaviour and regulate interactions. Examples are laws, incentive structures, protocols and standards. Normative rules are the type that traditional sociologists tend to focus on. Examples are values, norms and role expectations. Cognitive rules constitute the nature of reality; they give meaning to or make sense of the world. Examples of cognitive rules are priorities, problem agendas, beliefs and search heuristics.

---

Table 2.1. Three kinds of rules/institutions (Scott, 1995, in: Geels, 2004)

<table>
<thead>
<tr>
<th></th>
<th>Regulative</th>
<th>Normative</th>
<th>Cognitive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Examples</strong></td>
<td>Formal rules, laws, sanctions, incentive structures, reward and cost structures, governance systems, power systems, protocols, standards, procedures</td>
<td>Values, norms, role expectations, authority systems, duty, codes of conduct</td>
<td>Priorities, problem agendas, beliefs, bodies of knowledge (paradigms), models of reality, categories, classifications, jargon/language, search heuristics</td>
</tr>
<tr>
<td><strong>Basis of compliance</strong></td>
<td>Expedience</td>
<td>Social obligation</td>
<td>Taken for granted</td>
</tr>
<tr>
<td><strong>Mechanisms</strong></td>
<td>Coercive (force, punishments)</td>
<td>Normative pressure (social sanctions such as ‘shaming’)</td>
<td>Mimetic, learning, imitation</td>
</tr>
<tr>
<td><strong>Logic</strong></td>
<td>Instrumentality (creating stability, ‘rules of the game’)</td>
<td>Appropriateness, becoming part of the group (‘how we do things’)</td>
<td>Orthodoxy (shared ideas, concepts)</td>
</tr>
<tr>
<td><strong>Basis of legitimacy</strong></td>
<td>Legally sanctioned</td>
<td>Morally governed</td>
<td>Culturally supported, conceptually correct</td>
</tr>
</tbody>
</table>

The broad definition of a technological regime suggests that retention is embedded not only in the variation environment, but also in the selection environment, for instance in user practices and government policies. Schot (1991:84; 1992) argues that (through a technological regime) variation and selection are aligned and he investigates what linkages between variation and selection can be distinguished. Following the quasi-evolutionary approach introduced by Van den Belt and Rip (1987), he proposes three types of linkages. First, engineers and designers anticipate the future selection environment inside laboratories. They develop variations on the basis of what they expect the future selection environment will look like. Engineers’ expectations thus link the selection and variation environments. Second, linkages can occur in a ‘nexus’, where variation and selection are explicitly brought together. Company marketing departments are an example: in a marketing department, variation and selection are linked through market research. Third, actors can try to create a protected space outside the laboratory (a niche) to expose novel variations to the selection environment, but protect such variations from a too rapid and rigid selection. In a niche, variations and selection are linked through users or other stakeholders who give feedback to technology producers about the use of technologies in real-life circumstances.

Geels (2004) refines the concept of technological regime. First, he makes an analytical distinction between rules, socio-technological systems (including knowledge), and human actors and social groups (see Figure 2.1). This figure illustrates that regimes are a dynamic concept. Rules can change; they do not determine actor behaviour or technological development. Rules exist because they are supported and reproduced by social groups. Complex interactions between human actors, technological change and rules can produce tensions in the triad or in parts of it (e.g. a mismatch between the preferences and views of

---

4 Van Lente (1993) has extensively investigated the role of expectations in technological development.
different social groups). Second, Geels introduces the concept of socio-technical regime to emphasise that many social groups, not only the engineering community, incorporate rules, as illustrated in Figure 2.2. Actors within a specific social group (like the social groups of consumers, policy makers or engineers) share routines, perceptions and other rules specific to that social group. Geels calls these regimes 'user and market regime', 'policy regime', 'technological regime', etc. A socio-technical regime refers to the alignment of the rules upheld by the different social groups and is centred around a technological system or technological artefact. Thus, the electricity regime, for example, refers to the alignment between the rules upheld by users (e.g. their preferences regarding electricity supply), policy makers (e.g. regulations regarding emissions), engineers (e.g. design heuristics regarding power production), etc. A socio-technical regime results in a socio-technical trajectory, the pattern that emerges from dominant practices in engineering, use, policy making, scientific research, etc. This trajectory can be defined in terms of technological characteristics (e.g. size, efficiency), but also in terms of socio-economic characteristics (e.g. increasing demand).

Figure 2.1. Three interrelated analytic dimensions (Geels, 2004:9)

Figure 2.2. Meta-coordination through socio-technical regimes (Geels, 2004:13)
Radical innovation and niches

The second problem in the basic evolutionary model for understanding technological change is that it does not explain radical innovation. Variety in technological designs will eventually be minimised in this model, because the cycle of variation, selection and retention implies the emergence of one dominant design. Then how do radical innovations come about? How does a new technological regime emerge? Following Kuhn (1970), Van den Belt and Rip (1987: 141) argue that the success of a paradigm (or regime) is initially largely a promise of success: “Drawing on the expectations about the success of the heuristics, influence is exerted on the selection environment and a niche is created that protects the trajectory against too harsh a selection”. They offer the example of the development of the Stirling engine at the Dutch Philips company. No Stirling engine was ever produced for a market, but Philips extensively researched and developed it for a long time. Expectations about the future selection environment created a niche for the Stirling engine in R&D activities. There was selection on the basis of expectations, not on the basis of actual market failure or success. A protected space in R&D activities, created on the basis of expectations, enabled engineers to focus on the development of a technology that was (potentially) a radical innovation, but had no contemporary market value.

Levinthal (1998) also uses the concept of niches, but differently. He starts with the punctuated equilibrium framework of evolutionary biology. Variation does not hinge on a single mutational event, but on genetic variation in a distinct selection environment. Levinthal uses this analogy for his evolutionary perspective on technological development. Like in evolutionary biology, a new application domain (a different selection environment) can trigger the development of an evolutionary (technological) trajectory different from the dominant trajectory. He distinguishes between two important forces. First, the new domain of application may have a distinct basis of selection; functionality and price sensitivity are likely to differ substantially across domains. A new application domain may value particular elements of functionality that were largely irrelevant in the domain in which the technology was applied previously. Application of the technology in the new domain triggers a new technological trajectory. Second, domains may differ substantially as to the resources they are associated with. While a new application domain may have a different set of selection criteria, if the resources in the niche are quite limited, a new technological trajectory will probably not develop rapidly. The combination of a different set of selection criteria and the presence of a substantial amount of resources to support innovative activities may result in the development of a new trajectory. Eventually, after a period of development in the isolated niche, the innovation may invade other niches, or even the mainstream market. This does not necessarily mean that the new technology replaces the old one. Technologies from previously separated application domains may be combined in either one of the domains (‘convergence’), or the combined technologies may be applied in a third application domain (‘fusion’).

I criticise Van den Belt and Rip’s and Levinthal’s approaches, because in order to understand radical change they focus either on the variation environment (Van den Belt and Rip) or on the selection environment (Levinthal). In the work of Van den Belt and Rip, niches are seen as protected spaces in R&D activities. Levinthal sees niches as separate application
domains with distinct selection criteria. Neither approach explains how innovations can affect and be part of radical transformations in both the variation and selection environment. In Schot’s work, more emphasis is placed on the co-evolution of variation and selection (Schot, 1991). Schot et al. (1996) introduce the concept of ‘technological niche’. A technological niche is situated in-between the variation and selection environment. In a technological niche, distinct selection mechanisms are created through (temporary) protection, e.g. in the form of subsidies or expectations about future markets. Protection enables a (temporary) exemption from dominant regime rules; there is space for a new set of rules to emerge. Technological niches are thus located between early technological variation in R&D niches on the one hand, and selection of the variations in market niches with distinctive selection criteria on the other. The advantage of considering technological niches as the locus for radical innovation is that such a view improves understanding of the emergence of new variation and selection rules, and thereby the emergence of a new socio-technical regime.

**Multi-level perspective**

A group of Dutch authors has combined the insights listed above into a multi-level perspective. The first level is the level of socio-technical regimes, which I have already discussed in detail. A socio-technical regime should be understood as a dynamic concept: rules (regulative, normative, cognitive), embedded in human actors and technical systems and artefacts, provide structure and stability to technological development, but do not determine it. The second level is the level of niches, at which actors experiment with new variations in a protected environment (see previous section). Niches are the breeding places for radical innovations and create linkage between the variation and selection environments. The third level in the model has not been discussed previously. This is the level of ‘socio-technical landscape’ (see below). Originally, the model was developed to understand regime shifts: the shift from one stable regime to another stable regime. I describe the model, because previous research on SNM is an elaboration of one of the levels (niches). In this section, I will focus on what this body of literature says about the interaction between the levels, and in particular about the interaction between niches and regimes. First I briefly discuss the level of the socio-technical landscape.

In the multi-level perspective, socio-technical regimes and technological trajectories are embedded in a wider context consisting of deep structural trends, external to the development of the regime. For this level, Rip and Kemp (1998) introduced the concept of ‘socio-technical landscape’ to refer to the relatively hard material and immaterial context of societies. Natural resources, infrastructures (electricity, roads, city planning), political cultures and coalitions, political cultures and coalitions,

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5 See also Schot, Slob and Hoogma (1996), Kemp, Schot and Hoogma (1998) and Hoogma et al. (2002).
7 The levels in the model are not ontological descriptions of reality, but analytical and heuristic concepts designed to understand the complex dynamics of socio-technical change (Geels, 2002:1259).
8 Although socio-technical landscapes can also be distinguished on the level of firm organisation or everyday life in households, Rip and Kemp specifically introduced them on the level of societies (Rip and Kemp, 1998:334).
lifestyles, macro-economic aspects (oil prices, recessions), demography, and so on are part of this wider context (Geels and Kemp, 2000:18). The heterogeneous set of factors limits the number of possible directions for technological trajectories. Some technological trajectories face less resistance than others (see Figure 2.3). Analytically, the socio-technical landscape is important because it is the context that forms an external structure for the influential sphere of actors. It emphasises that actors cannot shape all factors.

Figure 2.3. Topography of technological development (Sahal, 1985:79)

The three levels in the model can be understood as a nested hierarchy (Figure 2.4). The differences between niches, regimes and landscape can be viewed as the level of structuration they provide to local practices (Schot, Lintsen and Rip, 1998:38; Geels, 2002a:101). On the level of niches, there is only limited structuration for local practices, originating from, for instance, vague expectations or visions. Activities in niches go in many directions and are accompanied by an element of uncertainty. Actors have to invest time and effort into creating and maintaining structures from which they can derive knowledge or practices (e.g. platforms, participation in conferences, etc.). At the regime level, a reversal occurs. Regimes are much more a reservoir for legitimising actions and they require fewer resources to maintain. For local actors, it is more difficult to deviate from dominant trajectories at the regime level. Socio-technical landscapes provide even stronger structuration of local activities. Generally, socio-technical landscapes are impossible for local actors to change.

Figure 2.4. Multiple levels as nested hierarchy (Geels, 2002:1261)
The most important insight from the multi-level perspective into technological change is that direction and outcome of technological change are not the result of dynamics at any specific level, but occur as linkages between different levels. Timing is important, as are other contingencies. A socio-technical regime provides the stability that results in certain socio-technical trajectories. The regimes are embedded in the socio-technical landscape. The relative harshness of these factors (e.g. global oil prices, availability of natural resources, political coalitions) makes some regime changes more likely than others. Nevertheless, the landscape does change, for instance in the form of deep, long-term and aggregated trends (e.g. changes in GDP, emerging environmental awareness) or sudden events (e.g. wars, sudden increase in oil prices, environmental disasters). Dynamics at the landscape level can put pressure on regimes and result in changes at the regime level, e.g. the establishment of new policies or the emergence of new user practices. Changing regimes may create opportunities for new technologies (Geels, 2002a) or result in decreasing stability and uncertainty (Raven, 2004). Interactions also go in other directions, e.g. when novelties are developed in specific application domains and when they invade mainstream markets and change regimes. Technological development is the result of interaction between the three levels. It cannot be understood as the outcome of dynamics on a single level.

*Stability in regimes*

Geels (2002a) has used the multi-level perspective as a starting point for analysing regime transitions. He came up with an interesting two-by-two matrix for illustrating different patterns in transitions (see Figure 2.5). The vertical axis differentiates between a stable regime and an unstable regime. The horizontal axis indicates the moment when a new functionality of an innovation (novelty) emerges. When a novelty emerges, the functionality may not be different from the dominant technology. Geels provides the example of a jet engine. Initially the jet engine was mainly a technical replacement at the level of components. These new components only gradually changed the form of the airplane and functionality remained close to the domain of military transport and flying for the elite. New functionalities only emerged much later as a result of engine improvements and changes in the socio-technical regime: flying for the masses and worldwide tourism. In other cases, however, new functionalities are articulated from the beginning, e.g. in the case of automobiles in the late 1890s. Combining the two axes results in four characteristic patterns:

- ‘Peat moor fire via detour’: the novelty emerges in the context of a stable regime. Because there are no problems at the level of regimes, there is little stimulus for regime actors to invest resources in the technology. Particular characteristics of the novelty lead to articulation of new functionalities, which are used to create new markets. The new markets are initially small and offer no threat to the existing regime. The new technology is further developed in the new markets ‘below the surface’, as a peat moor fire. In the new markets, the novelty does not have to compete with the existing technology. When the performance is improved, it invades mainstream markets, surprising incumbent firms;
• ‘Contestation/fighting’: the novelty emerges in a stable regime. Regime actors experience no problems and have vested interests. The novelty is used only in small niches with particular selection criteria. Because the regime is stable, there are no widespread expectations about the future potential of the novelty. The novelty emerges in existing markets (existing functionalities) and has to fight head-on with existing technology in the context of existing performance dimensions (contestation). Every market niche has to be conquered in a battle with the existing technology. As the performance of the novelty increases, it may (gradually) replace the existing technology;

• ‘Wide transformation’: the novelty emerges in the context of an unstable regime. Regime actors may look for new technical options, and niche actors try to link their novelty to the problems as a possible solution. There is much articulation about new functionalities. The new technology links up with ongoing processes in many dimensions (e.g. user preferences, public policies) and reinforces them. Transformation and co-evolution occur early in the process;

• ‘Substitution and problem solver’: the novelty emerges in the context of an unstable regime. In this case, the technology plays the role of solver for specific regime problems; there is no articulation of new functionalities. The new technology emerges in existing markets, where it substitutes the existing technology. Existing regime actors are interested because it enables them to deal with specific problems.

![Figure 2.5. Four patterns in early phases of transitions from one stable regime to another (Geels, 2002a:342)](image)

Geels emphasises that this matrix is only a first hypothesis made up of four patterns that can occur in transitions and that there are still several problems. Nevertheless, I can use the matrix to position SNM literature in relation to the multi-level perspective. Previous SNM literature has focused mainly on two of the patterns that Geels proposes, i.e. the pattern of ‘peat moor fire via detour’ and ‘contesting/fighting’. SNM was developed based on electric vehicles
research. This technology developed against the backdrop of a very stable transport regime. Geels’ matrix suggests that there are more patterns of change, in particular when the regime is unstable. The research in my thesis offers the opportunity to investigate patterns when the regime is in flux – a useful aid, as energy regimes have been very much in flux since the 1970s (Hofman and Marquart, 2001). I will come back to this issue in section 2.4.

Summary
In this section I discussed the basic starting points of evolutionary theories for technological change. The cycle of variation, selection and retention (routines) results in the emergence of a dominant technological regime and trajectory. This simple model has been criticised on the basis of historical and sociological insights. First, the concept of technological regime concept has been broadened to include not only routines, but also rules in general. Rules are embedded in the variation and selection environments; there are more social groups than just the engineering community that shape technological development (a socio-technical regime). Second, technological niches have been identified as important tools for understanding the emergence of a new socio-technical regime. In technological niches, new rules can emerge, both in the variation and selection environments. I also discussed a model that combined insights from evolutionary theories into a multi-level perspective. The main insight is that technological development is the outcome of linkages and interactions between different levels, rather than dynamics at a single level. Finally, I argued that SNM has only focused on the development of niches against the backdrop of stable regimes and has neglected the situation of unstable regimes.

2.2.2 Constructive Technology Assessment

Constructive Technology Assessment (CTA) builds upon the literature in the previous sections. CTA was explicitly developed to explore methods for influencing technological development rather than for understanding and explaining it; it aims to derive policy and management consequences. In the following paragraphs I briefly discuss CTA, as SNM can be seen as one of the elaborations of CTA.

CTA is one of several forms of Technology Assessment (TA). TA emerged in the 1970s and 1980s in different countries, including the USA, the Netherlands, Germany and Denmark. It was part of a reaction to growing concern among several social groups about technological development, in particular about technologies with potentially large political, ethical or environmental consequences (nuclear power, DNA technologies). Several forms of TA were developed, including awareness TA (ATA), strategic TA (STA) and interactive or participatory TA (ITA, PTA) (Smiths and Leyten, 1991; Schot and Rip, 1996). Generally, TA includes the exploration of new technological trajectories and an assessment of the impact on society, the aim being to anticipate negative consequences as much as possible and make arrangements to minimise them (Smit and Oost, 1999:197). Early TA methods mainly focused on assessing the impact of technologies, while later methods placed more emphasis
The development of CTA was triggered by the insight that most existing methods of promoting and regulating new technologies often lack success (Rip, Misa and Schot, 1995). These methods can be characterised as ‘two-track approaches’: there are promotional activities to stimulate new technologies (e.g. R&D funding), and there are regulating activities to control and minimise the negative effects of technologies (e.g. emission regulations). The disadvantage of such two-track approach is that the second track exists mainly to solve problems rather than to prevent them; it does not lead to the inclusion of social concerns (e.g. environmental protection) in the design process. This explains why many technologies that come on the market face resistance from social groups, even when the new technology may have considerable advantages. CTA proposes a method for bridging promotional and control activities.

The goal of CTA is not so much to realise a particular outcome (e.g. a sustainable energy system) as it is to improve the process so that societal concerns are integrated into the design process. Although CTA is normative in itself (it is assumed that CTA will result in a better outcome), it accepts that the outcome of the process is uncertain. What is desirable and what is not is defined during the process, and is not a fixed objective at the beginning (Schot, 2001:42). Sustainability of a new energy technology, for example, should not be defined at the beginning (e.g. the level of carbon dioxide reductions), but its definition should be part of the outcome of that technology’s development (e.g. a broad set of criteria that reflects interests of environmental movements, users, and other groups).

CTA emphasises three issues important to the development of new technologies. First is the integration of all interested actor groups at a very early stage of design. Schot (2001:41) distinguishes between four categories of actors often involved in CTA processes. Technology actors invest in and maintain technological development programmes; societal actors (e.g. users) experience the impact of technologies; regulating actors develop rules and represent some kind of general interest; meta-actors, like ‘platforms’, are involved in facilitating and modulating interactions among different actor groups. Second, societal learning and anticipation of future consequences must occur in the process of new technology development, including exploration of possible new linkages between a range of aspects such as designs, user demands, regulations, as well as societal acceptance and learning about underlying values and beliefs. Societal learning can occur through articulating these factors during an early phase of design. Third, the process should include a high level of reflexivity. Reflexivity refers to the ability of actors to consider technological design and social design as one integrated process, a quality needed to understand that every design option simultaneously creates potential social effects, both desirable and undesirable. Reflexivity is also needed to recognize the different roles of actors and how these roles may evolve throughout the process (Schot and Rip, 1996; Schot, 2001).

CTA (and TA in general) has several limitations in practice, in particular because generating insights into possible impacts does not necessarily result in the design process being adjusted. Although integration of interested actors at an early phase of the design may
in theory contribute to a broader design process, in practice it appears to be very difficult for actors to be reflexive or to articulate their demands (Schot and Rip, 1996:257). The integration of societal concerns into the design process does not occur naturally, instead requiring a process of continuous feedback between the design environment – or variation environment – and the interests of actor groups that represent the selection environment. Schot and Rip (1996) argue that SNM can be one of the strategies that realises such a process.

2.3 SNM: the research model

Understanding the process of technological development and influencing it in desired directions are two different things. SNM has been used for both purposes. The approach was used to analyse historical case studies (e.g. Hoogma, 2000; Van Mierlo, 2002), and to formulate suggestions for policy makers, firms, or other technology promoters (e.g. Kemp, Schot and Hoogma, 1998; Weber et al., 1999; Hoogma et al., 2002). In most cases, the two applications were strongly related: SNM was used as a research model for historical cases and the cases were used to make policy and formulate governance suggestions. I will refer to these two ways of using SNM as a research model for understanding technological change and a policy tool for influencing technological change. In this section, I discuss SNM as a research model; in section 2.5 I discuss SNM as a policy tool.

In sections 2.2.1 and 2.2.2, I introduced the concept of niches as locus for the emergence of a new socio-technical regime. The discussion, however, remained abstract: niches as a locus for linkages between the variation and selection environment. In SNM, the concept of niches (in particular technological niches, see section 2.2.1) has been further elaborated. In this approach, societal experiments like pilot plants are investigated as a way to create niches. Kemp, Schot and Hoogma (1998:186) define SNM as:

> the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology.

In line with Hetland (1994), Hoogma (2000:67) distinguishes four types of experiments that may play a role in creating niches. This list displays an increasing level of knowledge about the features and conditions needed to introduce the innovation:

- **Explorative experiments**: their most important role is to help researchers define problems, discover user preferences, explore possibilities for changing the innovation, and learn how future experiments should be set up. They are especially useful at the very early stages of learning, when there are many uncertainties about the potentials and impacts of an innovation;
- **Pilot experiments**: their objective is to raise public and industrial awareness, stimulate debate and open policymaking. Such experiments can test the applicability of innovations in locations with similar conditions to those where the explorative
experiments were conducted, and also test the feasibility and acceptability of innovations in new environments;

- Demonstration experiments: the main purpose of such experiments is to show potential adopters how they may benefit from the innovations. They may either be the follow-up of explorative or pilot experiments, or be designed specifically to promote the adoption of an innovation;
- Replication or dissemination experiments: these experiments aim to disseminate tested methods, techniques or models through replication. They involve full-scale implementation of a technological system.

Experiments – whether they are explorative, pilot, demonstrative or replicative – are important in creating niches, because they reflect three important evolutionary and sociological aspects of niches. First, experiments bridge the gap between variation and selection environments (evolutionary aspect). Interaction between technology actors (firms, research institutes), societal actors (users, environmental groups), and regulating actors (public authorities) may contribute to integrating the concerns of different groups into the design. Second, experiments are often protected from (some of) the rules that make up the dominant socio-technical regime (evolutionary aspect). Public authorities often subsidise pilot plants due to limited economic feasibility or in order to lower the risks involved for firms. Firms may also protect the experiment, e.g. because of strategic decisions. Similar to the example of the Stirling engine in the Philips company, a firm can allow a group of engineers to test the feasibility of a technology in a pilot plant without imposing the customary constraints on a project. Third, experiments are often characterized by high uncertainty and limited structuration, in particular in the early phases of experimentation (sociological aspect). In SNM research, experiments are therefore often used as unit of analysis for investigating the development of niches and they are recommended for the creation of niches in policy and management orientated SNM.

Niches and experiments are not the same concepts, however. Hoogma (2000:91) argues that niches are at the cosmopolitan level of – and above – the local practices in societal experiments. At the cosmopolitan level of niches, local experiments and practices are compared, lessons and expectations are transferred between locations, and delocalised general knowledge of the technology in question is formulated. Hoogma, following Nelis (1998), distinguishes three mechanisms in the process towards cosmopolitanism. The first is the circulation of the practitioners involved in different projects in niches, who carry knowledge and experiences between the locations. The second mechanism is publications that offer empirical descriptions of local practices. The third mechanism is meetings between practitioners at conferences and other forums. Although Hoogma makes this distinction between experiments and niches, he does not further elaborate on it (see also Van Mierlo, 2002). He pays limited attention to the difference between experiments and niches, mainly because he places too much emphasis on the evolutionary dimensions of niches (bridging variation and selection, protection), while the sociological dimension (structuration) is neglected. I come back to this problem in section 2.4.
In previous SNM work, Schot, Slob and Hoogma (1996) identified three processes important to societal experimentation and niche development. I will discuss these processes in the following sections.

2.3.1 Voicing and shaping expectations

Actor expectations play an important role in the early development of a technology. Promises and expectations about the future provide the legitimacy for actors to invest time and effort into a new technology that does not yet have any market value. In the beginning, the expectations may be broad and fragmented. Actors may have different visions of the future and different expectations about the viability of a technology. Some actors may opt for one technological trajectory, while others opt for a different one. Actor expectations affect many parts of the innovation process, e.g. when companies decide to invest in R&D for promising technologies, or when users decide to purchase a new technology because they expect it to become the standard. In the phase of experimental introduction, too, expectations are important.

Results from experiments may change actor expectations. Hoogma (2000:86) distinguishes between three characteristics of expectations that can be impacted by experiments. First, expectations can become more robust, when a larger variety and a larger number of relevant actors share the same expectations. Experiments can increase the robustness, because they may contribute to the stabilisation of expectations. Second, the quality of expectations can rise, when more experiments (but also research reports, experts or other important actors) support the actor expectations (e.g. about efficiency improvements). Third, expectations can become more specific, when it becomes clear which steps should be taken in developing the technology to realise the expectations. Hoogma gives the example of the electric vehicle: rather than the general statement that ‘the future belongs to electric vehicles’, a more specific expectation is ‘electric vehicles will be suited for commercial traffic in cities’. Generally, when expectations become more robust and specific and the quality of the expectations increases, the chances of successful niche development increase. However, despite his initial hypothesis, Hoogma did not find much evidence that experiments contributed to changes in expectations. On the contrary, shifts in expectations were mainly caused by external changes, e.g. changes in policies or in the development of alternative options.

In general, Hoogma found that dynamics in actor expectations resulted in shifts in application domains, i.e. they explain ‘niche branching’. Shifting expectations triggered actors to search in different directions, looking for new opportunities in other domains.

2.3.2 Network formation

Dynamics in the composition of social networks is the second process identified in SNM. An emerging niche is accompanied by a social network, including producers, users, regulators, societal groups, etc. These actors are important; they sustain development, carry expectations
and articulate new requirements and demands. In the early years of experimentation, the size of the network can be limited: only one or a few firms are investing in the development of the technology, the number of users is limited and the technology may be invisible to regulating actors. When the network expands, more resources become available for experimental activities. The network may also become more stable. In the beginning, the actors’ commitment to the niche is limited; they do not yet have many vested interests and withdrawal does not result in large losses. Furthermore, the role of actors in the network may be unclear: supplier-producer-user relationships have not yet stabilised, it is unclear who the user is, and firms lack long-term security of supply. In the course of time, when actors have gained more experience, the role of actors and their relations becomes clearer. There may also be specific meta-actors that coordinate interactions in the network (e.g. platforms) and stimulate expansion of the network.

Hoogma (2000:84) argues that two characteristics of networks are important in the outcome of niche development. First, the network composition is important. Niche development requires actors who are willing to invest in maintaining or expanding the niche, even when short-term market value is absent. Such actors may be large firms that also support the incumbent technology; they often have the resources to maintain niche development for a long time. On the other hand, these firms may participate in the developments for defensive reasons, trying to slow down the development, because of vested interests in the incumbent technology (Kemp, Schot and Hoogma, 1998:191). Moreover, the dominance of established firms in the network can lead to innovations that are more incremental rather than radical, because their activities are structured by the dominant regime. Therefore, involving actors that have no strong ties with the dominant regime is important (e.g. new firms or firms from other sectors), because they are more likely to introduce radical innovations (Tushman and Anderson, 1986). These firms, however, may have limited mobilisation potential for resources and may not be able to maintain niche development for a long time. SNM also emphasizes the involvement of users. In line with Von Hippel (1988), Hoogma and Schot (1999) argue that users (not only industrial users, but consumers in particular) are an important source of innovation. This requires the active involvement of users in the innovation process, rather than viewing them merely as sources of information (e.g. by letting them use an electric vehicle for six months rather than allowing them to drive in the car for an afternoon on a test terrain). Finally, following the CTA approach, Hoogma (2000:85) argues that non-users should also be able to contribute to the innovation process. Non-user groups are actors that are affected by the impact of the technology, but that do not use the technology themselves. Examples are neighbouring residents in the case of wind turbines, or environmental groups that represent general societal concerns. Hoogma (2000:348) has shown that the composition of the network explains the radicalism of niche development: if actors who are not strongly linked to the regime are present in the network, the chances of more radical niche development increase.

The second network characteristic that determines the outcome of niche development is the alignment of actors’ activities. Alignment refers to the degree to which actors’ strategies, expectations, beliefs, practices, visions, and so on go in the same direction, run parallel.
Established firms may have different visions about the purpose of a new technology (e.g. add-on technology for improving established technologies) from new firms (e.g. increasing market share by replacing the established technology), and established and new firms’ strategies of realising their visions may therefore diverge significantly. Hoogma (2000:85) argues alignment in a network is high if the network has a substantial history, if stable relations have been formalised in co-operations and if the network is complex, with many cross-relations. Alignment does not emerge naturally, but requires special effort. Macro-actors like large technology introducers, public authorities and other general interest actors, or relatively independent and specially constructed actors like platforms or consortia, can increase alignment in a network (Rip, 1995:426). Generally, the alignment in the network reflects the scope of niche development: if alignment in the network is higher, then the scope of niche development is larger (Hoogma, 2000:348).

Experiments can play a role in creating social networks for niche development. Hoogma (2000:353) argues that often there are already networks at a national or state level before local experiments are started. Experiments have mostly contributed to maintaining or extending these established networks. In other words, new experiments are often embedded in (part of) longer, existing networks that were themselves constructed around another technology or activity; experiments can benefit from previously established networks, because these networks offer stability through established role relations. On the other hand, existing networks can also hamper the experimental design, because important actors (societal groups, users) are left out of the network, resulting in incremental designs close to the established technology.

2.3.3 Learning processes

Learning is a central issue in the experimental introduction of technologies in society. Experiments can be designed to learn about different aspects, e.g. technological performance or economic feasibility. In an ideal situation, experiments produce results, actors learn from the results and make adjustments to improve the technology or societal embedding. Learning should improve the alignment between the socio-technical configurations of an experiment. Hoogma et al. (2002) distinguish five aspects for actors to focus on when learning about an experimental introduction:

- Technical development and infrastructure: this includes learning about design specifications, required complementary technology and infrastructure;
- Development of user context: this includes learning about user characteristics, their requirements and the meanings they attach to a new technology and the barriers to use they encounter;
- Societal and environmental impact: this entails learning about safety, energy and environmental aspects of a new technology;
- Industrial development: this involves learning about the production and maintenance network needed to broaden dissemination; and
- Government policy and regulatory framework: this involves learning about institutional structures and legislation, the government’s role in the introduction process, and possible incentives to be provided by public authorities to stimulate adoption.

In SNM it is emphasised that the role of users is important in the learning process (see also above). In relation to the role of users, Hoogma (2000:58) distinguishes between first-order and second-order learning. First-order learning refers to learning about the effectiveness of a certain technology to achieve a specific goal. First-order learning aims to verify pre-defined goals, to reach goals within a given set of norms and rules. Second-order learning refers to learning about underlying norms and assumptions and is about questioning these norms or changing the rules. Hoogma illustrates the difference with an example from the car industry: users are assigned the role of providing information about how a product functions to the manufacturers, who learn to make better cars. The manufacturers consider the users’ preferences a given entity that needs to be discovered. Double-loop learning involves users who are able to learn about their own needs and who are able to interact with producers about products that can satisfy these needs. Producers can then learn about their assumptions regarding markets or product portfolios.

Learning about all the aspects above, however, does not occur naturally. Actors have to articulate their ideas and values and be able to recognise possible barriers or opportunities. Open structures that aim to increase the level of interaction between different actors may stimulate the articulation process, but that does not necessarily result in an adjustment of the socio-technical configuration of a technology. Ayas (1996:39) argues that the learning cycle from recognising a problem to actually solving the problem may be incomplete. First, actors may learn that changing their ideas, values or behaviour improves the feasibility of the technology, but this does not result in any changes in the behaviour of the actors due to external constraints of the actors’ role (role-constrained learning). Second, actors may learn about required actions, but they undertake the wrong actions, because there is no real basis between their actions and the required outcome (superstitious learning). Third, the actor that learns does not codify the learning process for later use – learning is situation-specific and is not carried over to the next experiment and therefore has no long-term impact (situational learning). Fourth, individual actors learn, but their lessons are not recognised at a higher level (or cosmopolitan level); the loss of the actor in the innovation process results in the loss of learning (fragmented learning). Fifth, a group of actors learns and undertakes action to seize an opportunity and although the results may be desirable, they have no further influence (opportunistic learning). Learning is thus important, but does not necessarily result in a required adjustment.

Hoogma et al. (2002) have found a relationship between the quality of learning (first-order versus second-order) and the actors involved in the experiment (see Table 2.2).
Generally, higher order learning and/or involvement of users and outsiders in the network improved the chances of a technological niche evolving into a market niche or becoming an element in a (new or existing) regime.

Table 2.2. Relations between learning process, the carrying network and outcomes of niche development (Hoogma et al., 2002:195)

<table>
<thead>
<tr>
<th>Carrying network</th>
<th>Learning</th>
<th>First-order learning (mostly technical)</th>
<th>Second-order learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network dominated by traditional actors</td>
<td>Exit or option stays in technological niche</td>
<td>Option stays in technological niche, or becomes element in existing regime</td>
<td></td>
</tr>
<tr>
<td>Broad network involving users and outsiders</td>
<td>Option becomes element in existing regime or market niche develops</td>
<td>Option becomes market niche and/or becomes element in a new regime</td>
<td></td>
</tr>
</tbody>
</table>

2.3.4 Dynamic interaction between three processes

Voicing and shaping of expectations, network formation and learning are interrelated. Geels and Kemp have visualised the interaction (Figure 2.6). On the basis of promises and expectations, actors may decide to participate in experiments. In the early stages of development perhaps only a limited number of actors are involved. The network characteristics (composition, alignment) and the actor expectations are important in understanding the particular set-up of the experiments. The experiments produce results, which contribute in turn to learning processes, but the type of learning also depends on the network characteristics, e.g. the active involvement of users. Temporary outcomes of the learning processes can result in adjusted expectations – they may confirm or falsify the expectations, and become more robust. In addition, the network composition may change, because changing expectations and promises attract new actors, while other actors leave. Changes in network and expectations may then result in the design of a new experiment. In this cycle, the number of experiments can increase, there is variation in design and use, and actors can combine experiences from different locations or exchange codified experiences. In other words, a cosmopolitan niche level may emerge, which increasingly structures the behaviour of the actors in the experiments. In time, the technological design improves and stabilises and protection of new experiments can be reduced.

Figure 2.6 is a depiction of the dynamics of internal niche processes. This figure lacks a satisfactory explanation for changes in expectations. Hoogma’s research suggests namely that dynamics in actor expectations are caused mainly by external circumstances and not by results from experiments. I will come back to this topic in section 2.4.
Weber et al. (1999:20) and Hoogma et al. (2002:31) identified four patterns of niche formation that may emerge from the cycle of experimentation. The first pattern, *technological niche proliferation*, results from a continuous process of new experiments. This pattern may include niche branching, i.e. jumps from one application domain to another, but also geographical jumps (Schot, 1998). The niche does not gain a substantial market share, however. The technology is not able to compete with the dominant technology, and protection remains necessary. The second pattern, *development of market niches*, is characterised by the development of technological niches into one or more market niches, i.e. the technology has become economically sustainable in specific situations. Their scale and scope are limited however. Only a restricted number of users switch to the new technology and almost no effect is visible at the level of the dominant regime. In the third pattern, *regime transformation*, the new technology develops through several stages of technological and market niches into the dominant technology, and transforms the regime. The new regime is usually composed of old and new elements, but the essential difference is that it is organised around a new set of technologies and practices (Hoogma, 2000:92). In the fourth pattern, *technological or market niche extinction*, the novel technology fails to attract further support and becomes (again) an R&D option. These patterns demonstrate important mechanisms in the development patterns of niches:

- changing level of protection (technological niche versus market niche);
- niche branching from one application domain to another;
- geographical niche branching from one location to another;
- growth in size (absolute numbers or market share).

Although these elements are important, the patterns are too simplistic; they do not differentiate enough between different types of niches. Niches are only differentiated on the
basis of protection and size – with the emphasis on seeking ways to overcome a threatening selection environment. Too little attention is paid to the sociological dimension of stability. Moreover, the dynamics of regimes are neglected: in these patterns, regimes are understood to be static and niches simply replace parts of the regime. These SNM shortcomings are important, and I shall return to them in the next section.

2.4 Additions to the SNM research model

In this section I will discuss several puzzles and problems in SNM. First, SNM comprises simplistic ideas about the development of experiments and technological niches into market niches, in particular because of limited interest in the sociological dimension of niches. Second, in SNM the dynamics in actor expectations and visions have not been worked out sufficiently. Third, there is a lack of focus on regime dynamics and niche-regime interaction.

2.4.1 From technological niche to market niche

The distinction between individual experiments and niches is not always clear in SNM literature. In earlier research on electric vehicles, experiments were often simply treated as small technological niches: they were small protected environments in which different actors cooperated to learn about the technology. There was no clear difference, because the distinction emerged from the emphasis on protection. Protection was the main dimension upon which was based the distinction between niches and regimes. Hoogma (2000:83) argues that protection can be understood as a selective exposure to the selection environment. Public authorities or other actors give the protection in the form of subsidies for products, funding for experimental introduction projects, and preferential treatment for users of the new technologies, within the legal framework. When suppliers and users have learned enough, the technology may be launched commercially and protection may be phased out: the technological niche then evolves into a market niche. On the basis of this distinction, there is no difference between experimentation and niches: both can be exposed selectively to the regime by means of subsidies, company strategies, regulatory exemptions or other types of ‘protection’.

A major consequence of rejecting distinctions between experiments and niches was that ideas about how experiments evolve into market niches or change regimes were too simple. Hoogma et al. (2002:195) recognised this. They argued:

We were certainly over-optimistic about the potential of SNM as a tool for transition. [...]. The positive circles of feedback by which a technology comes into its own and escapes a technological niche are far weaker than expected and appear to take longer than expected (5 years or more). [...] The experiments did not make actors change their strategies and invest in the further major development of a technology.

Single experiments do not result in regime changes; they require a long trajectory of many experiments and the emergence and stabilisation of a niche level. Current SNM research pays too little attention to this process. How does a process of niche development unfold over a
longer period with more experimentation? What happens when technological niches become market niches or contribute to regime changes? What are the characteristics or crucial factors in this process? Previous research has not yet provided sufficient insight into these questions.

Deuten (2003) and Geels (2002a) placed more emphasis on the sociological dimensions of experiments, niches and regimes. I can use their findings as a stepping-stone for understanding what happens when single experiments evolve into technological and/or market niches, or contribute to regime changes. The sociological dimension emphasises the distinction between experiments, niches and regimes on the basis of stability and structuration. Experiments are local practices in which actors are learning under local circumstances. Niches and regimes are both sets of rules (preferences, heuristics, regulations, norms etc) that provide structuration to these local practices. Niches and regimes are characterised by a different level of stability. In niches, there is limited stability in rules; there is uncertainty about future directions. Structuration for local practices in experiments is therefore limited. Nevertheless, actors that participate in experiments can draw from experiences in other locations, e.g. because actors have codified their experiences in reports or because some actors have participated in several experiments. Regimes are characterised by a higher level of stability. Rules are similar and shared among many different locations. They are stabilised and embedded in a system of actors, social networks, technological artefacts and infrastructures. Regimes offer more structuration to local practices; there is a high level of certainty about ‘which configurations work and which do not’.¹⁰

According to Deuten (2003), the process of emerging stability and structuration can be understood as a process of cosmopolitanisation. Although his work is mainly related to the production of knowledge, I use it to demonstrate the differences between experiments and niches. Deuten argues that the cosmopolitan level does not exist from the moment new knowledge (or in this case rules) is produced under local circumstances, but that it requires effort to diffuse the rules from these local practices to other locations. He distinguishes between four phases in cosmopolitanisation (Deuten, 2003:266). In the local phase, a heterogeneous set of relatively independent local actors create their own rules, sufficient for their purposes (e.g. local and separated experiments). There is no collective set of rules. In the inter-local phase, there is increased circulation of knowledge and exchange of experiences within social networks (e.g. across experiments), and rules may become shared among different locations. In the trans-local phase, there is increased production of knowledge and rules, which are intended to be trans-local rather than local, e.g. standardisation based on consolidated knowledge. There are actors at the cosmopolitan level but their actions are ad hoc. In the cosmopolitan phase, local practices are structured through rules produced at the cosmopolitan level. At this level, there are dedicated actors at the cosmopolitan level that play

¹⁰ On the basis of this distinction between experiments, niches and regimes, we have argued elsewhere that local practices in experiments are a mixture of elements from niches and regimes (Raven and Verbong, 2004). Actors that experimented with heat pumps drew from experiences in other locations, e.g. about the feasibility of specific designs. However, elements of the socio-technical regime were also involved, e.g. engineers used heuristics from the design of the dominant technology (boiler systems) to design heat pumps, and over dimensioned the heat pumps, resulting in high investment costs.
a structural role in the dissemination of experiences. The niche has evolved into a new regime. According to Deuten’s work, the emergence of a niche level is thus a gradual process of rule creation and sharing that starts from local practices and slowly becomes trans-local and cosmopolitan. This is illustrated in Figure 2.7 for experiments and the emergence of a niche and regime level. Figure 2.7 represents the sociological difference between experiments and niches, i.e. in terms of structuration.

![Figure 2.7. Emerging level of niches in relation to local practices in experiments](image)

The evolutionary and sociological dimension of niches can be combined in a matrix, one which gives more insight into different types of niches (see Figure 2.8). The horizontal axis represents the level of stabilisation in heuristics, regulations, preferences, etc; it represents the stability in rules at the niche level and to what extent this level provides structuration to local practices in experiments. The vertical axis represents the level of protection from rules in the regime. Protection refers to the shielding of the niche against harsh design and selection rules of the socio-technical regime, e.g. through subsidies or other financial resources, regulatory exemptions, expectations and strategic decisions. The combination of these axes results in four different types of niches:

- Niches in the upper left-hand corner are characterised by a high level of protection and low stabilisation (technological niches). These niches are especially likely to occur during the early phases of experimental introduction of technologies. There are only a few experiments, there is limited interaction between the experiments, and limited exchange of information and experiences. Nevertheless, actors have high expectations, they protect the new technology by making ample resources available for testing and
experimentation, e.g. investment grants or regulatory exemptions; they protect the technology because it would otherwise be rejected by the market;

- Niches in the lower right-hand corner are characterised by limited protection and a high level of stabilisation (regular market niches). This type of niche is especially likely to occur during the later phases of experimental introduction. At least some users benefit from the technology, e.g. because there is a distinct set of selection criteria, and protection is needed no longer or only in a limited form. Stability in the niche has increased, with more certainty about technological design and functionality;

- The niche in the lower left-hand corner has limited protection and there is limited stability in the niche (dedicated market niches). Technological design and functionality have not stabilised, but there are special markets, in which users prefer the technology despite the absence of stability, e.g. because out of curiosity, because of local benefits, or because no other option is available;

- The niche in the upper right-hand corner is characterised by a high level of protection and a high level of stabilisation (protected market niches). Despite much certainty about the technology and its functionality, there is still protection.\(^\text{11}\)

![Diagram of niches](image)

**Figure 2.8.** Several types of niches in relation to the levels of protection and stabilisation

Based on the discussions above and the distinction between protection and stability, I now define a technological niche as follows:

a loosely defined set of formal and informal rules for new technological practice, explored in societal experiments and protected by a relatively small network of industries, users, researchers, policy makers and other involved actors.

\(^{11}\) It can also be argued that protection is no longer temporary, that it has become part of the selection environment. An example is the permanent implementation of fuel taxes to incorporate environmental externalities (Hoogma, 2000).
The distinction between protection and stability can be used to investigate my second research question: What are the crucial factors for the emergence of market niches? The scheme provides a more detailed distinction between different types of niches. The idea is that changes in protection and changes in stabilisation are important for understanding the development of niches over longer periods. How did protection and stabilisation change, what were the causes (e.g. from changes in network composition or learning effects) and how did this affect the development of niches? The matrix also allows a more detailed description of routes. Did a technology start in a technological niche and evolve through a process of niche-branching into a market niche (traditional SNM)? Or were there market niches from the beginning? My basic hypothesis is that the linear pattern from technological niche to regular market niche represents actual developments too simplistically.

2.4.2 Dynamics in actor expectations and visions

A second puzzle in SNM is related to the role of actor expectations. Hoogma's case studies (2000:358) suggested that experiments did not contribute to changing expectations, but that changing expectations were mainly caused by external circumstances. He did not further elaborate on the relations between results from experiments, expectations and external circumstances in regimes or in the socio-technical landscape. Extrapolating along the lines of Van Lente (1993), I clarify the relationships. Van Lente has investigated the role of promises and expectations in technological development. His findings illustrate how promises about technologies are converted into design specifications (Figure 2.9). External circumstances or developments in protected spaces may create opportunities for developing new technologies. These technologies, however, are still mostly a promise; there may be teething troubles or they may lack a clear market and functionality. When the promises become shared (at the level of firms, sectors or societies), they can become part of an agenda. Once established, agendas are converted into requirements and into task divisions that are needed to further develop the promising technology, which can in turn result in the creation of new protected spaces or in the extension of existing protected spaces (e.g. through subsidies) and in activities required to realise the technology.
Van Lente distinguishes between different levels at which actor expectations are transformed into requirements. At the micro-level, search-expectations are particularly important. Search-expectations are specific ideas about promising routes for solving specific problems. At the meso-level, visions and expectations about functionality are important. These visions are related to the promises of the area as a whole, rather than specific promises about technological solutions. These visions result in functional requirements for the technology. The expectations, visions and functional requirements create a rhetorical space to which local actors can refer. They form the justification for local practices, while expectations at micro level guide the search process.\(^\text{12}\)

I can use the insights above to illustrate the role of expectations in the experimental introduction of technologies. External circumstances (e.g. liberalisation of energy markets) or developments in existing niches (e.g. breakthrough in R&D research) may create new opportunities for a technology. Actors raise high expectations about the technology (e.g. gasification of biomass will result in a much more sustainable energy sector). The expectations become a rhetorical space when they are widely accepted, e.g. in a White Paper on energy. Actors now have ideas and visions (whether or not contested) about the future of an area as a whole (niche level). Actors can refer to the rhetorical space to justify experimentation at the local level. They may develop (search-) expectations of how to solve problems or improve performance, and test these in experiments. Lessons from the experiments may change their search-expectations, but also contribute to changes in actor visions and expectations about the area as a whole (e.g. biomass gasification is not yet commercially attractive).

Hoogma's work on electric vehicles, however, suggested that expectations change in particular because of external circumstances; experimental results do not have much effect on

\(^{12}\) Van Lente also distinguishes a macro-level or cultural level of expectations. These are related, for example, to the justification of technological development as a way to enable sustainable development in society.
expectations and visions at the niche level, let alone on external circumstances. I have combined Van Lente's insights with Hoogma's results in Figure 2.10. The figure illustrates the relation between changing expectations (on micro and meso level), external circumstances and experimental design in.

Figure 2.10. Relation between design and results from experiments and dynamics in expectations: (1) external circumstances change visions at niche level; (2) changing expectations result in different experimental designs; (3) results from experiments change expectations at niche level; (4) changing visions and expectations at niche level change external circumstances.

I will take this model of expectations as a starting point in my cases. I focus on the dynamics in expectations and visions at the niche level because I am more interested in the development of niches as a whole, rather than in the design of a single experiment. How did visions and expectations change at the level of niches? What were the external circumstances or the local experiences that resulted in change? How did they affect the development of niches? My hypothesis is that changing actor expectations are caused by external circumstances [1] and not by experimental results [3].

2.4.3 Niche-regime interaction

Previous SNM work has focused too much on internal niche dynamics, i.e. how voicing and shaping of expectations, network dynamics and learning processes account for niche development, in combination with too little interest in niche-regime interactions. This has resulted in a simplistic explanation of niche development patterns: as long as the internal processes occurred as proposed in SNM, niche development would result in the emergence of market niches or regime change. Until now, regime dynamics have not been considered significant in the explanation of niche development patterns.

The multi-level perspective that I introduced in section 2.2.2 emphasises that technological development and the emergence of new (radical) innovations is not the outcome of processes at a single level, but the result of linkages between dynamics on different levels. In line with this model, I will take a different approach than SNM – which does not pay sufficient attention to these linkages – focusing on the interaction between niches and regimes. How do regime dynamics interact with niche development? To answer this question, we first need more insight into the kind of regime characteristics that facilitate understanding
the interaction with niches. Figure 2.5 already presented a first insight, i.e. the stability of regimes, which provides insight into why technologies (and functionalities) that were developed into niches may (or may not) breakthrough. When the regime is stable, actors may not be looking for the solutions offered by niche technologies, nor be willing to invest in associated risks. Figure 2.5, however, remained vague about what stability is, what its origins are, and how it changes.

As a starting point for investigating these questions, I take the triad developed by Geels (Figure 2.1). He distinguishes between the set of rules (the regime), and the technical system and social groups in which the regime is embedded. Generally, a regime is stable because there is alignment between rules. For example, the transport regime is stable because there is alignment between the kinds of cars users prefer, the way automobile manufacturers design cars and their ideas about what users want, the regulations that allow, prescribe or forbid certain behavioural or design choices, etc. Alignment between these rules is a source of stability. However, the rules are not just ‘out there’ – they are embedded in the minds of people, in the organisation of sectors, in regulations and policies, in standardisation bodies and in technical artefacts like an infrastructure or consumer products. The fact that rules are embedded in technical artefacts and human actors also creates stability.

Stability can be dynamic, however (Geels, 2002a:98). A public authority can introduce new laws, industry platforms can negotiate new standards or change existing standards, users can develop new preferences; new technologies may require new practices of use or new regulatory frameworks; environmental problems may result in new policies. Nevertheless, a regime that is stable will have an internal drive to remain stable, because of deep and embedded linkages between rules, technological artefacts and human actors. Most change will be incremental and occur slowly; there is internal resistance to change, as several authors recognise. Jacobsson and Johnson (1998:633), for example, have investigated what the key issues are in transformation processes in the energy sector. They suggest three issues important to understanding resistance to change, i.e. the way variety is created (in knowledge, technologies), the institutional setting, and actors and their strategies. In addition, Unruh (2000, 2002) comes to a similar conclusion and emphasises technological, organisational and institutional elements as sources of resistance.

In previous SNM work the focus was very much on stable regimes. The idea is that a niche is successful if it is able to attack the stability in the dominant socio-technical regime. Through a process of niche branching, the technology becomes more widespread and receives increasing support from users and producers. New standards, regulations, preferences and design heuristics emerge, beginning to replace existing ones. This provokes resistance from dominant regime actors who will try to maintain control and stability. However, at a certain point, regime stability may drop too low, creating substantial problems at the regime level. At the same time, the niche has gained enough momentum through niche branching, and a reversal occurs: the dominant technology is abandoned and replaced with the niche technology, a development that is accompanied by a reconfiguration of the social network and the set of rules. Eventually, the new regime (a mixture of old and new rules) is embedded in (a mixture of) old and new technologies and supported by (a mixture of) old and new actors.
I expect that in the bioenergy cases in this thesis, the storyline will be different. Firstly, as my case studies will show, none of the niches has reached a point where it begins to replace the dominant socio-technical system. I am therefore not able to investigate exactly what happens in the case of reversal. However, I am able to investigate how instability at the regime level can increase or decrease the chances of successful niche development. As I will show in my cases, the electricity regimes in both the Netherlands and Denmark were increasingly in flux in the 1973-2003 period, and stability decreased. My hypothesis is that the reduction of stability created opportunities for niche development, resulting in larger niches. In other words, I expect regime stability to be an extra explanatory factor in understanding niche development, especially niche size.

In addition, I will explore three other issues in niche-regime interaction, though I do not yet have a specific hypothesis for these aspects. First, despite the niches not having reached the point of reversal, reactions to niche development at the regime level are still possible. Regime actors, for instance, may counteract the development of the niche because they perceive it as a future threat, or they may participate in niche development because they find it a promising technology. Moreover, changes in regimes (e.g. in regulations) may result from niche development (e.g. because of lobbying), but do not (yet) result in niche reversal or contribute to regime instability. Therefore, besides investigating the effect of regime instability on niche development, I will also investigate the effect of niche development on regimes. What kinds of changes in regimes did niche experiments trigger?

Second, focussing on the electricity regime may exclude developments (in other regimes) important to understanding niche development. In the case of manure digestion, for example, dynamics in the agricultural regime may have affected niche development. In my research cases, I take the electricity regime as a starting point for analysis, but also focus on other regimes if they are relevant for understanding niche development.

The third issue related to niche-regime interaction explores the causes of instability in the electricity regime: as none of the niches in my cases have come to a point of reversal, this is a logical factor to consider. There are several explanations for regime instability. One explanation is that other niches were successful and able to attack regime stability. Another explanation is that regime instability was caused by internal misalignment, i.e. that problems which emerged within the regime could not be solved by further optimising the dominant technology. A third explanation for regime instability is that structural changes in the landscape put pressure on the regime. My final conclusions will discuss the sources of instability in the electricity regime.

2.5 SNM: the policy tool

In the previous sections I discussed the SNM research model. The literature also explicitly positions SNM as a policy tool, particularly as a tool for introducing sustainable technologies like electric vehicles or PV systems. Sustainable technologies often lack a clear advantage for the individual user or producer; there is no existing and clear market. Economic incentives like subsidies and taxes may play a role in creating markets, but often they have an impact
only if they are drastic, as they must compete with the dominance of existing technologies (Kemp, Schot and Hoogma, 1998:184). SNM presents an approach based on improving the innovation process through learning and articulation, rather than based on defining the end-state and implementing incentives to reach that state. The definition of the end-state is part of the process’s outcome, and not a pre-defined goal. In this respect, SNM is indeed closely related to the approach used in Constructive Technology Assessment.

Elzen, Schot and Hoogma (1996) have made a first attempt to link policy strategies and possible (scenario) outcomes. They make a distinction between on the one hand creating expectations through technology forcing and network management, and on the other hand stimulating learning and articulation through experimentation. Technology forcing occurs when public authorities exert external pressure on industries to develop technologies with certain (sustainable) characteristics, by a specific deadline. Elzen et al. argue that technology forcing is most important when the goal is to realize optimisation of the existing system or regime, because such forcing creates expectations about future markets within the existing system; it focuses on established firms and networks, and stimulates them to develop advanced technologies with improved (environmental) characteristics. Stimulating learning and articulation processes, or managing the formation of new networks is less important in this strategy, because new technologies can be fit into existing systems as well as developed in the context of existing networks. However, if the goal is to completely renew the existing system (i.e. to realise a regime shift), the focus should be on stimulating articulation and learning processes. Producers, consumers and public authorities need to learn about the new technology, as existing experience is limited or nonexistent; they cannot build upon an established socio-technical system. Nevertheless, renewing an existing system also requires technology forcing and network management. Network management is necessary to attract actors into the experimental network already established, while technology forcing can be used to pressure the established system, to change expectations of established firms, and to stimulate such firms to accept technologies and market institutions developed within the learning and articulation approach. The relations between technology forcing, network management, and learning and articulation, and the two scenario outcomes, are shown in Table 2.3.

Table 2.3. Policy strategies for different scenarios (Elzen, Hoogma and Schot, 1996)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Policy strategy</th>
<th>Technology forcing (creation of expectations)</th>
<th>Network management</th>
<th>Learning and articulation processes through experimentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regime optimisation</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Regime shift</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td></td>
</tr>
</tbody>
</table>

Note that technology forcing is part of another distinction made by Schot (1991). He distinguished between strategies to influence the variation environment, strategies to change the selection environment, and strategies to exploit linkages between the selection and variation environments. In Schot’s distinction, technology forcing is part of a strategy to change the selection environment.
The table above suggests that for realising regime optimisation, creating expectations through technology forcing is a sufficient strategy, but for regime shift, there should also be a strong focus on network management and learning. However, insights about the relationship between different policy strategies and possible scenario outcomes can be improved. In policy sciences a different type of distinction in policy strategies is often used, based on the type of dominant coordination mechanism. As a starting point for investigating policy strategies, I adopt a distinction made by Geels, Elzen and Green (2004), in line with De Bruijn, Kickert and Koppejan (1993). Geels et al. phrase the distinction in terms of different policy paradigms and present typical characteristics of the paradigms, including often used instruments (see Table 2.4). The classical steering paradigm focuses on instruments like formal regulations, laws and rules, leaving little room for local actors to make decentralised decisions. Technology forcing may also be used to define specific end-goals that industries must fulfil. The second paradigm (bottom-up market model) uses instruments such as generic financial incentives and tax exemptions, leaving the choice of participation to local actors. The third strategy is similar to the modulation strategy (policy network paradigm) in that it employs instruments like organising learning processes, seminars and experiments.

Table 2.4. Different policy paradigms (Geels, Elzen and Green (2004), based on De Bruijn, Kickert and Koppejan (1993: 22))

<table>
<thead>
<tr>
<th></th>
<th>Classic steering paradigm (top-down, command-and-control)</th>
<th>Market model (bottom-up)</th>
<th>Policy networks (processes and networks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of analysis</td>
<td>Relationship is between principal and agent</td>
<td>Relationship is between principal and local actors</td>
<td>Network of actors</td>
</tr>
<tr>
<td>Perspective</td>
<td>Centralized, hierarchical organization</td>
<td>Local actors</td>
<td>Interactions between actors</td>
</tr>
<tr>
<td>Characterization of relationships</td>
<td>Hierarchical</td>
<td>Autonomous</td>
<td>Mutually dependent</td>
</tr>
<tr>
<td>Characterization of interaction processes</td>
<td>Neutral implementation of formulated goals</td>
<td>Self-organization on the basis of autonomous decisions</td>
<td>Interaction processes in which information and resources are exchanged</td>
</tr>
<tr>
<td>Foundation of scientific disciplines</td>
<td>Classic political science</td>
<td>Neo-classical economics</td>
<td>Sociology, innovation studies, neo-institutional political science</td>
</tr>
<tr>
<td>Governance instruments</td>
<td>Formal rules, regulations and laws</td>
<td>Financial incentives (subsidies, taxes)</td>
<td>Learning processes, network management through seminars and strategic conferences, experiments, vision building at scenario workshops, public debates</td>
</tr>
</tbody>
</table>

This table does not provide insight into the kind of outcome scenario that a strategy (or paradigm) is likely to produce. In Chapter 7 I will therefore first discuss what kinds of strategies (top-down, centralised planning, market-based, bottom-up, or process and network
management) dominated in my case studies. I will do so by mapping the cases using the following table.

Table 2.5. Table for mapping policy strategies used in case studies

<table>
<thead>
<tr>
<th></th>
<th>Period 1</th>
<th>Period 2</th>
<th>Period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-down, centralised planning strategy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Market–based, bottom-up strategy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process and network management strategy</td>
<td></td>
<td></td>
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</tbody>
</table>

I will then reflect on the kind of outcome scenarios (in terms of regime optimisation or regime shift) the different strategies may produce. I expect that in the case of co-firing, top-down strategies have been used most (inducing the scenario of regime optimisation), while in the case of manure digestion, process and network management strategies have been used most (inducing the scenario of regime shift). Market-based, bottom-up strategies will in most of my cases be part of the strategy to achieve sufficient economic feasibility for local projects.

2.6 Research protocol

In this chapter I introduced the conceptual perspective I will use to analyse the case studies in this thesis. Strategic Niche Management was introduced as the main research perspective with which I can describe and analyse the experimental introduction of bioenergy technologies in the Netherlands and Denmark. However, I also identified three puzzles that require attention in SNM, i.e. the difference between experiments and niches and the consequences for emerging patterns, the sources for changing actor expectations, and niche-regime interaction. In Box 1 I have combined this chapter’s concepts and ideas into a research protocol. I will use this protocol, in three parts, for the four case studies. The first part can be seen as traditional SNM, i.e. experiments, voicing and shaping of expectations, network dynamics and learning processes (internal niche processes). The second part addresses the issue of emerging niche patterns with respect to stabilisation and protection. The third part is about niche-regime interaction.
Box 1. Research protocol

Experiments and internal niche processes:

1. Which experiments were implemented and what experiences resulted?
2. Which visions/expectations did actors have? How did expectations and visions change at the niche level? What was the source of these changes? Did lessons learned from experiments change the visions and expectations or were external circumstances important? How did this affect niche development?
3. What was the composition and alignment in networks? Were there outsiders in the network, or did traditional actors dominate? How did this affect niche development?
4. What was learned from the experiments? What kind of learning processes occurred? Did first- and second-order learning occur? How did they affect niche development?

Emerging niche patterns:

1. Did stability increase or decrease in the niche? What caused the changes in stability?
2. Did protection increase or decrease in the niche? What caused the changes in protection?
3. What kinds of niches emerged from the experiments (technological niches, dedicated market niches, protected market niches, market niches)? What pattern emerged?
4. What are the crucial factors for the emergence of market niches?

Niche-regime interaction:

1. How did relevant regimes develop in terms of rules and institutions, actors and the socio-technical system?
2. Were the regimes stable? How did stability change and what were the sources of change?
3. Was there interaction as the niches developed? Did decreasing stability result in larger niches?
4. Did experimenting in niches result in any changes in regimes?
5. Which regimes were important in the cases?
6. What were the sources of instability in the regimes?
Chapter 3.
Manure digestion in the Netherlands

3.1 Historical overview

3.1.1 Farm-scale plants (1973-1985)

Dutch farmers were faced with rising energy prices in the 1970s and 1980s. In an attempt to utilise local energy sources, researchers of the Agricultural University of Wageningen began to investigate energy generation from manure. In 1981, the Dutch researcher Lood van Velsen (Wageningen University) published a thesis on the anaerobic digestion of pig manure (Velsen, 1981). Part of his project was the construction of a small pilot plant, in cooperation with a pig farmer in Garderen (1979). This pilot plant was one of the first manure digestion plants installed in the Netherlands. It was a small plant: the plant only digested manure from the 270 pigs on the farm in a digester of 270 m$^3$; the maximum annual biogas production was about 40,000 m$^3$ (920 GJ). The biogas was used for heating the farm and sty (Poelma, 1987:45).

The experiences with the plant in Garderen were promising, leading to a three-year, follow-up research programme between 1980 and 1983. The programme was coordinated by the Institute for Mechanisation, Labour and Buildings (IMAG), an institute closely related to the Agricultural University of Wageningen. IMAG had previously investigated energy supply on farms and had much practical farm knowledge and many farmer contacts. From the Agricultural University, the Departments of Microbiology and Water Treatment (with Van Velsen) participated. The Institute for Road Transport Means (IW-TNO) was also involved, particularly due to its experience and knowledge of gas engines. The budget for this programme was 2.8 million Dutch guilders (about 1.3 million euros). The Ministry of Economic Affairs, responsible for Dutch energy policy, financed 60% of the programme (Hoek, 1984:6).

The researchers tested the technological feasibility of manure digestion on an experimental farm in Duiven, near Wageningen. The biogas plant was of a similar design as the plant in Garderen; both were completely mixed plants (see Section 1.4.3). The plant in Duiven further existed of a blower (to stir the manure), a mono-pump to cut up the manure and supply it to the digester, a heat exchanger to maintain the temperature at 30 °C, a storage tank for the biogas and a gas engine to generate heat and electricity. The heat was used to maintain the digester temperature; electricity was used to operate the biogas plant (pumps and

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1 In Dutch: Instituut voor Mechanisering, Arbeid en Gebouwen IMAG).
2 In Dutch: Instituut voor Wegtransport Middelen (IW-TNO).
so on), and was used on the farm. Electricity surpluses were fed back into the grid (Hoeksma and Arkenbout, 1984).

Experiences with the plant were not positive. Several parts of the plant broke down or did not operate satisfactorily. The pump that supplied and cut the manure caused blockage and needed replacement; the biogas contained high levels of hydrogen sulphide, causing severe corrosion problems in the gas engine and other parts of the system; the biogas yields were much lower than expected, making the process economically unfeasible (lower revenues). Researchers argued that they could overcome most of the technical problems. Economic problems could be tackled by constructing a centralised biogas plant. Besides economy of scale, a centralised plant had the advantage of releasing individual farmers from operating the plant. Farmers were not process operators, they had no experience with the digestion process, and poor plant operation required much effort on the part of the farmer (Hoeksma and Arkenbout, 1984; Hoek, 1984).

The biogas plants in Garderen and Duiven were followed by a large number of farm-scale plants in different locations (see Figure 3.1, below and Table 3.8, Appendix 2.1). The plants were small, with an average digester volume of 225 m$^3$. Eleven plants used pig manure, fifteen plants used cattle manure and one plant used a mixture of pig and cattle manure. In seven locations, the farmers also added organic sources like flocculation sludge, fatty waste and chicken manure. Many of the plants were financed with support from the Dutch Ministry of Economic Affairs.$^3$ By 1985, a total of twenty-seven plants had been constructed. IMAG monitored the plants and analysed technical and economic results. The programme showed that biogas plants were vulnerable to technical breakdowns, caused in particular by stirring mechanisms and the corrosive properties of biogas, which caused damage to combustion units and transport pipes. Biogas yields were much lower than expected. All plants showed a negative economic performance (Hoeksma, 1984). An inventory by the Centre for Energy and Environment (CE) came to a similar conclusion.$^4$ Only on very large farms could a biogas plant be profitable (Boks and Nes, 1983).

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$^3$ In Dutch: ‘Steun demonstratieprojecten energiebesparing’.

$^4$ In Dutch: Centrum voor Energie en Milieu (CE).
The experiments with biogas plants did not result in a stable, dominant design. There were many different types of pumping mechanisms, different designs for the digester tank, different heating and stirring mechanisms, different gas storage and combustion systems. For example, there were six different types of pumps, all with specific advantages and disadvantages, but no design emerged as dominant (Poelma, 1987). Nevertheless, researchers, technology suppliers and a few enthusiastic farmers continued to use and improve the biogas plants. In the late 1980s, researchers argued that the plants had improved technologically and that further simplification could lower investment costs for farm-scale plants (Hoek, Kruijdenberg and Voermans, 1995:6; Nes, 1987). However, the number of plants did not increase. The focus shifted towards the construction of centralised plants, while most farm-scale plants were abandoned in the late 1980s and early 1990s.

3.1.2 Centralised plants (1986-1995)

After 1985, centralised digestion of manure was initiated with two experimental plants. The first one was a small centralised plant in the town of Deersum in northern Netherlands. The second one processed manure into fertilizer grains. This plant was established in Helmond, in southern Netherlands.

In the late 1980s, Deersum was a small village of 115 inhabitants; total energy demand was low. In the early 1980s, the town had faced problems with its sewer system and the town board had began to discuss the possibility of anaerobically purifying the waste water with the Paques B.V. company (this company had also constructed farm-scale biogas plants). The ideas gradually shifted towards a plan to make Deersum a self-supplying town for its own electricity. The town and Paques investigated several options and decided to establish a wind turbine and a centralised biogas plant (Paques, 1982:6). The European Commission, the Ministry of Environment and the province of Friesland (the meso-level in the Dutch policy...
system) financed the project.\(^5\) A new foundation was established, which organised the preparation, construction and exploitation of the project (Nes, Gemert and Diemen, 1990:1).\(^6\)

Preparation and construction started in 1986. The biogas plant was small, similar in size to previous biogas plants (210 m\(^3\)). Only seven farmers supplied manure to the plant. The plant was located on the farm of one of the suppliers. The other farmers supplied manure to a pumping station along a central road. The pump transported the manure over a small distance to a storage tank near the biogas plant. An automated clock pump added the manure to the digester tank. The digester tank was a silo lying on its side. A gas injection system mixed the manure, a system used in several of the farm-scale plants. After digestion, the manure was pumped back to the station along the road, where farmers could remove the manure to fertilize farmland. Two desulphurisation boxes (using iron hydroxide) purified the biogas from hydrogen sulphide (the gas that causes corrosion in gas engines). The biogas was used for heat and electricity production (Nes, Gemert and Diemen, 1990:11).

The project was monitored during the first year of operation, 1988. The wind turbine operated satisfactorily, but the biogas plant presented many technical problems. The pumps, the desulphurisation boxes and the generator needed modification or replacement; the digester caused troubles due to the formation of a scum layer. Most problems were solved during the first year, but the digester only produced half the amount that had been expected. In the first year of operation, costs of producing electricity were about 1.5 Dutch guilders per kWh (about 0.7 euros), while the average electricity price to consumers was 0.18 Dutch guilders per kWh (about 0.08 euros).\(^7\) Calculations showed that if biogas yields increased, if the plant was reconstructed on a less expensive location and on a larger scale, if payback rates increased and if additional advantages were valued (e.g. the fertilising value of the digested manure), energy production would still be very expensive. Nevertheless, the farmers continued to use the biogas plant until 1995 (Nes, Gemert and Diemen, 1990; Diemen, Poppen and Zandstra, 1992; Joustra, 1996).

Although several visitors from abroad visited the Deersum plant, the project was not copied elsewhere.\(^8\) Another centralised plant using digestion received more attention. In 1984, several agricultural organisations and public authorities had founded a steering committee called Stuurgroep Mestproblematiek Noord-Brabant, to develop a strategy for reducing the large manure surplus in southern Netherlands. The committee proposed the construction of a large manure processing plant; in 1986, Promest B.V. was established. In this company, agricultural organisations, chemical companies and financial companies cooperated to construct a large demonstration plant for the processing of 100,000 tons of manure annually. In 1987, construction started and in 1988 the plant began operating. Construction costs were high (twenty-three million guilders or ten million euros), but Promest

\(^5\) The full name of the Ministry of the Environment is ‘The Ministry of Spatial Planning, Housing and the Environment’.

\(^6\) Foundation participants were the municipality of Boarnsterhim, the public authority of Friesland, Frigem Zuidoost, a gas company, and the inhabitants of Deersum (Nes, Gemert and Diemen, 1990:1).

\(^7\) One of the reasons was a low feed-in tariff in this region: 0.11 Dutch guilders per kWh (about 0.05 euros).

\(^8\) In the 1988-1990 period, about 350 people visited the biogas plant.
expected to be able to reduce costs through the construction of larger plants, and through lower investment costs in the coming years (Promest, 1986).

The plant processed manure into fertilizer granules (Figure 3.2). Trucks transported manure (from pigs) to the plant, where it was weighed. The manure was divided among three digester tanks. Two tanks, each with a capacity of 1,000 m$^3$, were a new type that divided the digestion process into two steps (two-phase digester). The advantage was that these digesters produced two gasses, one gas containing most of the hydrogen sulphide (hydrolysis gas) – the substance that caused corrosion in combustion units and odour nuisance – and one gas without hydrogen sulphide (biogas). The design reflected the expectation that gas purification could be less expensive, because most of the hydrogen sulphide would be in the relatively small volume of hydrolysis gas. After cleaning, the hydrolysis gas was emitted into the atmosphere, and the biogas could be combusted directly. The Promest plant was equipped with a third digester, a conventional digester with a 2,000 m$^3$ capacity. A gas engine combusted the biogas; all energy was used to maintain the process. The manure leaving the digesters was first centrifuged and separated into a liquid fraction and a solid fraction. Aerobic purification removed some of the organic fraction from the liquid. Finally, an evaporator produced water that could be drained. The solid concentrate leaving the evaporator and the solid fraction leaving the centrifuge were mixed, dried and palletised, producing the main product from the Promest plant: fertilizer granules (Anonymous, 1987; MVH and Promest, 1993).
Promest experienced many difficulties. The heat exchangers were not able to heat the manure inside the tank sufficiently; the chopper (for cutting large parts into smaller parts, e.g. straw) got stuck. A large problem occurred with the formation of a scum layer. Adding anti-scum substances could have solved the problem, but the substances were very expensive (MVH and Promest, 1993:10). Neither did the two-phase digesters produce the expected results: the biogas leaving the digester still contained high levels of hydrogen sulphide and it was necessary to install an (expensive) caustic bath. Other parts of the factory were also troubled by technological problems, including corrosion in the drying system. Finally, the granules leaving the factory were very unstable. In 1992, a load of granules for transport to Spain and Portugal spontaneously burst into flames; research confirmed in 1994 that the granules were unstable (Feyaerts, Huybrechts and Dijkmans, 2002:322; Bloemendaal, 1995:82).
The design choices and technical problems caused overall low plant performance. Nevertheless, the Minister of Agriculture officially opened a new plant adjacent to the existing plant in 1992. This upgraded the Promest factory to a processing capacity of 600,000 tons of manure per year. The existing digesters were replaced with seven new digesters. Plant operation began in 1993. Total investment costs increased to more than 100 million Dutch guilders (45 million euros); 40% were investment grants. Plant operation continued to be problematic, the production of granules continued to be below the expected level and the economic losses sky-rocketed (Bloemendaal, 1995:85). Eventually the plant was shut down in late 1994. The upgraded plant had only been in operation for two years and had never reached full capacity (Van Ruiten Adviesbureau and Projectbureau BMA, 1998).

3.1.3 Reintroduction of biogas plants (1996-2003)

After 1995, no biogas plants operated in the Netherlands any longer. New experiments with manure digestion took place only in the late 1990s; a farm-scale plant in Denekamp, three plants erected at farms owned by an agricultural research institute, a centralised plant in Elsendorp and a centralised plant in Nijverdal.9

The biogas plant in Denekamp was the first farm-scale plant constructed in the Netherlands since the 1980s. Ecogas supplied the plant, a joint venture of the Biomass Technology Group (BTG) and Wiefferink. BTG was a well known company in the field of biomass research and development; Wiefferink was a company specialised in storage systems, such as silos. Ecogas began preparing the construction of a biogas plant in 1998, including its design and location. A farmer from Denekamp was willing to participate in the project. The Netherlands Organisation for Energy and the Environment (NOVEM) and BTG financed investment in the plant (114,000 euros). Only if the plant operated successfully for two years would the farmer have to pay for it (Ecogas, 2001).

Ecogas copied the design of a German biogas plant: an existing silo for manure was rebuilt into a digester. The digester capacity was 500 m$^3$ and it operated at 30 °C. The biogas was stored in an empty space above the manure, but inside the digester. An inexpensive biological purification system purified the biogas from small amounts of hydrogen sulphide. A CHP plant combusted the biogas, producing heat to maintain the digestion process and

9 Two other plants were installed, the first in Miste, a small town in the region of Gelderland. The plant processes 1000 m$^3$ manure annually and is supplied by the German company WISA (Koppejan and Annevelink, 2003). The other plant was installed by Ecogas in Zuid-Velde in 2003. No data on plant design and experiences are available. Furthermore, a large number of plants have been in several phases of design, but never constructed. In 2000, a total of 21 plants using codigestion with a total capacity of 1.6 million tons were planned (Boo, 2000). In one project (a codigestion plant in Ysselsteyn), the ETC company tried to copy the layout of Danish cooperative biogas plants (see also Chapter 6). However, the project was never implemented. Farmers did not want to sign long-term supply contracts, while the energy company involved did not want to invest without supply guarantees. Changes in agricultural policy also played a role, i.e. the implementation of a new system for manure contracts and plans for reducing livestock (Buiter, 2002; Buiter, Winter and Zanstra, 2000).

10 In Dutch: Nederlandse Organisatie voor Energie en Milieu (NOVEM).
electricity for farm use during milking periods; surplus electricity was sold to an energy company. Manure leaving the digester was spread on the farmers’ fields.

Experiences with the plant were promising. Technologically, the plant operated as expected. Only minor problems occurred. A transport pipe for the biogas turned out to be unsuitable for biogas; the generator sometimes stopped during morning hours because of fluctuations in the grid voltage. Both problems were solved. Although the farm was too small to make the plant economically feasible, biogas production was very promising and more than expected.\textsuperscript{11} The plant demonstrated the technological feasibility of manure digestion and provided insight into the requirements for farm size. Novem granted Ecogas funding for another five plants in the Netherlands (Ecogas, 2001; Dooren, 2002).\textsuperscript{12}

Ecogas searched for partners to implement the biogas plants and found one in the Dutch Animal Science Group.\textsuperscript{13} This institute developed and tested innovations at several of its farms. Ecogas constructed biogas plants at two of the experimental farms, one in Sterksel (Praktijkcentrum Sterksel) and one in Hengelo (De Marke). Another biogas company (Biogas Nederland) constructed a biogas plant at a third farm, part of the research institute in Goutum (Nij Bosma Zathe). The research institute tried to gain insight into the process parameters of a biogas plant, evaluate the plants economically, demonstrate the feasibility of biogas technology and investigate the digestion of manure with organic waste (codigestion) (Kool and Verdoes, 2001). All plants were farm-scale plants. In Goutum, Biogas Nederland constructed a lying tank with a volume of 80 m\textsuperscript{3}; manure remained inside the digester for thirty-five days. Cow manure was digested with corn (Dooren, 2002). In Hengelo, Ecogas constructed a plant similar to the plant in Denekamp and converted an existing silo into a biogas plant. In Sterksel, Ecogas constructed a completely mixed digester with a volume of 605 m\textsuperscript{3}. All plants began operating in the early 2000s.

At the time of writing (2003), data on experiences with the plants are limited, but three preliminarily observations are clear. First, the plants’ technological performance was much better than was the case in the 1980s. All plants operated satisfactorily, no major breakdowns occurred, and after the initial start-up phase, they all produced biogas yields equal to or higher than expected. Second, the plants were still not economically feasible, though this presented no obstacle for these three plants; all plants received investment grants, and the plants were constructed for research purposes, putting less emphasis on economic feasibility. Third, getting a permit from public authorities was very difficult and procedures could take very long. Despite the experiments’ positive results, the number of plants did not increase rapidly (Wagenberg and Timmerman, 2003; Wijland, 2002a; Dooren, 2002).

In Elsendrop, a centralised biogas plant was constructed. Biorek Agro owned the plant, a collaboration between a Dutch manure distribution organisation (Mestac) and a Danish supplier of biogas plants (Bioscan). Bioscan supplied the technology and had operational experience, while Mestac supplied the manure and purchased the fertilizer products produced in the plant. Eneco, an energy company, agreed to buy the electricity. The biogas plant

\textsuperscript{11} About 26 m\textsuperscript{3} biogas per m\textsuperscript{3} manure, compared to 13-15 m\textsuperscript{3} biogas per m\textsuperscript{3} manure in the 1980s.

\textsuperscript{12} Later, the farmer emigrated and the biogas plant stopped operations.

\textsuperscript{13} In Dutch: Praktijkcentrum Veehouderij.
produced fertilizer products from 25 kton of pig manure annually (Figure 3.3). Manure was first pulverised into smaller parts before being fed into the digester. The biogas was cleaned via the same biological method used in the biogas plant in Denekamp. A combined heat and power plant (CHP) produced heat and electricity. The manure leaving the digester was led through an ultra-filter, an ammonia stripper and a reversed osmosis unit and converted into three products: a product containing nitrogen, a product containing phosphate and potassium, and water.

![Figure 3.3. Layout of the manure processing plant in Elsendorp](image)

The Minister of Agriculture officially opened the plant in 2001. From the start, the plant was plagued by problems. First, there were technological problems. In particular, the ultra-filter and reversed osmosis unit caused problems, and the combination of these technologies into one plant complicated daily operation. Second, there were economic problems. About two years had passed since the plant was designed (1999), and market prices for manure had decreased. Biorek Agro decided to rebuild the plant into a codigestion plant, to increase the income from energy sales (Smulders, 2002a). Nevertheless, Mestac was forced to reorganise and the biogas plant was taken out of operation (Anonymous, 2003c).

A second centralised plant was built in Nijverdal in the early 2000s. The project was started by a farmer in 1998 to process the manure from his animals. When research indicated that a farm-scale plant would be too expensive, focus shifted towards centralised manure

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14 The official name of the Ministry of Agriculture is ‘The Ministry of Agriculture, Nature and Food Quality’.
processing. Other actors became involved, too, including Shücking Energietechniek, a supplier of biogas plants with close connections to the German biogas industry. When the supplier went bankrupt, an energy company (EDON) bought the project (including plant and location). They contracted a new supplier, Wolter en Dross Biowatt. Seeking collaborators, Edon approached two companies: Verkooijen, a manure distribution company and Geva, a company involved in mowing roadside grass. The companies signed contracts for ten years and established a new company for operating the biogas plant (De Scharlebelt). Verkooijen supplied the manure, Geva supplied grass and Edon bought the electricity. Plant construction continued in 2001, and operations began in 2002 (Kasper, 2002; Koppejan and Annevelink, 2003; Broek et al., 2002; Kasper, 1998).

The biogas plant could process 25 kton of manure per year. Manure and grass were stored on-site. Manure was pumped from storage tanks into two digesters; a cutting device reduced the size of the grass before adding it to the digesters. The addition of air cleaned the biogas. The mixture of digested manure and grass was separated into a solid fraction and a liquid fraction. The solid fraction contained most of the organic matter and was sold as humus, while the liquid fraction was further processed in a similar system as the one in the Biorek Agro plant, including an ultra-filter and a reversed osmosis unit (Kasper, 1998). Total project realization took longer than expected due to a bankruptcy and take-over, and there were other delays. The plant supplier had expected to construct the plant within half a year, but it took much longer. The process of getting approval also took much longer than expected, especially approval to sell the humus and fertilizer products on the Dutch market (Kasper, 2002; Broek et al., 2002).

Conclusion
Three periods of biogas plant development since the 1970s can be distinguished in the Netherlands. Between 1973-1985 the focus was on farm-scale plants. Most of these plants were taken out of operation in the 1990s. In the 1986-1995 period, the focus shifted towards centralised biogas plants, but experiments with these plants also failed. Finally, between 1996-2003, first there was a period with no development, followed by a second period during which biogas plants were reintroduced in the early 2000s. In 2003, five small farm-scale plants were in operation with a total processing capacity of about 9 kton manure annually as well as two centralised biogas plants with a total processing capacity of 50 kton annually. In comparison, total manure production in 2001 was more than 74,000 kton.

Several questions emerge from this historical overview. First, why did the development of farm-scale plants continue until the late 1980s, although the majority of experiments lacked stable operation? Second, why did actors in the late 1980s focus on very large manure processing factories like the Promest plant? Why did they not put more effort into developing

15 Edon is now part of Essent.
16 Geva is a daughter company of the larger ‘Koop’ group, an international operating company.
17 At the time of writing (2003), no data are available on the technological experiences with the plant.
18 Numbers are based on various project documents mentioned in the main text. Total manure production is from http://www.rivm.nl/milieuennatuurcompendium.
smaller centralised plants (like the Deersum plant)? Technological and economic risks might have been much lower in these plants. Third, why did Promest B.V. upgrade the plant in 1993 from 100,000 to 600,000 tons annual processing capacity, despite poor plant performance? If performance was so poor, why did Promest not try to deal with the problems, before upgrading? Fourth, why was Promest shut down in 1995? The government and several companies had invested huge amounts of money in the plant. Fifth, how is it possible that farmers and inhabitants of the Deersum town continued to use and support the biogas plant, despite very poor operation, until 1995? Sixth, why was the plant eventually shut down in 1995? Seventh, what were the reasons for renewed attention for biogas plants in the late 1990s? Finally, why did the number of plants not increase rapidly, despite improved plant performance?

In the following section, I answer these questions by analysing niche development in terms of visions and expectations, the social network involved and learning processes. I will argue that internal niche dynamics cannot explain everything. Consequently, I pay attention to regime dynamics in section 3.4. In the section below, I will sometimes refer to regime dynamics for reasons of clarity and readability, but I will not yet involve them in my explanation.

3.2 Analysis of niche dynamics

I analyse the three niche processes in three different sections, the advantage being that I can show the role of these processes over a longer period. The processes, however, are interlinked and can only be separated analytically. I therefore discuss the relation between the three processes and niche development in section 3.3.

3.2.1 Visions and expectations

In the late 1970s and early 1980s, influenced by the high energy prices at that time, the dominant vision in the Dutch biogas niche was related to energy generation. Biogas plants were viewed as a technology for producing inexpensive alternative energy and saving energy. In Van Velsen’s thesis on manure digestion, and in the final report on the IMAG research project, researchers argued as follows:

The energy crisis of 1973 forced the developed countries to realize their dependence on finite natural resources. This and the consequent prospect of ever-increasing prices of raw materials in the near future, has strongly revived the interest and the research into anaerobic digestion as an energy-producing method and an energy-saving waste treatment technology. The main objective of the present investigation was to assess the energy recovery and malodour abatement potentials of piggery waste digestion (Velsen, 1981:2).
In the mid-1970s, farmers and industries were extremely interested in anaerobic digestion. Digestion was mainly seen as a method for generating energy and, as such, a way of saving on fossil fuels (Hoek, 1984:6).

These citations illustrate that the focus was on energy generation. The vision was similar across the European countries. Table 3.1 shows the motivations for setting up biogas plants: plants that digested manure were mainly constructed to generate energy.

Table 3.1. Motivations for setting up biogas plants. Data from a 1981 survey among all European Community member states and Switzerland (Demuynck, Nyns and Palz, 1984:130)

<table>
<thead>
<tr>
<th>Type of waste</th>
<th>Motivations</th>
<th>Energy production</th>
<th>Pollution prevention</th>
<th>Energy + Pollution prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agro-waste</td>
<td>62%</td>
<td>8%</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Industrial waste</td>
<td>0</td>
<td>63%</td>
<td>37%</td>
<td></td>
</tr>
</tbody>
</table>

Researchers and farmers focused on optimising biogas yields as much as possible. They investigated the process’s thermal conditions in relation to biogas yields; farms were chosen on the basis of size and energy demand; economic performance was calculated on the basis of energy yields and savings. An important invention, adding organic waste like flocculation sludge and fatty waste to the manure, increased biogas yields enormously. In 1987, seven of twenty-six biogas plants were digesting manure and waste; their biogas yields doubled (Poelma, 1987). Experiments into agricultural benefits like stench reduction or changes in the composition of manure were largely absent.

Researchers raised high expectations about biogas yields, but most experiments were not able to meet the expectations (see Table 3.2). Only six of the seventeen plants installed before 1982 showed biogas yields as expected, or higher. The experiments did not confirm the expectations.

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19 Original text (in Dutch): In het midden van de zeventiger jaren ontstond er grote belangstelling van zowel veehouders als het bedrijfsleven voor anaërobe vergisting van mest. Vergisting werd hierbij voornamelijk gezien als een methode voor productie van energie en daarmee een besparing op fossiele energiedragers.

20 There was incidental research on these aspects. Some farmers experimented with the quality of digested manure and its acceptance by cows after it had been spread on grasslands. The first, more structural research project was only executed in 1992. In this project, the researchers concluded that, overall, no additional benefits could be expected from manure digestion (Haskoning, 1992).
Table 3.2. Biogas production compared to the expected production in seventeen farm-scale biogas plants (Boks and Nes, 1983)

<table>
<thead>
<tr>
<th>Biogas plant location</th>
<th>Year established</th>
<th>Biogas production compared to expected production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuw-Millingen</td>
<td>1978</td>
<td>as expected</td>
</tr>
<tr>
<td>Klarenbeek</td>
<td>1979</td>
<td>as expected</td>
</tr>
<tr>
<td>Hemelem</td>
<td>1980</td>
<td>too many technical problems</td>
</tr>
<tr>
<td>Schijndel</td>
<td>1980</td>
<td>expected production was not reached</td>
</tr>
<tr>
<td>Jutrijp</td>
<td>1980</td>
<td>as expected</td>
</tr>
<tr>
<td>Barneveld</td>
<td>1980</td>
<td>65% of expected production</td>
</tr>
<tr>
<td>Lelystad</td>
<td>1980</td>
<td>50% of expected production</td>
</tr>
<tr>
<td>Witharen</td>
<td>1980</td>
<td>50% of expected production</td>
</tr>
<tr>
<td>Aalten</td>
<td>1981</td>
<td>expected production was almost reached</td>
</tr>
<tr>
<td>Eibergen</td>
<td>1981</td>
<td>as expected</td>
</tr>
<tr>
<td>Milheeze</td>
<td>1981</td>
<td>60% of expected production</td>
</tr>
<tr>
<td>Woedens Verlaat</td>
<td>1981</td>
<td>expected production was not reached</td>
</tr>
<tr>
<td>Lievelede</td>
<td>1981</td>
<td>expected production was not reached</td>
</tr>
<tr>
<td>Den Ham</td>
<td>1981</td>
<td>expected production was not reached</td>
</tr>
<tr>
<td>Heeswijk-Dinther</td>
<td>1981</td>
<td>125% of expected production</td>
</tr>
<tr>
<td>Slagharen</td>
<td>1981</td>
<td>expected production was almost reached</td>
</tr>
<tr>
<td>Diessen</td>
<td>1981</td>
<td>75% of expected production</td>
</tr>
</tbody>
</table>

The high expectations about energy generation and the negative results with biogas yields explain why only a limited number of plants were installed after 1981. Future markets turned out to be much smaller than expected, while to make a biogas plant economically feasible the minimum required size of farms was quite large. Researchers continued to be optimistic. They argued that increasing energy prices would eventually result in competitive biogas plants. In a 1982 IMAG report, researchers calculated future costs:

The expectation is that energy prices will increase more rapidly than the costs of biogas plants. The result is that in the future, economic feasibility will increase. [...] The value of 1 m$^3$ biogas will also increase, due to the expected price increase of domestic fuel oil, and an estimated inflation rate of 5%. For 1982, calculations use a value of .52 Dutch guilders; in 1983 the value will already be .552 Dutch guilders per m$^3$ manure. In 1985 the value will be .615 Dutch guilders and in 1990 the value will be .812 Dutch guilders. Of course, the reliability of the value decreases for estimations over longer periods. However, if these calculations are continued, the value will be 1.608 Dutch guilders per m$^3$ in 2000! (Werkgroep Bedrijfsopzetten Biogasinstallaties, 1982:78)

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21 Original text (in Dutch): De verwachting bestaat dat de energieprijzen sneller zullen stijgen dan de kosten van biogasinstallaties. Dit betekent dat het economische rendement in de toekomst gunstiger wordt. [...] Door de verwachte prijsstijging van huisbrandolie en de geschatte inflatie van 5% stijgt ook de waarde van 1 m$^3$ biogas. Voor 1982 is gerekend met 52 cent, in 1983 zal dit reeds 55.2 cent/m$^3$ bedragen. In 1985 wordt een waarde bereikt van 61.5 cent/m$^3$, terwijl die in 1990 zal zijn opgelopen tot 81.2 cent. Natuurlijk wordt de waarde steeds minder betrouwbaar naarmate de toekomst verder weg ligt. Maar op deze wijze doorgerekend zal de waarde in 2000 op 160.8 cent/m$^3$ liggen!
Researchers used these calculations to legitimise more investigation into biogas plants. Nevertheless, the assumptions regarding energy prices were proven wrong when global oil prices dropped in 1986, rendering biogas plants economically unfeasible in the short term – and expectations about future feasibility no longer provide legitimisation, either. At a meeting of the Dutch biogas community in 1986, Van Velsen described the situation as follows:

Participants’ attitudes towards manure digestion are fairly clear. If solely energy generation is considered, the application of manure digestion is not feasible at this time. Neither is improved feasibility likely in the short term. The optimal biogas yields from manure are known, and we cannot foster high expectations about rising gas production from manure (Velsen, 1986:2).22

The biogas community concluded at the same meeting that they expected another large market for manure digestion, i.e. the market for processing manure. These expectations were linked to increasing environmental problems in the agricultural sector (see section 3.4). A new vision emerged on manure digestion technology, i.e. digestion as a step in processing and distributing manure. The research agenda shifted from the development of farm-scale plants to the development of centralised processing plants. In a policy plan based on the 1986 meeting, researchers proposed the following financing scheme (see Table 3.3): Research line I aimed at consolidating and describing the existing experiences and knowledge of farm-scale manure digestion. Research line II aimed at developing and optimising large scale digestion technologies that met the conditions of large scale manure processing. The table illustrates that the research agenda shifted from optimising energy generation towards manure processing. The table also illustrates that expectations were very high again: researchers expected that budgets could be cut down in five years. These estimations were supported by expectations in national policy documents on manure processing. In 1990, the Dutch Ministry of Agriculture expected that by 1992 two million tons of manure could be processed, by 1994 at least five million tons and by 1996 ten million tons. In 2002, processing capacity would be enough for twenty million tons of manure. As a comparison there was only one plant (Promest) with a capacity of 100,000 tons in 1990 (Ministerie van Landbouw, Natuurbeheer en Visserij, 1990:58).

22 Original text (in Dutch): De standpunten van de deelnemers ten aanzien van mestvergisting alléén lagen redelijk vast. Wanneer uitsluitend de energieproductie wordt gewaardeerd is toepassing van mestvergisting momenteel niet rendabel. Een verbetering van de rentabiliteit valt in de naaste toekomst ook niet te verwachten. De optimale gasproductie uit mest staat al vast en er mogen geen hoge verwachtingen zijn t.a.v. een verhoging van de gasproductie uit mest.
Table 3.3. Proposed financing scheme (in 1,000 guilders) for manure digestion divided over two research lines (Velsen, 1987:3)

<table>
<thead>
<tr>
<th>Year</th>
<th>Research Line I (1000 NLG)</th>
<th>Research Line II (1000 NLG)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>420</td>
<td>360</td>
<td>280</td>
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<tr>
<td>500</td>
<td>875</td>
<td>875</td>
<td>400</td>
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<tr>
<td>-</td>
<td>35</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>-</td>
<td>35</td>
<td>35</td>
<td>16</td>
</tr>
</tbody>
</table>

The vision on manure processing and high expectations about increasing capacity had consequences for plant design. Plant size increased enormously, because the size was now based on the availability of manure in a region, not on a farm’s energy demand. The original digester capacity in the Promest plant was 16 times larger than the average size of a farm-scale plant; after scaling up the plant, capacity was almost 100 times larger.\(^{24}\) The plant produced products for new markets: farm-scale plants produced energy and the manure was used on local fields; Promest produced a new product (fertilizer granules) for new markets (mainly southern Europe). Changing visions on manure digestion and high expectations about the manure market resulted in a biogas plant design that radically differed in terms of plant complexity, plant size and markets.

Actors supporting the centralised plant in Deersum had different ideas about manure digestion. A research institute and technology supplier previously involved in farm-scale plants continued to support the vision of small scale energy systems based on local resources (see Section 3.2.2). The design of this experimental plant was very different from the design of the Promest plant – the plant was small, and it combined energy generation with manure storage and distribution.

Promest was shut down in 1995, contributing to a period of pessimism and a lack of support for any technology related to manure processing, in particular in the agricultural sector. The high expectations combined with very poor results explain why no biogas plants were implemented after 1995.

New expectations about manure digestion emerged in the late 1990s. Technological development had continued in countries like Germany and Denmark. Experiences in these countries proved that manure digestion was technologically feasible. Energy companies became interested, because of expectations about large green energy markets (see section 3.4). In addition, some Dutch manure distribution companies began to investigate and experiment again. The combined vision on energy generation (supported by energy companies) and on manure processing (supported by manure distribution companies) resulted in centralised plants in Nijverdal and in Elsendorp. These plants were designed to optimise biogas yields

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\(^{23}\) Research line I aimed at consolidating knowledge from farm-scale biogas plant experiences. Research line II aimed at developing and optimising large-scale biogas plants as part of manure processing plants. These figures are indications from 1987. They are the budget from one particular research programme (NOH) and do not represent total research budgets in the Netherlands. The amounts are in 1,000 Dutch guilders (450 euros).

\(^{24}\) The average capacity of a farm-scale plant was about 250 m\(^3\). Total digester capacity in the original Promest design was 4,000 m\(^3\), and the plant was scale up from 100,000 tons manure annually to 600,000 tons manure annually.
Manure digestion in the Netherlands

(codigestion with organic waste) and to process manure into new products (separation technologies) (Smulders, 2002; Kasper, 2002).

Manure digestion on farms in the early 2000s was guided by ideas and expectations about energy generation similar to the ideas and visions of the 1980s. A researcher of the Dutch Animal Science Group, involved in the experiments with the Goutum biogas plant, argued as follows:

The objective of manure digestion in Sterksel and Goutum was to see to what extent we could produce energy with manure digestion. [...] The consideration was mainly economic. In my opinion, this is also why other companies should start with manure digestion. The grants and subsidies are of course for environmental reasons, but this is not the point of departure for farmers. The argument that manure digestion contributes to sustainable agriculture was mentioned, but only limited information was available when we started the feasibility studies. One might consider a better absorption of minerals, which could contribute to reducing artificial fertilizer usage. [...] But the basis of the plant is still energy generation, which is why we did not choose a separation system, for example (Dooren, 2002).

Conclusion
I draw the following conclusions on dynamics in expectations and visions: changing visions and expectations contribute to niche branching, in particular branching between farm-scale plants and centralised plants. Farm-scale plants were constructed for energy generation, while centralised plants were constructed for manure processing (in the late 1980s) or a combination of manure processing and energy generation (in the late 1990s). When visions and expectations changed, plant design was affected: codigestion was important for optimising energy yields, while separation equipment was essential for manure processing. The dynamics in visions were mainly caused by external circumstances like energy prices, environmental problems in agriculture and the emergence of green electricity markets. Results from experiments hardly affected visions and expectations, with the exception of the poor results from the large Promest plant.

3.2.2 Network formation

In this section I discuss the role of farmers, public authorities, research institutes, energy companies and technology suppliers during different periods of biogas plant development. In the concluding paragraph of this section I discuss the composition and alignment of this social

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25 Het doel van mestvergisting in Sterksel en Goutum was om te kijken in hoeverre we met mestvergisting energie konden produceren. [...] De overweging was vooral financieel-economisch. Mijn inziens is dat ook de reden waarom andere bedrijven zouden moeten beginnen met mestvergisting. De subsidiëring is natuurlijk wel vanuit het oogpunt van milieudrukvermindering, maar dat is voor melkveehouders en varkenshouders geen uitgangspunt. Het argument dat mestvergisting bijdraagt aan een duurzame landbouw is in het begin wel gebruikt, maar daar waren, toen we begonnen met de haalbaarheidsstudies, weinig gegevens over. Je zou kunnen denken aan zaken als betere opneembaarheid van de mineralen e.d. waardoor het kunstmestgebruik zou kunnen afnemen. [...] Het uitgangspunt van de installatie is toch energieproductie, vandaar dat er ook niet is gekozen voor een scheidingsinstallatie bijvoorbeeld.
network during different periods, and how these aspects provide an explanation for niche development.

Farmers and farmer organisations

Farmers who participated in the biogas niche in the early 1980s were actively involved in testing, experimenting and developing the technology. They operated and controlled the plants, often assisted by research groups and biogas plant suppliers. Some farmers designed and constructed plants in cooperation with a supplier or research group, e.g. in Nieuw-Millingen (1979), Heerhugowaard (1980) and Aalten (1981) (see Table 3.8, Appendix 3.1). Farmers also provided feedback to researchers and companies, and commented on research reports (Nes, Diemen and Schomaker (1990:13). After 1985 the role of farmers changed. In the case of Deersum, farmers continued to be involved in the development and construction phases, and cooperated to supply manure. Financial benefits from collective storage stimulated farmers to participate (Nes, Diemen and Schomaker, 1990:16).

In the case of Promest, farmers were no longer active participants, having no influence on the decision and design processes. Dominant actors from the agricultural regime like the ‘Noord-Brabantse Christelijke Boerenbond’, the ‘Limburgse Land- en Tuinbouwbond’ and the ‘Cooperatieve Brabantse Vee- en Vleescentrale’ dominated the decision process. They were powerful actors, with representatives in the national and local public authorities. These organisations were established in the late nineteenth century, and represented the majority of farmers in the southern Netherlands. They had stimulated the specialisation process and the increase in scale and productivity in Dutch agriculture after World War II, a process that resulted in a very intensive bio-industry in the Netherlands (see section 3.4).26 These actors’ participation in manure digestion explains the focus on large scale centralised technologies. The organisations tried to keep control of the agricultural sector and to minimise interference from national and local public authorities. Individual farmers, however, did not support the choices of the agricultural organisations for two reasons. Economic motivations played an important role: processing manure turned out to be twice as expensive as distributing the manure unprocessed. Moreover, farmers had no sense of urgency. Bloemendaal (1995:114) argued as follows:

Perhaps the most important cause for the failure of manure processing is that cattle breeders never really believed in it. Cattle breeders tend to look at the present, and they see that they can remove their manure for a reasonable price. They do not at all, or hardly, look at the long-term situation. As far as they tried, their leaders did not succeed in convincing the farmers of the long-term importance. Because the organisations invariably aimed at collective solutions, the individual farmers did not feel that they had to solve a problem (Bloemendaal, 1995:114).27


27 Original text (Dutch): Maar misschien wel de belangrijkste oorzaak van de mislukking van mestverwerking is dat veehouders er nooit echt in hebben geloofd. De veehouder is geneigd naar het hier en nu te kijken, en hij ziet dan dat hij zijn mest kwijt kan tegen een betaalbare prijs. Hij kijkt niet of nauwelijks naar de situatie over een paar jaar. Voor zover ze het hebben geprobeerd is het de voormannen niet gelukt hun achterban van het
Promest was able to continue operating, because the government forced farmers to supply manure. Promest also negotiated an exploitation levy with the public authority, paid by farmers. However, the European Union rejected the legitimacy of the levy, on the grounds of unfair competition, and forced Promest to compete with other solutions to the environmental problems, in particular the distributing of unprocessed manure. The EU allowed the Netherlands to implement the levy only until 1995 (Bloemendaal, 1995).

After 2000 the role of farmers remained very limited in the biogas niche. In Denekamp, the plant was constructed on a farm, but the farmer did not have to pay for the plant; it was an experimental plant for demonstrating the technological and economic feasibility of biogas plant technology. In the Biorek Agro plant, the members of the Mestac cooperative (farmers), voted in favour of implementing a biogas plant. Nevertheless, Mestac faced the same problem as the Promest plant: farmers stopped supplying manure because other methods were less expensive. In other biogas plants, farmers were hardly involved in the biogas plant; farmers were either not involved in the project (Nijverdal) or the plants were implemented on experimental farms (Sterksel, Goutum and Hengelo).

**Public authorities**

The national government was mainly involved in pilot projects for providing financial support through grants and subsidy schemes. In the early 1980s, in particular the Ministry of Economic Affairs financed biogas plant projects.²⁸ Pilot plants were granted in a scheme for supporting demonstration projects on energy saving, and within a national research programme also for energy saving by re-using waste products (Hoeksma, 1984:3; Hoek, 1984:6; Boks and Nes, 1983:1).²⁹ After 1985 Dutch authorities became more involved in manure digestion through top-down decision making and interference. In particular in agricultural policies, manure processing was seen as one of the dominant solutions to deal with environmental problems (see also section 3.4) and the government provided support for large centralised plants (16 million euros for Promest).

After 1995, the national government no longer supported biogas plants explicitly, but there were generic instruments for renewable energy. Moreover, the Ministry of the Environment was increasingly interested in agricultural affairs because of the reduction of methane emissions, a strong greenhouse gas. This ministry, in participation with the Ministry of Economic Affairs and the Ministry of Agriculture, financed research on biogas plants from the programme ‘Reduction Plan Other Greenhouse Gasses’ (ROB). The Ministry of Agriculture, however, was reluctant about manure processing (including digestion) and attempts from the biogas community to simplify agro-environmental regulations and permits

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²⁸ The Ministry of Agriculture also invested in research on biogas plants, but on a limited scale. For example, the Ministry of EZ financed 63% of the research project on methane production and use, while research institutes and the Ministry of Agriculture together financed the remaining portion (Hoek, 1984:6).

²⁹ In Dutch: ‘Regeling Demonstratieprojecten Energiebesparing’ and ‘Energie- en Grondstoffenbesparing door hergebruik van Afvalstoffen’.
for biogas plants often failed or required large efforts (Kasper, 2002; Leeden, Roovers and Wassenberg, 2003).

*Research institutes*

Research institutes dominated the biogas niche in the late 1970s and early 1980s. Institutes involved included the Wageningen Agricultural University (the Department of Water Treatment and the Department of Microbiology), the IMAG institute, also in Wageningen, the IW-TNO Institute in Delft and the CE Institute, also in Delft. In particular, the researchers Van Velsen and Lettinga (Wageningen University) made important contributions in the 1970s; they designed and investigated the first biogas plant in the Netherlands. IMAG supported seven farmers with the operation of biogas plants; the institute monitored biogas plants and suggested improvements. IMAG also (co-) supplied biogas plants. CE researchers constructed a biogas plant in Assendelft, together with a supplier (JOZ) in 1982 (Nes, 1987). CE also had contacts with the Danish biogas industry (Diemen and Nes, 1989). Moreover, the CE institute also participated in the Deersum biogas plant as an advisory company. Together with IMAG and Wageningen University, CE was responsible for most of the research, experimentation and monitoring of farm-scale biogas plants in the Netherlands. The work of these research institutes was instrumental in producing and stabilising knowledge about the design and operation of biogas plants.

After 1985, most research institutes continued to be involved, but no longer as dominant actors. In the Promest case, IMAG, TNO and Wageningen Agricultural University performed research on (parts of) the plant. They participated in a national research programme on manure processing in 1988 and 1989, financed by the Dutch government (Anonymous, 1987). The institutes cooperated with research groups from chemical companies. Moreover, other research institutes were now also involved, including large agricultural research institutes like the Agricultural Economics Research Institute (LEI). These institutes’ role in and influence on technological development was limited compared to the post-1985 roles and influence of technology consortia and agricultural organisations. Research institutes criticised these organisations for too optimistic expectations about the economics of manure processing.

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30 In 2000, a lobby organisation from the bio-energy sector (Stichting Platform Bio-Energie) asked for more clarity about trading products from codigestion plants. Companies that codigested manure with other products needed an exemption to sell the end product as manure. They could only get an exemption if they were able to show a sample of the end product. This created uncertainty for investors, because it was impossible to show a sample before plant construction. If the exemption was not given after construction, the plant could not be used. The Ministry acknowledged the problem and allowed a temporary exemption to be granted on the basis of calculated samples. This did not solve the problem, because the uncertainty for investors remained (Boo, 2000).

31 The Ministry of Agriculture's vision on codigestion, see Boo (1997:11). In 2002 and 2003, new working groups were established with the purpose of investigating possible solutions to the regulatory problems regarding codigestion (Kasper, 2002; Ministry of Economic Affairs, 2003).


33 In 1989, two CE researchers travelled to Denmark where they visited several Danish biogas plants.

34 In Dutch: Landbouw Economisch Instituut (LEI).
After 1995 most institutes discontinued the investigation of manure digestion, but in the late 1990s manure digestion was again investigated by IMAG, the Dutch Animal Science Group, ETC (a consultancy company), the Dutch Agricultural Research Institute (LEI) and the Centre for Agriculture and Environment (CLM). These companies reported on both farm-scale and centralised digestion of manure. Most of the reports were desk research projects, not based on experiments with biogas plants in the Netherlands. The reports used information from foreign experiments and emphasised advantages of biogas plants, including energy aspects, agricultural aspects and benefits regarding climate change (Tijmensen et al., 2002; Lent and Dooren, 2001; Antuma, Scheppingen and Boo, 1998; Tijmensen et al.; 2003).

Energy companies
Energy companies did not participate in the establishment of farm-scale biogas plants in the early 1980s. In most plants a generator combusted the biogas for heat and electricity generation (Poelma, 1987:34). The feed-in tariff for electricity from biogas was much lower than the price farmers paid for electricity, and most farmers decided to use the electricity on the farm. This had consequences for the design of biogas plants; plants’ dimensions were based on energy demand and not on the amount of manure production (for maximum energy generation). Plant design was therefore often smaller than possible on the basis of manure availability. Generally, energy companies were not involved in the biogas niche; they did not participate in projects, public discussions, research or seminars. They behaved the same way in the case of centralised processing and digestion of manure (Promest, Deersum). Promest did not produce any net energy and no energy company participated in the Promest organisation. In Deersum, the regional energy company was involved in buying surplus electricity, but the company did not participate in the biogas project.

The role of energy companies changed in the late 1990s. Energy companies began to experiment with biogas plants, in particular Essent energy company at its Scharlebelt digester in Nijverdal. Essent owned and operated the plant, together with a supplier of manure (Verkooijen) and a supplier of road-side grass (Koop). Their main interest was renewable energy generation and learning about the technological feasibility of such a process (Kasper, 2002). In the second centralised digester (Biorek Agro), an energy company, though it did not participate in the biogas plant organisation, promoted the energy as renewable energy for sale on the green electricity market (Anonymous, 2002a, Smeulders, 2002a). In the case of farm-scale plants, energy companies did not participate in the projects and were often not interested in buying the electricity, because the amount of energy generated at these plants was limited (Dooren, 2002).

Technology suppliers
The farm-scale biogas plants in the late 1970s and early 1980s were developed by research institutes with farmers, by research institutes with technology companies, or by technology companies.

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34 In Dutch: Centrum voor Landbouw en Milieu (CLM).
35 In 1982, the average price that farmers paid for 1 kWh electricity was 0.22 Dutch guilders (0.10 euros), while the average price farmers received for 1 kWh was 0.08 Dutch guilders (about 0.04 euros) (Hoeksma, 1984:94).
companies alone. Most companies were small and often established by farmers trying to commercialise their design. Paques, established in the late 1970s, was the largest supplier of plants. Between 1978 and 1987, it supplied ten of the twenty-eight biogas plants. In the 1990s, the company no longer developed manure digestion plants, but focussed on other markets for anaerobic digestion, including industrial waste water purification. Other companies, like JOZ, Van Wanrooij and GTI, were large contractors. These companies had no prior experience with biogas plants and often could not react adequately to plant breakdowns (Hoeksma, 1984:26; Diemen and Nes, 1989:48).

In the Promest plant, a more complex network of technology suppliers supported plant development. Companies – such as machinery suppliers for the cattle feeding industry – established consortia with suppliers of drying and separation machinery. In sum, ten companies were involved in Promest, most of them with backgrounds in engineering and construction work. These consortia were very optimistic about the development of manure processing equipment. They presented overly optimistic calculations, in contrast to calculations from research institutes, which often showed large exploitation shortages. Technology suppliers and consortia assumed that processing costs would be low, which eventually turned out to be too optimistic (Bloemendaal, 1995:81; MVH and Promest, 1993:9).

After 1995 there was no longer a domestic biogas plant industry in the Netherlands, no specialised biogas plant companies. The only company that continued to develop anaerobic digestion technology (Paques) moved to different markets and did not return to the manure market. Most companies continued their core business when the introduction of biogas plants failed. In the late 1990s, the Netherlands lacked companies with sufficient experience in the biogas plant industry; most of the practical experience and lessons learned were lost (see section 3.2.3). Companies like the Wolter en Dross Biowatt company (supplier of the biogas plant in Nijverdal), the Ecogas company (supplier of plants in Denekamp, Sterksel and Hengelo) and the Biogas Nederland company (supplier of the plant in Goutem) tried to build up new expertise, often in cooperation with the German and Danish biogas industries.

Conclusion
In the early 1980s the social network consisted of farmers, technology suppliers and research institutes from the agricultural sector. These actors cooperated in designing, constructing and developing biogas plants. The network was small – only a limited number of people participated – but alignment in the network was high. Researchers compared the local experiments in different reports, while all actors shared a similar vision on the development of biogas plants, which could build upon existing agricultural network relations between farmers and research institutes. The high alignment enabled the relatively rapid growth of the biogas niche in the 1980s.

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36 Exploitation shortages could be as high as thirteen to eighteen euros per ton of manure.
37 Ecogas and Biogas Nederland cooperated with German suppliers; Biorek Agro was a Danish supplier.
Part of this network continued the development of biogas plants with the centralised plant in Deersum, resulting in a similar design, but on a centralised level. In the Promest plant, established agricultural organisations and technology consortia dominated the network, explaining the choice for large technological solutions. The lack of farmer support partially explains the failure in the Promest case: there was no alignment between the design choices of technology consortia and agricultural organisations, and the preferences and practices of farmers.

In the late 1990s, the composition of the social network for centralised plants was characterised by cooperation between manure suppliers and energy companies. A research institute and a technology supplier dominated the network for farm-scale plants, and entailed a very small number of actors. Network alignment was limited; there were no experienced actors, nor a dedicated network builder.

3.2.3 Learning processes

In the late 1970s farmers, research institutes and technology suppliers had no experience with biogas plants. They constructed plants based on general agricultural knowledge (e.g. construction of silos) as well as scientific knowledge from Wageningen University. The first research project and experimental plant (Garderen) resulted in basic technical knowledge on the relation between process parameters and biogas yields. IMAG implemented a three-year research programme on the basis of these results. Actors involved in the project (Wageningen University, IMAG, TNO, CE) combined experiences from different biogas plants and codified the knowledge in several reports (Werkgroep Bedrijfsopzetten Biogasinstallaties, 1982; Hoek, 1984; Hoeksm, 1984; Poelma, 1987). The research programme gave the necessary insights into the technological and economic feasibility of biogas plants; researchers, farmers and technology suppliers learned detailed lessons about the composition of manure, about microbiological processes inside the digester, about the effect of digester temperature, processing time and biogas yields. They learned about different applications of the biogas (e.g. central heating systems, different gas engines, tractors). Actors also reported about advantages and disadvantages of different components of biogas plants: manure storage systems, gas transport and storage systems, manure pumps, engines, heat exchangers etc. This programme was successful in generating an enormous amount of technical knowledge. Nevertheless, these lessons could hardly be applied for the construction of new biogas plants, because farmers began to lose interest in biogas plants, due to poor results.

The programme also contributed to lessons about the economic feasibility of biogas plants. In the late 1970s, there was limited knowledge of economic parameters. The programme that monitored seven biogas plants showed that the plants’ economic feasibility was poor, that no plant was economically feasible (all plants had a negative return on

38 The design of the digester in Duiven (the IMAG farm) was based on experiences with the Garderen plant (Hoek, 1984:22).
Researchers attributed the poor feasibility to technical issues like a low biogas yield and breakdown of the plant. The research project did not contribute to learning about the additional value of manure digestion like improvement of manure’s fertilizer characteristics or emission reductions. There was limited learning about societal embedding in the energy and agricultural sectors. Most learning was first-order, with a focus on technological learning.

By 1985, a large amount of data had been collected on the design and operation of biogas plants. The main lesson was that farm-scale plants were too expensive. Biogas plant operation was still unstable, but researchers continued to adapt process design on the basis of expectations. CE learned about the potential of benefits like improved fertilizer characteristics. In the research report on the Assendelft biogas plant, CE recommended that future research should focus more on non-energy benefits from biogas plants and biogas yields should rise to at least twenty to twenty-four m$^3$ gas per m$^3$ manure (Nes, 1987). A 1989 visit to Denmark emphasised the necessity of codigestion to reach these yields (Diemen and Nes, 1989). In 1990, CE combined all knowledge into one conclusive report. This report not only focussed on energy-related aspects, but also on agricultural and environmental benefits, and mentioned codigestion of manure and organic waste as a promising option. Manure digestion was only promising if it combined all these benefits (Nes, Diemen and Schomaker, 1990).

In the centralised biogas plant in Deersum, CE was able to apply these lessons in practice, showing that digesting manure resulted in a reduction of artificial fertilizer use (Diemen, Poppen and Zanstra, 1992:22). Farmers learned about the advantages of a centralised biogas plant that were not considered previously, in particular the benefits of centralised storage space and easier handling of digested manure. The biogas plant also helped reduce the town’s energy demand. The foundation that operated the biogas plant constructed a signalling post in the village, which showed the amount of energy produced; inhabitants became more aware of their energy use, and energy demand decreased. The biogas plant project in Deersum is interesting with respect to learning. The actors involved learned the same lesson as previously with small scale biogas plants: a biogas plant was technologically and economically very difficult. Yet the design of the plant as a centralised plant and the participation of CE contributed to learning about other aspects than technological and economic aspects. Despite the poor economic and technological results, these learning processes stimulated farmers to continue plant operation.

Learning in the Promest case was driven by an enormous pressure to succeed. Expectations were very high, while there was little time to investigate and improve plant design and operation. Increased technological complexity, size and markets forced the participating actors to learn much in a limited period of time, i.e. about operating a manure processing plant (including innovative digesters, separation technologies and dryers), about marketing new products in new markets and about securing the supply of manure. Plant

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39 They learned that the viscosity decreased and homogeneity increased, both resulting in easier manure handling.

40 Comparisons showed that energy usage of the Deersum town was lower than the average at the national and regional levels (Diemen, Poppen and Zanstra, 1992).
upgrade in 1993 came too early. In 1992, several people within the Promest organisation advised against upgrading the plant because of technological problems; findings from research institutes showed a much higher price for processing manure, and Ministry of Agriculture employees supported the suggestion. Nevertheless, the plant was still upgraded (Bloemendaal, 1995:83).

In the late 1990s, biogas plant technology had improved in Denmark and Germany. Dutch actors tried to import foreign designs and test the plants in a Dutch setting. The foreign experiences promised many agricultural and environmental advantages. Dutch advocates of biogas plants (research institutes, technology suppliers) emphasised these issues:

- improved availability of minerals in the manure (minerals are separated from organic matter due to the digestion process);
- the possibility of reduced artificial fertilizer use (because the minerals are no longer attached to organic matter, more minerals are available for crops and the effect on crop growth is more predictable);
- improved homogeneity of the manure (due to mixing the manure);
- reduced pathogens and weeds in the manure (in particular when digesting at high temperatures);
- reduced stench (due to breakdown of several fatty acids);
- reduced greenhouse gases (due to collecting and using the methane);
- improved recycling (of minerals in waste and manure).

Despite the findings from experiments in other countries, Dutch biogas plants were not designed to experiment with the issues listed above. Learning continued to focus on building up operational experience, learning about biogas yields and learning to improve economic feasibility. Neither were biogas plants monitored structurally nor were lessons from different biogas plants combined structurally. The manager of the Nijverdal biogas plant argued:

This project is a demonstration project according to subsidy schemes. This is not a demonstration project to us, we do not construct this to demonstrate something [...]. We want to learn something, we want to gain knowledge. Thus there are two sides to the project: on the one hand you have internal learning experiences and on the other hand you have external learning experiences. The internal learning experiences are rather unstructured. There is no plan for transferring lessons between the actors involved. There are times when knowledge goes from one party to another. For example, we have contact with the province to report on our progress and sometimes they visit us unannounced to check on the situation. But knowledge exchange is not the aim of these meetings. [...]. The external learning processes are another story. Within the EWAB programme of the Ministry of Economic Affairs, few demands are placed on what you must do to get your money. The only demand is that you draw up a report on your findings. [...]. The ROB programme of the Ministry of the Environment is entirely different; a number of demands are coupled to the subsidy. We had to make a plan regarding knowledge diffusion, e.g. regarding visitors. We have promised to publish in twenty journals, make a cd-rom and a
website, organise an open-house, and publish 2,000 leaflets. We must spend 150,000 euros on these kinds of activities (Kasper, 2002).

Most experiments in the early 2000s were successful in technological terms, with the most important lesson participating actors learned being that the regulatory framework in the Netherlands did not favour codigestion of manure and waste. Strict regulations on the use of waste products in agriculture also prevented the use of slurry from a codigestion plant. Codigestion had been an elementary innovation in other countries; it enabled high biogas yields and improved the economic feasibility of biogas plants. The biogas community lobbied for a clear regulatory framework, but embedding biogas plants in the existing regulatory framework became the most important barrier to the diffusion of biogas plants.

Conclusion

In general, learning in the Netherlands was mainly first-order technical and economic learning, with limited attention for (the integration of) a large number of potential biogas production benefits. Learning was well organised in the case of early farm-scale biogas plants, through various research programmes and intensive participation on the parts of farmers, research institutes and technology suppliers. This process generated an abundance of knowledge on biogas plants and manure digestion. Although it did not result in a dominant design, learning was very successful in this period, because it produced the basic technical knowledge necessary for plant operation. In the Promest case, however, this knowledge could not be used, because of radical changes in technological design and plant size, and too little participation on the parts of the actors involved in the construction of farm-scale plants.

Moreover, the time for learning was very limited and there was mainly first-order learning of technological and economic issues. The fact that the plant was upgraded despite many people and organisations emphasising large technical and economic problems is illustrative for the poor learning process in this case. The Deersum case is different; more attention was paid to learning about additional advantages like energy savings and agricultural advantages, which explains why plant operation could continue despite poor performance. After 1995, experiences with previous experiments were forgotten, which explains why most learning...
focussed again on basic techno-economic parameters in the late 1990s. Successful experiments in other countries stimulated Dutch actors to construct new biogas plants again, but there was limited verification of foreign lessons learned in Dutch plants. The most important lesson from abroad was that codigestion is a necessary condition for the improvement of economic performance – but implementing this option in the Netherlands faced major obstacles.

3.3 Interaction between internal niche processes

In the following table I have combined the previous analyses. I conclude that the quality of niche processes in the Netherlands was limited. In the first period, niche actors were able to learn a great deal from the experiments, despite a lack of experience prior to 1973. Nevertheless, the lessons could not be used for the construction of new plants, because farmers were no longer interested in participating. Most importantly, the experiences in the first period do not result in the construction of a centralised plant before 1985. In the second period, the quality of niche processes is very poor in the case of the Promest plant. The socio-technical design of the plant deviates too much from previous experiences, while the actors are not able to learn from the results. The Deersum experiment is characterised by high quality learning, but this plant has only limited support. In the third period, the quality of niche processes remains limited, because of a lack of experienced actors and limited testing of expectations in practice.
Table 3.4. Main characteristics of niche processes in the case of manure digestion in the Netherlands

<table>
<thead>
<tr>
<th>Period</th>
<th>Main characteristics of niche processes</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973-1985</td>
<td>Researchers, farmers and technology suppliers have high expectations about biogas plants in agriculture. The network is small, but there is high alignment due to several social groups’ active participation. These actors design experiments to learn about basic process parameters, biogas yields and economic performance. The main lesson is that the plants are economically unfeasible and technological performance is low (first-order learning). Particularly farmers and technology suppliers leave the network. Researchers still have high expectations about the future market and they continue research at existing plants, resulting in abundant knowledge about biogas plants. Technical and economic performance remains low. The idea emerges that energy saving alone is not a sufficient condition for feasible biogas plants and that more attention should be paid to agricultural advantages.</td>
<td>Construction of large number of farm-scale plants for energy generation, followed by a period of optimising existing plants.</td>
</tr>
<tr>
<td>1986-1995</td>
<td>Part of the network involved in farm-scale plants continues with a small centralised plant in Deersum. The plant is part of a project that emerges from a vision of self-sufficiency and decentralised energy generation. The learning process is of high quality: farmers cooperate and learn about additional agricultural advantages; the Deersum community learns about energy savings. Another plant with large-scale manure processing is constructed, supported by large agricultural organisations and technology suppliers. They have high expectations about large-scale technological solutions for the manure surplus. The learning process is poor; there is very limited time, while there is no strong linkage with previous experiments. Expectations about technical and economic feasibility decrease, but the plant is still upgraded. Lack of support from farmers frustrates a continuous manure supply.</td>
<td>Construction of a small centralised plant, continuous operation of that plant despite poor performance. Many technical, economic and supply problems in the Promest plant, with no successful solutions.</td>
</tr>
<tr>
<td>1996-2003</td>
<td>Expectations about improved technological performance in foreign countries create a new market in the Netherlands in the late 1990s. There is a lack of experienced actors (small network) and alignment is limited due to limited exchange of experiences. Despite broad learning processes in foreign countries about agricultural and environmental advantages, the Dutch learning process remains limited to techno-economic optimisation of biogas plants. The main lesson is that the regulatory framework prevents codigestion. Niche actors try (without success) to change the regulations.</td>
<td>Construction of limited number of farm-scale and centralised plants.</td>
</tr>
</tbody>
</table>

The dynamics in expectations, network formation and learning can explain some of the puzzles I addressed in section 3.1.3, but not all. The first question was why niche actors had continued to work on farm-scale plants despite limited results. The niche analysis shows that
high expectations about biogas yields created a large (potential) market for biogas plants and, despite poor operation, researchers continued to improve existing biogas plants. Expectations thus legitimised continuing the optimisation of existing biogas plants. The second question was why Promest had been such a radically different experiment compared to previous biogas plants. Although experiments with farm-scale plants suggested that a centralised plant would be more economically feasible and relieve individual farmers of a heavy workload, it is still unclear why the Promest plant was so radically different from the previous plants. I will investigate this topic further in the regime analysis. The third question was why Promest had upgraded the plant despite poor performance. The answer is that learning was very poor at this plant, mainly due time pressures. However, this leaves out an important part of the answer, which I will come back to in section 3.5. The fourth question asked why the plant had eventually been shut down in 1995. The main reason is that the plant was never supported by farmers and depended on levies, which were no longer allowed after 1995. The fifth question was why operation of the Deersum plant had continued, despite the low performance. Niche analysis showed that this was due to high quality learning about agricultural advantages and a strong vision on self-sufficiency. However, the sixth question was why the Deersum plant had eventually been shut down in 1995, and the niche analysis did not provide an answer to this question – I will come back to this topic in section 3.5. The seventh question was what the reasons had been for the renewed attention for biogas plants in the late 1990s. Niche analysis has shown that learning in foreign countries created new expectations in the Netherlands. However, dynamics at the regime level were important too, as I will show in the next sections. Finally, the question was why the number of plants did not increase rapidly, despite improved performance. The niche analysis already revealed that this was due to regulations. In the following section, I will investigate why niche actors were not able to lobby for new regulations.

3.4 Dutch regime dynamics

3.4.1 Natural gas, energy crises and nuclear power (1973-1985)

Electricity and heating regimes

In the early 1970s, natural gas had become the dominant fuel in Dutch power generation. Between 1965 and 1973, the share of natural gas increased from 10% to 83%.\(^42\) This was enabled by the discovery of large amounts of natural gas in 1959. The majority of Dutch electricity (over 98%) was produced in large centralised units; almost no electricity was imported (Arnhemse Instellingen van de Electriciteitsbedrijven, 1970-1998). Natural gas was also the dominant source for heating purposes. After the natural gas discovery in Groningen in 1959, a national infrastructure was quickly constructed. By 1968, the majority of the Dutch population had access to natural gas for heating. Construction of the infrastructure was

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\(^{42}\) The rest was produced from oil (13%) and coal (2%). One nuclear power plant (Dodewaard) used uranium and produced 2% of the electricity.
accompanied by a transition from coal and oil heating to heating with natural gas, in particular in central-heating boilers. In 1970, natural gas surpassed oil as the dominant fuel for heating purposes (Overbeeke, 2001).

The electricity sector was dominated by a strong social network, in particular a group of institutions located in Arnhem. These institutions included the Cooperation of Electricity Producers (SEP), the Association for Electricity Company Owners (VEEN), the Association for Electricity Company Managers (VDEN) and the KEMA research institute. These institutions were strongly linked with production companies through ownership. Production companies produced and transported electricity to city or region borders. Regional and municipal companies (owned by provinces or municipalities) distributed the power to end-consumers. These companies owned most of the production companies, which participated in the Arnhem institutions. This network was characterised by a shared vision on the electricity regime: it advocated the development of large-scale production units for reasons of economies of scale. For a long time, these companies and institutions had been able to control technological development and energy supply.

A public-private company called the Gasunie dominated the heating sector. Esso, Shell and the state-owned company DSM established the Gasunie company in 1963. The government provided the company with a monopolistic concession for the transport of natural gas in the Netherlands (production remained a task of the Dutch Oil Company). After completion of the infrastructure in 1968, the Gasunie started selling gas to regional gas distribution companies (who sold the gas to households for heating purposes) and directly to industrial users, including power production companies (Overbeeke, 2001:226).

The electricity regime began to change in the early 1970s. The publication of the report ‘Limits to Growth’ (1972) and the 1973 oil crisis changed the general perception that fossil fuels were limitless available; it was predicted that fossil energy sources would become scarce and that irresponsible use of sources or interruption in supply could have large (environmental and social) consequences. Security of supply became an important political issue, as did energy savings and emission reduction. The Ministry of Economic Affairs published the first Dutch White Paper on Energy in 1974 (Ministry of Economic Affairs, 1974). The Ministry pleaded for diversification of fuels, energy saving and concentration in the electricity sector. It was a radical break with the past. The government had previously stimulated the growth of energy use to stimulate economic growth, but now tried to stimulate savings. It illustrated a changed vision of the electricity sector, in which the sector was no longer seen as a normal industrial sector, but as a sector with possibly far-reaching social,

43 In Dutch: Samenwerkende Elektriciteitsproducentie bedrijven (SEP), Vereniging van Exploitanten van Elektriciteitsbedrijven in Nederland (VEEN), Vereniging van Directeuren van Elektriciteitsbedrijven in Nederland (VDEN), NV tot Keuring van Elektrische Materialen (KEMA).

44 The Dutch Oil Company (NAM), a cooperation between Shell and Esso, had discovered the natural gas resources in Groningen. They were obliged to sell all the gas to the Gasunie.

45 The introduction of natural gas for domestic heating was accompanied by the introduction of central heating systems in houses to ensure that the market for natural gas would be large enough to legitimate the construction of the natural gas infrastructure (Overbeeke, 20001).
economic and environmental implications. Second, the government increasingly gained a
decisive voice in the electricity sector, in particular regarding choice of fuels (nuclear
power). In 1979, a second oil crisis occurred and global oil prices increased again. The
Ministry of Economic Affairs published a second White Paper on Energy (Ministry of
Economic Affairs, 1979). This White Paper was similar to the first, but intensified the
execution of policies. Diversification, energy saving and reorganisation of the energy sector
were the most important topics.

The oil crises, environmental problems and the Dutch government’s increasing
interference decreased stability in the electricity regime. Although regime actors like the SEP
protested against interference, they were forced to deal with new problems like oil
dependency and environmental impact, to which they responded mainly by optimising the
existing regime. Oil was replaced by natural gas and coal (Figure 3.4). In the long term,
nuclear power was expected to replace natural gas and coal-fired capacity. Energy demand
was lowered through extensive energy savings programmes (Figure 3.5), resulting in a 13% reduction of electricity usage in an average household between 1980 and 1988. Emissions from power plants were decreased by installing gas cleaning systems. In 1985, the electricity sector had reduced sulphur dioxide emissions ($SO_2$) by 35%. Nitrogen oxide emissions ($NO_x$) were reduced by 4%. Heating demand was also affected by the new policies; demand for natural gas decreased by 28% per household, on average.

46 The direct cause of this intervention was the construction of a second nuclear power plant in Borssele by a small energy company (Verborg, 2001; Raven, 2004). The introduction of nuclear power was not only discussed between the national government and the electricity sector. A lively social discussion, embedded in environmental organisations and protests from social movements, resulted in a changed perception of nuclear power into a symbol of large-scale technological development, environmental threats and a threat to global peace. In the following years, nuclear power was heavily debated in Dutch society, but the government and the energy sector continued their efforts in the field of nuclear power. Expectations about future electricity demand and low prices for nuclear power supported their vision. Even the outcome of a long public debate between 1981 and 1984, which showed that the majority opposed the implementation of nuclear power, did not change the ideas: in 1985 the government decided that three nuclear power plants had to be established in order to secure future energy supplies. Nevertheless, the accident with the Tsjernobyl power plant in 1986 stopped all further development (Verborg, 2001:108).
47 Source: http://www.energie.nl
48 Source: http://www.energie.nl
49 Source: http://www.energie.nl
In the 1970s and 1980s the focus was on regime optimisation, but opponents also proposed and lobbied for the development of alternative energy sources. Although this did not result in any major technological changes in the energy sector, several small and medium-sized national research programmes for alternative sources were established, in particular in the field of wind power and solar energy. Intermediary actors were also established in the 1980s,
including institutions like PBE and NEOM. The aim of these organisations was to carry out energy policies, to distribute grants and to manage national research programmes (Verbong, 2001). Only limited attention was paid to energy from biogas in these programmes. Within public policies, biogas was not expected to make a large contribution to national energy generation in the short term: this was the general perception of alternative energy sources, and thus resources invested in alternative technologies remained limited. Regime actors were not interested in biogas production; their perception was that regime optimisation and the introduction of nuclear power offered enough possibilities to deal with the new problems. Biogas was seen as an energy-saving option for agriculture.

Conclusion
In the 1973-1985 period, increasing oil prices and emerging notions on nature and environment resulted in the Dutch government’s increasing interference in the electricity regime. This regime remained quite stable, however, and regime actors could deal with the problems by developing options within the established regime. Niche technologies (including manure digestion) were not considered.

3.4.2 Energy prices, competition and environmental considerations (1986-1995)

Electricity regime
In 1986, global oil prices decreased, and in the Netherlands this resulted in a 34% average decrease in electricity price for end-consumers between 1985 and 1987 (Arnhemse Instellingen van de Electriciteitsbedrijven, 1970-1998). The price of natural gas also decreased, because it was linked to the price of oil, complicating the further development of alternative energy sources; competition with fossil fuels was now more difficult. Moreover, the replacement of oil with natural gas, energy savings and reduced emissions had been a successful strategy for dealing with problems in the previous period.

In the following years, the notion of sustainable development emerged in several reports on the environment, such as “Our Common Future” put out by the Brundtland Commission (1987) and the first Dutch policy plan for the environment (NMP, 1989). These documents emphasised the need for sustainable development and emphasised the possible effects of greenhouse gas emissions, in particular carbon dioxide (CO₂). Unlike SO₂ and NOₓ, emissions of CO₂ are inevitably linked with generating energy with fossil fuels. New technologies and renewable energy sources became necessary, as well as continuous efforts in energy conservation. The Minister of Economic Affairs implemented these notions in a 1990 policy document (Ministry of Economic Affairs, 1990). To finance the desired change in the energy sector, the government implemented subsidy schemes and increased the amount of available money: in 1988, it projected 183 million Dutch guilders (about 83 million euros) for

50 Projectbeheerbureau Energieonderzoek (PBE) and Nederlandse Energie Ontwikkelings Maatschappij (NEOM) later merged into the Nederlandse Organisatie voor Energie en Milieu (Novem). Another organisation was the Organisatie voor Duurzame Energie (ODE), established in 1979. This organisation continued to be an advocate of renewable energy in the 1990s.
energy savings (of which 17% was for renewable energy). This amount increased in 1989 to 220 million Dutch guilders (about 100 million euros), of which about half was for renewable energy (Verbong, 2001:125). The available money was divided among several (research) projects, including a new research programme on energy generation from waste and biomass (EWAB, 1989). These incentives particularly stimulated the investigation of energy from waste (see next chapter).

The construction of decentralised CHP units that were run on natural gas increased in the late 1980s. In 1989, the Dutch government enacted a new electricity law, the result of a long negotiation process between the government and the Dutch electricity sector. The law introduced limited competition in the electricity sector, aimed at increasing the efficiency of energy generation. Energy companies were forced to separate production and distribution activities, creating a new actor in the electricity regime, the distribution company. These companies, as well as industrial actors, were allowed to establish decentralised production units (not larger than 25 MWe) and to import electricity. Profitable investment grants stimulated the construction of decentralised production units. Distribution companies became responsible for making environmental action plans, in which they formulated their environmental aims and achievements on an annual basis. These developments resulted in the rapid growth of decentralised generation capacity (combined heat and power units in industry) and imported electricity. Combined heat and power fuelled by natural gas was economically very attractive for distribution companies, and enabled them to gain market share in an electricity market dominated by production companies. Distribution companies could also claim CHP as environmental achievement in the environmental action plans. Decentralised renewable energy options were not considered an important part of distribution companies’ strategies around 1990. The growth in decentralised CHP was so large that it soon resulted in the overcapacity of energy production. Power production companies tried to regain control of energy production by trying to realise a temporary stop on new CHP. These steps towards competition were the beginning of further change in the electricity regime in the late 1990s.

**Agricultural regime**

Manure digestion developed primarily against the backdrop of the agricultural regime. After the 1890s, a process of modernisation had characterised Dutch agriculture, both in crop and meat production. Farmers had organised their activities in cooperatives to benefit from economics of scale. The government had stimulated such orientation by organising scientific research and technological development, agricultural schooling, information services and financial policies. The main heuristic in the agricultural regime had been to increase the production per acre or per animal as much as possible. This was not a typically Dutch development; production per acre and animal increased worldwide after WWII, in particular through the development of artificial fertilizers and artificial insemination techniques (Bieleman, 2000; McNeill, 2000; Gourlay, 1992). In the 1950s and 1960s, increasing labour

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51 In Dutch: Milieu Actie Plan.
costs had resulted in the emergence of a new guiding principle, i.e. to increase labour productivity. Between 1950 and 1980, specialisation, increased farm size, and increased efficiency characterised Dutch agriculture (Bieleman, 2000:227). The number of animals increased rapidly (Figures 3.6, 3.7, 3.8). These animals were held in limited space, especially in south-eastern and north-eastern Netherlands. The rapid growth of artificial fertilizer use, the application of feeding concentrates with high mineral content and the production of meat for foreign markets eventually resulted in a huge mineral surplus in Dutch agriculture (Table 3.5) (Raven and Verbong, 2004).

Table 3.5. Cattle density and nitrate surplus in selected countries and regions in Europe in 1995. Cattle density is measured in Large-Cattle-Unit (GVE), which is the equivalent of the phosphate production of one milk cow (Anonymous, 1999a).

<table>
<thead>
<tr>
<th></th>
<th>Cattle Density (GVE/ha)</th>
<th>Nitrogen Surplus (kg N/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Netherlands</td>
<td>3.7</td>
<td>320</td>
</tr>
<tr>
<td>Belgium</td>
<td>2.6</td>
<td>170</td>
</tr>
<tr>
<td>Nordrhein Westfalen (Germany)</td>
<td>2.0</td>
<td>140</td>
</tr>
<tr>
<td>Brittany (France)</td>
<td>2.4</td>
<td>135</td>
</tr>
<tr>
<td>Denmark</td>
<td>1.5</td>
<td>115</td>
</tr>
<tr>
<td>Lombardy (Italy)</td>
<td>2.3</td>
<td>90</td>
</tr>
<tr>
<td>European Union</td>
<td>0.9</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 3.6. Number of cows in the Netherlands between 1900-1999 (source: www.cbs.nl)
In the late 1960s, environmental organisations began questioning the consequences of uncontrolled manure spreading. However, a lobby network supported by farmers and farming organisations, agricultural industries and farmers’ representatives in the government could keep the problem off the political agenda. Moreover, ongoing public discussions on nuclear power weakened the attention for environmental problems in agriculture in the 1970s (Bloemendaal, 1995:16). In 1984, a new Minister of Agriculture finally took action and enacted a temporary law that prohibited the establishment of new farms, followed by two permanent laws in 1987. The first law aimed to protect the soil under supervision of the Ministry of the Environment. This law limited the time a farmer was allowed to spread manure, as well as the total amounts of manure spread per acre. The limits became stricter in subsequent years. The second law was under supervision of the Ministry of Agriculture and regulated all other issues regarding manure, including complicated systems for manure bookkeeping, a system for manure distribution (including the establishment of distribution
centres) and a permanent ban on either new farms or the expansion of existing farms (Bloemendaal, 1995:24).

The laws were enacted during a period of intensive debates and power struggles between the agricultural community and the national government, and between farmers and their organisations. Farmers protested against complicated manure bookkeeping and against levies; agricultural organisations lobbied against public interference. Uncertainty about regulations, standards and future developments was high, because of regular changes in policies and regulatory frameworks, and resistance from the farming community. Dutch farmers, for example, were not obliged to have storage capacity, but the ban on manure spreading in fall and winter periods required a certain amount of capacity. The exact period and amount of capacity, however, was uncertain; the law did not specify how much. In the late 1980s, public authorities argued that storage capacity should cover at least for six months. In 1991, the amount of space required turned out to depend on the soil (Bloemendaal, 1995:44; Boo, Schomaker and Moen, 1993:23). In addition, the choice of measuring emissions on the basis of phosphate caused trouble. Nitrate turned out to be a much larger source of pollution (in particular for drinking water), and thus nitrate became the standard measure in an international context (in particular in the EU).

The government was forced to change the Dutch system for controlling pollution, causing further uncertainty in the agricultural regime. Public agricultural policies continued to change dramatically during this period.

The formidable environmental problems resulted in strict regulations for using manure and organic waste in agriculture. Codigesting manure with organic waste was no longer feasible, unless it complied with very strict standards, in particular for heavy metals, or when the farmer received an exemption from the Ministry of Agriculture. In practice, it was no longer possible to add organic waste streams to the manure to increase biogas yields (Caddet, 1994).

Three solutions emerged for the environmental problems in agriculture, all based on one general strategy, i.e. to remove and keep minerals out of Dutch agriculture. The first solution was to decrease minerals imported in the form of feed concentrates for animals. The second solution was to distribute manure from problem areas to areas that were lacking minerals, resulting in the transportation of large amounts of manure from south-eastern and north-eastern Netherlands to western and northern Netherlands. The third solution was to process manure into products that could be sold on foreign markets. A solution that was not discussed was a reduction in the number of animals, which was only mentioned as a final solution if other strategies failed (Bloemendaal, 1995:32; Ministry of Spatial Planning, Housing and Environment, 1988:5). Agricultural organisations and technology consortia investigated the third strategy, i.e. manure processing. Manure digestion was only part of that solution. The digestion process does not reduce the amounts of minerals in the manure. Nevertheless, digestion was investigated because it could stabilise the manure for further processing and reduce energy demands for the factory.

52 In Dutch: Wet Bodembescherming en Meststoffenwet.
Conclusion
After 1986, emerging notions on climate change and the introduction of limited competition in electricity generation targeted the stability in the electricity regime, eventually increasing attention for alternative energy sources in public policies; but distribution companies (a new regime actor) mainly focused on another technology, decentralised CHP, in cooperation with industry. CHP was inexpensive and enabled the companies to quickly gain a market share and to meet aims identified in environmental policy plans. The share of decentralised CHP generation fuelled by natural gas grew rapidly, resulting in overcapacity and decreased stability. Electricity regime actors paid limited attention to renewable energy, and manure digestion remained invisible to these actors. Digestion mainly developed against the backdrop of the agricultural regime. The stability in this regime was challenged by large environmental problems, the introduction of new laws and continuous changes in policies. Agricultural regime actors accepted manure processing as the dominant solution to deal with environmental problems as well as political and social pressure. Codigestion of manure with organic waste was no longer possible.

3.4.3 Competition and sustainability (1996-2003)

Electricity regime
In the early 1990s, the discussions within the European Commission on liberalising the European energy market intensified. The number of Dutch energy companies continued to decrease in the 1990s, and the companies developed competitive strategies (Anderson Consulting, 1993).\textsuperscript{54} Sustainable development (and the reduction of CO\textsubscript{2} emissions) became another driver for change in the electricity regime after 1995. Both issues – sustainable development and liberalisation – were the basis for the third policy plan on energy, published in 1995 by the Dutch Ministry of Economic Affairs (Ministry of Economic Affairs, 1995).

The policy plan emphasised the importance of renewable energy sources for sustainable development, and defined specific goals: in 2020, 10\% of all energy produced was to come from renewable energy sources including wind, sun, heat pumps and, in particular, waste and biomass. The interim goal for 2000 was to save 83 PJ on fossil fuels by using renewable sources, a fourfold increase compared to the 1995 level (21 PJ) (Joosen, Jager and Ruijgrok, 2002). About 65\% of the renewable energy was expected to come from waste and biomass, in particular from waste incineration. In 1997, the Ministry published an action plan to reach the goals, which included the necessary financial means (Figure 3.9). The basic elements were a combination of technology push instruments through the stimulation of research and development, and fiscal instruments through market stimulation.

\textsuperscript{54} The number of distribution companies decreased from seventy in 1988 to twenty-one in 1998. The number of production companies decreased from sixteen in 1984 to four in 1990.
Figure 3.9. Budgets from the Ministry for Economic Affairs for renewable energy 1996-2000 (Ministry of Economic Affairs, 1997)

One of the fiscal instruments was an energy tax exemption for renewable energy. This tax (REB) was established in 1995, after long but unsuccessful discussions about a European energy tax. The main argument in favour of the tax had been energy conservation: all energy carriers – including electricity from renewable sources – were taxed increasingly in the following years. From 1998 on, the government exempted the tax on electricity from renewable sources in several phases. This resulted in an equal price for green electricity and electricity from fossil fuels in 2001.\(^{55}\) Moreover, a new electricity law was enacted in 1998, regulating the introduction of full competition in the electricity sector.\(^{56}\) Subsequently, established networks disintegrated, and there were changes in the roles and relations in the electricity sector (see also next chapter). The law also enabled all electricity consumers to choose an electricity supplier by the year 2007 (later changed to 2004). A ‘green market’ for electricity from renewable sources was liberalised earlier, in 2001. End-consumers could now switch between suppliers of green electricity (Raven, 2004).

Distribution companies (in particular the PNEM company) anticipated the ongoing development towards liberalisation and sustainability.\(^{57}\) In 1993, the idea emerged of having customers pay a premium price for so-called ‘green electricity’, and for various reasons, the company board accepted this idea.\(^{58}\) After a pilot project in one municipality, PNEM made green electricity available to all its customers. Other distribution companies followed with similar marketing concepts. The introduction of these concepts, the REB exemption and the

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\(^{55}\) This is only true on average, because energy prices could differ slightly between energy companies and between different regions.

\(^{56}\) Two years later, in 2000, a new gas law was enacted, which aimed at liberalising the gas market.

\(^{57}\) In Dutch: Provinciale Noord-Brabante Electriciteitsmaatschappij (PNEM).

\(^{58}\) PNEM tried to become less dependent on (uncertain) subsidy flows from the government, and expected more independence through market funding. Furthermore, the company and its top management were committed to the further development of renewable energy, because they wanted to develop a green profile for the company. A change of dominance in the top management team from people with backgrounds in engineering towards people with business management backgrounds contributed to this process (Hofman, P.S., 2002:101).
The liberalisation of green market resulted in a rapid increase of green electricity consumers. In 1997, the total number of customers was 25,000; in 1998 the number increased to 225,000; in 2000 it was 700,000; and in 2002 the number surpassed one million (ECN, 2002; Ministry of Economic Affairs, 2002). The growing market for renewable energy stimulated energy companies to investigate the construction of all kinds of renewable energy plants (including manure digestion) in the late 1990s.

Nevertheless, the number of new renewable energy projects remained limited in the Netherlands for three reasons. First, the tax exemption was decided on an annual basis. This created uncertainty for investors (e.g. energy companies), because annual cash flows depended on annual governmental decisions. Second, experiences at the niche level showed that the construction of renewable energy plants often did not fit in existing regulatory frameworks (which was also the case for codigestion in the Netherlands), causing delays and increased investment costs. Third, the demand for renewable energy grew so quickly that energy companies could not keep up with its production. These three factors resulted in a large increase of electricity imports (the favourable tax tariffs also applied to imported electricity), while Dutch production remained limited. In 2003, the government wanted to discourage import and replaced the tax exemption with a new instrument (MEP), which guaranteed a feed-in tariff for domestic production for three to ten years, depending on the type of renewable energy technology. This reduced the uncertainty for investors in the projects, including manure digestion plants, and limited the profitability of importing green electricity.

**Agricultural regime**

The Dutch agricultural regime continued to change after 1995. In the late 1980s, the government had implemented a long term strategy for reducing the manure surplus; three periods had been identified in the policy plans. In the first period (1987-1990), the focus was on stabilising the production rate of manure by prohibiting the establishment of new farms. In the second period (1990-1997), the focus was on reducing environmental effects by minimising the import of minerals, stimulating the national distribution of manure and manure processing for foreign countries. In the third period (1998 and later), the aim was to realise balanced fertilizing through optimising the previous paths. The applied strategies brought some success in the agricultural sector. In the late 1990s, the number of animals began to drop (Figures 3.6, 3.7). Manure was now distributed on a large scale (fifteen million tons annually) and millions of tons of chicken manure were exported. Furthermore, the use of artificial fertilizer had decreased by 30% in 2000 as compared to the 1986 level (Anonymous, 2001d).

Nevertheless, there were still substantial problems. A European Directive on Nitrate Pollution came into force in 2003, imposing severe limitations to nitrate leaching from

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59 Import of renewable electricity increased from 1,500 GWh in 2000 to 7,600 GWh in 2001 (35% of total import of electricity). Total Dutch production of renewable energy was 2,963 GWh in 2001, an increase of 15% as compared to 2000 (source: http://www.cbs.nl).

60 In Dutch: Milieukwaliteit Electriciteitsproductie (MEP).
farmland. One of the solutions to the manure surplus (large scale manure processing) had failed in the previous years; further reductions had to be reached by other means. One solution was the introduction of a new system for manure bookkeeping, the MINAS-system. This system obliged farmers to keep track of the total amount of minerals present in cattle feed, artificial fertilizer, manure, animals, animal products and crops. If the net supply was larger than zero, the farmer was obliged to enter into a contract with another farmer who could use the manure. It was different from previous bookkeeping systems, because it counted the flow of minerals rather than the flow of manure. The new system produced a much more detailed account of mineral flows in the Netherlands and improved the distribution and usage of minerals. The number of pigs also decreased because of increasing standards for animal welfare, a buying-up arrangement for pig farmers who decided to quit their business, and a large outbreak of swine fever in 1997. The number of pig farms decreased by almost 40% between 1998 and 2001 (source: CBS). These developments contributed to the reduction of the mineral surplus in the Netherlands, in particular the surplus of nitrate (Figure 3.10).

The combination of several successful options to reduce the mineral surplus, and the failure of large-scale manure processing in the past, limited the possibilities for manure processing and digestion in the late 1990s. Although some manure distribution companies and farmers participated in manure digestion plants, the general perception among agricultural actors was that manure digestion was no longer a necessary trajectory for dealing with the manure surplus (Boo, 1997). This affected the implementation of biogas plants. Regulations established in the early 1990s made codigestion practically unfeasible. Niche actors were not able to lobby successfully for changing the regulations, because digestion was no longer a desirable solution within the agriculture regime.

![Figure 3.10. Surplus of minerals on Dutch farming land in 1990-2002. The numbers are a net surplus, which is the total of minerals not used by crops, and is equivalent to the emissions in water, soil and air. The numbers for 2002 are temporary (source: CBS).](image)

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In this system, cattle farmers had to count the supply of minerals to farms (in cattle feed and artificial fertilizer) and the removal of minerals from farms (in animals, animal products and crops). A portion of the difference was free of charge (called ‘verliesnormen’), but farmers had to pay a levy on the other portion. If they distributed the manure through contracts with crop farmer, they did not have to pay the levies.
The emergence of climate change as the dominant environmental problem in the late 1990s created new opportunities for biogas plants, however. In the early 1990s the main environmental problem had been over-fertilisation of farmland, the main strategy being to remove minerals from use in Dutch agriculture. Manure processing in factories was part of the strategy to remove minerals; these plants could produce products for foreign markets. Manure digestion was only an indirect part of the solution; it made the manure better suitable for further processing and could reduce a factory’s energy demand. In the late 1990s, climate change put more emphasis on methane emissions in agriculture – methane is much stronger greenhouse gas than carbon dioxide. Agriculture was one of the dominant sources of methane emissions. The reduction of these greenhouse gasses was the topic in a policy plan published by the Ministry of the Environment in 1999 (Ministry of Spatial Planning, Housing and Environment, 1999). Following the Kyoto protocol of 1997, this plan not only focused on CO$_2$ emissions, but also on other greenhouse gasses. Part of that plan was the establishment of a research programme for reducing emissions of greenhouse gasses other than carbon dioxide (ROB). The Ministry, together with the Ministry of Agriculture and the Ministry of Economic Affairs, made resources available for the emission reduction in several sectors, including agriculture (a total of 200 million euros). Biogas plants became a more direct solution to an important environmental problem in the agricultural sector than they had been in the early 1990s. A biogas plant prevents the emission of methane into the atmosphere and converts it into an energy source. The desire to reduce methane emissions stimulated new research on biogas plants within the agriculture regime.

**Waste regime**

Also developments in the waste regime interacted with the biogas niche. In 1995, after a long period of political debate, the Dutch government decided to implement a new system for waste collection based on household separation. Most Dutch households received two containers, one for organic waste (GFT) and one for all other waste. This fitted a general guiding principle in the waste regime, i.e. that it was better to recycle waste than to use the waste as landfill. By collecting the GFT separately from other waste types, it could be used in special factories to produce new products. Although some of the plants used anaerobic digestion, most of the GFT was processed in a newly constructed infrastructure of composting factories. Composting (or aerobic digestion) degrades organic matter by adding air. Instead of producing energy (as is the case with anaerobic digestion), these plants use energy (to pump air). Most provinces – responsible for waste collection – and waste companies chose composting as the dominant processing route. By 2000, already 25 factories were processing GFT with a total capacity of 1,526 kton GFT annually, with most of them using composting technology. The separate collection of household waste and a waste processing infrastructure interacted with development of the biogas plant in Deersum. Despite attempts to rebuild the plant for codigestion with organic household waste, the foundation

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62 In Dutch: Reductie Overige Broeikasgassen (ROB).
failed to contract the waste, due to the development of an infrastructure for composting in the region (Werkgroep afvalregistratie, 2001:31; Joustra, 1996).

Conclusions
After 1995, stability in the electricity regime further decreased, because of the introduction of full competition. New regulations, changing roles and strategies of energy companies, and favourable tax exemptions created a new market for green energy. Although energy companies were thus stimulated to investigate renewable energy projects as promising technology, the limited success of these projects, uncertainty about the duration of tax exemptions, and the rapid rise in demand resulted in increasing electricity import and stalled development of Dutch renewable energy projects, limiting the construction of manure digestion plants.

In the agricultural regime, manure processing and digestion was no longer seen as a desirable trajectory due to previous failures with manure processing and the successful development of other options. Another environmental problem (methane emissions) was increasingly acknowledged by policy makers, and created new opportunities for manure digestion. The establishment of an infrastructure for composting prevented the codigestion of manure with household waste.

3.5 Conclusions
In this section I first discuss how the regime analysis helps analyse the remaining puzzles I addressed in section 3.3. Then I reconstruct the pattern that has emerged from biogas experiments in the Netherlands in terms of protection and stabilisation. Finally, I discuss how niche-regime interaction occurred.

Regime dynamics
The regime analysis enables me to answer the remaining questions posed in section 3.3. The first question was why Dutch actors chose such a radical disruption of biogas plant development after 1985. From the regime analyses we learn that this was due to the then recognized, enormous environmental problems and increasing pressure on the agricultural regime. In the Netherlands, such problems were much larger than in any other European country, leading to a sense of urgency among policy makers, who forced agricultural regime actors to deal with the problems. There was high instability and uncertainty in the agricultural regime. Large-scale technological solutions enabled regime actors to continue controlling the agricultural sector and prevent reducing the number of animals. The second question was why the Deersum plant was shut down, despite support from the local community. The main reason was the development of a new infrastructure for composting in the waste sector. The province (which collected the organic waste) decided not to supply organic waste to Deersum, because a composting infrastructure was under construction. Deersum had to discontinue plant operations. Finally, the third puzzle was why niche actors had such difficulties in lobbying for changed regulations in the early 2000s. The regime analyses explain that policy
makers and agricultural regime actors were no longer interested in manure digestion, because of the negative experiences with large-scale manure processing in the past, and the decrease of mineral surplus through other means.

Construction of niche patterns
In this section, I reinterpret the development of manure digestion in the Netherlands in terms of stabilisation and protection, in order to construct a niche development pattern (see section 2.4.1). I will compare this pattern with the other cases in Chapter 7 to understand which factors are important for the emergence of market niches.

In the early 1980s, a technological niche emerged for farm-scale biogas plants, because of high energy prices and optimistic expectations about future markets and biogas yields. Many experiments with manure digestion took place in different locations, but stability was minimal: there was very limited knowledge on how to design a manure digestion plant or how to use the biogas. Protection was provided by governmental research programmes and subsidies, and by the high expectations on the parts of technology suppliers and farmers. By 1987, this technological niche evolved into a dedicated market niche. Expectations had decreased and subsidies were withdrawn, leaving little protection for farm-scale biogas plants in the Netherlands. Nevertheless, knowledge and experiences were codified in reports and there was now more (but still limited) stabilisation. This trajectory continued with a limited number of farm-scale plants and with a small centralised plant; protection in the form of subsidies was minimal. Then these trajectories became extinct. The major trajectory after 1985 was a process of niche branching, towards large-scale manure digestion and processing. Some of the knowledge and experiences from the previous farm-scale niche was used, but the size and complexity of the Promest plant created uncertainty in technological design and markets; no structuration could be gleansed from similar experiences nor did the actors have experience with exporting the fertilizer products. The national government provided huge amounts of subsidies for experimentation; agricultural organisations and technology consortia promoted large scale processing as the solution to environmental problems. In 1995, supply subsidies were stopped though plant operation was still not stable, and inadequate farmer participation prevented effective societal embedding. The plant was closed. Around 2000, two new technological niches emerged, one for farm-scale plants (in particular for energy generation) and one for centralised processing and digestion (energy generation and manure processing). These niches were protected by renewable energy and climate change funds, and by expectations of energy companies about green markets. However, useful linkages with previous experiments no longer existed, nor was there sufficient interaction and exchange of information between experiments. Moreover, much uncertainty was caused by the legal framework for codigestion. Nevertheless, at this time there was more stability in biogas plant design, in particular coming from Germany and Denmark. Centralised processing plants still lacked an adequate working design, because of problems with separation technology. Both niches remained technological niches. Table 3.6 gives an indication of the development and size of the niches.
Figure 3.11. Niche development pattern for manure digestion in the Netherlands

Table 3.6. Indication of size of niches for manure digestion in the Netherlands and total annual manure production

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm-scale plants</td>
<td>65</td>
<td>56</td>
<td>14</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Centralised plants</td>
<td>0</td>
<td>100</td>
<td>600</td>
<td>0</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total manure production (kton/yr)</td>
<td>85700</td>
<td>84900</td>
<td>81800</td>
<td>74200</td>
</tr>
</tbody>
</table>

*Niche-regime interaction*

In Section 2.4 I argued that regimes changes can affect the development of niches. I have summarised the main developments at the regime level, the effects of regime dynamics on niche development and the effects of niche development on regime level in Table 3.7.

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63 Numbers for this table and the following tables are only an indication and are based on different literature sources. Total digester capacity (m³) has been recalculated to annual processing capacity (kton/yr) by using an average residence time of 30 days and an average density of 1.02 kg/l (Nes, Diemen and Schomaker, 1990). Total manure production is from [http://www.rivm.nl/milieuennatuurcompendium](http://www.rivm.nl/milieuennatuurcompendium).
Table 3.7. Niche-regime interaction: Dutch manure digestion case

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Stability in electricity and heat regime is high, but targeted by dependency on oil import, environmental issues (emissions, depletion of fossil fuels) and governmental interference. Actors find solutions in regime optimisation (energy savings, switch to coal and natural gas).</td>
<td>• Stability in electricity regime decreases, because of emerging notions on sustainable development, new regulations for competition, emergence of new actor (distribution company), and increased use of decentralised CHP on natural gas.</td>
<td>• Low stability in electricity regime, because of broad introduction of competition and increasing efforts for regime transformation towards sustainability. Instability in emerging green market due to changes in support mechanisms.</td>
</tr>
<tr>
<td></td>
<td>• Low stability in agricultural regime, because of broad recognition of environmental problems, governmental interference, continuous change in policies and regulations, and resistance from farmers. Regime actors try to maintain stability with large-scale manure processing.</td>
<td>• Low stability in agricultural regime, because of broad introduction of competition and increasing efforts for regime transformation towards sustainability. Instability in emerging green market due to changes in support mechanisms.</td>
<td>• New solutions and developments increase stability in agriculture (new manure distribution and bookkeeping system, reduced number of animals). Emerging emphasis on climate change within policy creates new environmental problem in agriculture (methane emissions).</td>
</tr>
<tr>
<td></td>
<td>• New solutions and developments increase stability in agriculture (new manure distribution and bookkeeping system, reduced number of animals). Emerging emphasis on climate change within policy creates new environmental problem in agriculture (methane emissions).</td>
<td>• Low stability in electricity regime stimulates regime actors (in particular former distribution companies) to support and investigate new opportunities, including niche technologies. They see manure digestion as promising technology (not as problem solver).</td>
<td>• Emerging market for composting in waste regime, because of source separation of household waste and establishment of composting infrastructure.</td>
</tr>
<tr>
<td></td>
<td>• Agricultural regime actors counteract niche development, because of new solutions and failed niche development. Regulations prevent codigestion. Climate change policies in agriculture result in new financial resources.</td>
<td>• Agricultural regime actors counteract niche development, because of new solutions and failed niche development. Regulations prevent codigestion. Climate change policies in agriculture result in new financial resources.</td>
<td>• Waste regime actors counteract niche development, because of vested interest in other technology.</td>
</tr>
<tr>
<td>Effect of regime dynamics on niche development</td>
<td>• Local opportunities for experiments on the basis of energy savings; no support or participation on the part of electricity or heating regime actors. Niche remains invisible.</td>
<td>• Electricity regime actors not interested in niche development.</td>
<td>• None</td>
</tr>
<tr>
<td>Effect of niche development on regime dynamics</td>
<td>• None</td>
<td>• Unsuccessful experimentation results in rejection of niche by agricultural regime actors.</td>
<td>• None</td>
</tr>
</tbody>
</table>

I conclude that regime dynamics are important in understanding the development of the Dutch manure digestion case. In the first period, manure digestion mainly developed against the backdrop of the electricity and heating regimes. Environmental, political and economic problems resulted in the emergence of a new vision on the electricity sector, advocated by the government, with the electricity sector no longer being seen as a regular industrial sector, but as a sector with a broader social and environmental significance. This vision and increasing interference on the part of the national government (a new actor) decreased stability in the
electricity regime. However, the technical system and social network supporting the regime hardly changed; electricity regime actors solved problems through regime optimisation (energy conservation, fuel replacement). The decreasing stability did affect niche development, because niche actors (farmers, research institutes, technology suppliers) could profit from (marginal) financial resources. Changing stability at the regime level also affected niche development through changing the visions and expectations of niche actors, which were linked to the problems at the regime level. However, in general the niche remained invisible to the regime.

In the second period, the agricultural regime changed rapidly because of huge environmental problems, causing high instability in this regime. Legislation and policies, relations in social networks (e.g. between farmers, corporations and public authorities), manure application techniques (e.g. distribution, storage) all changed, mainly in response to the environmental problem caused by the manure surplus. Subsequently, agricultural regime actors adopted manure processing as one of the main routes to re-establish stability. The participation of agricultural regime actors initially resulted in a rapidly increased niche size. However, it also resulted in specific design choices (very large plant, new markets) and limited time for learning, eventually contributing to the failure of centralised manure digestion plants.

The electricity regime also became less stable in this period. New formal rules (electricity law) and informal rules (visions on sustainable energy generation), changes in the social network (distribution companies searching for market share in electricity generation), and changes in the technical system (decentralised production, increasing import) created instability. This creates some opportunities (financial resources) for experiments with manure digestion, but the manure digestion niche remained invisible to the electricity regime. Moreover, the Deersum plant did not fit the large scale solutions that agricultural regime actors were looking for.

In the third period, the electricity regime changed rapidly due to new regulations (full competition, new market rules), new perceptions and marketing concepts (green energy market) and the completely overhauled social network involved in electricity generation and distribution. Old and new electricity regime actors began investigating all kind of technologies as promising niches, not as problem solver. The interest and participation of these regime actors in biogas plants resulted in a renewed takeoff of niche development. However, now the agricultural regime prevented breakthrough of the niche. Agricultural regulations complicated embedding of the niche in the agricultural sector. Agricultural regime actors hesitated to participate (or change regulations), because of the failure of earlier niche development.
### Appendix 3.1

Table 3.8. Farm-scale plants constructed between 1978 and 1987. Most plants were taken out of operation by 1993 (Nes, Diemen and Schomaker, 1990; Boo, Schomaker and Moen, 1993)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Digester volume (m$^3$)</th>
<th>Manure type</th>
<th>Additives</th>
<th>Supplier</th>
<th>In operation during 1990</th>
<th>In operation during 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuw-Millingen</td>
<td>1978</td>
<td>350</td>
<td>pigs</td>
<td>Own+IMAG</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Klarenbeek</td>
<td>1979</td>
<td>150</td>
<td>cattle</td>
<td>Paques+Imag</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Duiven</td>
<td>1979</td>
<td>110</td>
<td>cattle</td>
<td>IMAG+Van Wanrooij</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Garderen</td>
<td>1979</td>
<td>270</td>
<td>pigs</td>
<td>Flocculation sludge</td>
<td>??</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Hemelum</td>
<td>1980</td>
<td>125</td>
<td>cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Schijndel</td>
<td>1980</td>
<td>210</td>
<td>pigs</td>
<td>JOZ+Van Wanrooij</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Jutrijp</td>
<td>1980</td>
<td>200</td>
<td>cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Barneveld</td>
<td>1980</td>
<td>125</td>
<td>pigs</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Lelystad</td>
<td>1980</td>
<td>80</td>
<td>cattle</td>
<td>De Boer</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Witharen</td>
<td>1980</td>
<td>175</td>
<td>pigs</td>
<td>Fatty waste</td>
<td>Paques</td>
<td>yes</td>
<td>No</td>
</tr>
<tr>
<td>Heerhagowaard</td>
<td>1980</td>
<td>560</td>
<td>pigs</td>
<td>Own+JOZ</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Aalten</td>
<td>1981</td>
<td>100</td>
<td>pigs</td>
<td>Own+IMAG</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Eibergen</td>
<td>1981</td>
<td>130</td>
<td>cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Milheeze</td>
<td>1981</td>
<td>300</td>
<td>pigs and cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Woedense Verlaat</td>
<td>1981</td>
<td>150</td>
<td>cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Katwoode</td>
<td>1981</td>
<td>200</td>
<td>cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Lievelde</td>
<td>1981</td>
<td>120</td>
<td>cattle</td>
<td>JOZ</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Den Ham</td>
<td>1981</td>
<td>150</td>
<td>cattle</td>
<td>Paques</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Heeswijk-Dinther</td>
<td>1981</td>
<td>250</td>
<td>cattle</td>
<td>Fatty waste, Flocculation sludge</td>
<td>Van der Meijden</td>
<td>yes</td>
<td>No</td>
</tr>
<tr>
<td>Giessenburg</td>
<td>1981</td>
<td>340</td>
<td>cattle</td>
<td>JOZ</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Slagharen</td>
<td>1981</td>
<td>320</td>
<td>pigs</td>
<td>Fatty waste</td>
<td>De Boer</td>
<td>yes</td>
<td>No</td>
</tr>
<tr>
<td>Dwingeloo</td>
<td>1981</td>
<td>275</td>
<td>cattle</td>
<td>Flocculation sludge</td>
<td>JOZ</td>
<td>yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Diessen</td>
<td>1982</td>
<td>300</td>
<td>pigs</td>
<td>Fatty waste, Flocculation sludge</td>
<td>Van Wanrooij+IMA G</td>
<td>yes</td>
<td>No</td>
</tr>
<tr>
<td>Bodegraven</td>
<td>1982</td>
<td>70</td>
<td>pigs</td>
<td>Ecotech-Ijlst</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Assendelft</td>
<td>1982</td>
<td>100</td>
<td>cattle</td>
<td>JOZ+CE</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Ureterp</td>
<td>1982</td>
<td>70</td>
<td>cattle</td>
<td>Cebeco</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Nistelrode</td>
<td>1984</td>
<td>840</td>
<td>pigs</td>
<td>Chicken manure</td>
<td>Van der Meijden</td>
<td>yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hilvarenbeek</td>
<td>1986</td>
<td>100</td>
<td>cattle</td>
<td>GTI</td>
<td>no</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Rosmalen</td>
<td>1987</td>
<td>900</td>
<td>pigs</td>
<td>IMAG</td>
<td>yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4.
Co-firing in the Netherlands

4.1 Historical overview

4.1.1 Initial explorations in co-firing (1993-1995)

Dutch energy companies began to co-fire biomass and coal in the early 1990s.\(^1\) One of the first active companies was UNA, located in north-western Netherlands, near Amsterdam.\(^2\) This company investigated the co-firing of sewage sludge produced by twenty-four sewage treatment companies in the region. The twenty-four companies used to deposit the sludge on landfill sites, but depositing the sludge became an increasing problem during the early 1990s. Production of sludge increased, while the number of landfill sites that could deposit the sludge decreased. Some companies began drying the sludge to decrease its volume. This dried sludge was made up of organic material, and UNA proposed to combust it in a coal plant near Amsterdam, at the Hemweg plant (Dijkman, Geurts and Van der Valk, 1995).

The technological feasibility of co-firing was still uncertain. UNA decided to carry out bench-scale tests at an experimental coal facility of the KEMA research institute.\(^3\) The tests were promising, and UNA continued with a full-scale experiment in the Hemweg plant. UNA aimed to get an indication of the technical and environmental feasibility of co-firing sludge and coal. The Hemweg plant had only been in operation for one year and UNA did not want to take any major technical risks. The company decided to limit the share of sludge and to make no adjustments to the plant. UNA fuelled only one coal mill (out of six) with a blend of coal and sewage sludge. The total sludge mass was only 6% of the total fuel mass supplied to the plant (equivalent to about 3% energy content).\(^4\) UNA still needed huge amounts of sludge (about 270 tons daily). The company stored the sludge in a rented storage space, because they had no existing storage for this kind of fuel. A shovel at the location of the sludge dryer loaded the sludge into a truck. After transportation to the power plant, a conveyor belt transported the sludge into a small bunker. Conventional coal carriers then transported the sludge through the coal mills, into the boiler.

The experiment was successful. The coal mill and boiler operated as usual. Sulphur dioxide (SO\(_2\)) and mercury emissions did increase, but remained within legal limits. No major

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1 KEMA research institute investigated co-firing of biomass since 1989 (Beeks, 1996).
2 In Dutch: Energieproduktiebedrijf Utrecht, Noord-Holland en Amsterdam (UNA).
3 In Dutch: NV tot Keuring van Elektrische Materialen (KEMA).
4 The energy density of the dried sludge was about 11.65 MJ/kg. The average energy density of coal is 24 MJ/kg.
changes occurred in the composition of combustion residues. This was important, because UNA sold all residues to industries: ashes caught in the combustion gasses (fly-ash) were sold to the cement and concrete industry, ashes that remained on the bottom of the boiler (bottom-ash) were sold to the road construction industry, and gypsum (produced in the removal of SO$_2$) was sold to the building industry. UNA did not want to risk changing ash composition that prevented the sale of these products. One problem occurred in the storage bunkers. At times the sludge spontaneously heated, causing self-ignition in the storage bunker. On other occasions, dust clouds formed that were difficult to suppress, and were a danger to human health. Despite these problems, UNA decided to continue, and planned a new experiment for 1996. The company intended to co-fire 15,000 tons of sewage sludge per year, to construct a permanent system for loading, unloading, storing and blending sludge with coal, and to apply for the necessary permit (Voorter, 1996:15).

Another production company, EZH, experimented with co-firing in two 518 MWe pulverised coal plants at a large industrial site in February 1996 (Jansen, 1996; Beekes et al., 1998). Novem, a Dutch agency, provided investment grants. EZH aimed to investigate the production, transportation and co-firing of biomass pellets. EZH established a company called ‘BioMass Nederland’ to make pallets from eighteen sources of organic waste including green compost, woody industrial waste and waste from the paper industry. The experiment was promising: the mills operated as usual and no damage was found in the transport lines. The co-firing process caused no changes in the composition of by-products: the products were still suitable for application in road building and cement and concrete production. Nor were adverse effects found in emissions to air and water.

The EPON production company, located in eastern Netherlands, experimented with co-firing demolition wood in the Gelderland-13 power plant near Nijmegen (Penninks, 1995:2; EPZ, 1995:8). Calculations showed that approximately 240,000 tons of waste and demolition wood were deposited on landfill sites in the Netherlands annually. This wood had a negative price, because of gate fees for depositing the wood. EPON could save on fuel expenditures by replacing coal with demolition wood and have a supplementary income from gate fees for processing the wood – at lower prices than using landfill sites would cost. The company first tested the technological feasibility of wood and coal firing at KEMA’s experimental facility. EPON also approached the Fuller company in Sweden for tests related to milling the wood (Gast and Visser, 1994:5). Finally, the company embedded the experiments in a large European research project on co-firing, the EU-APAS programme. The experiments and

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5 In Dutch: Electriciteitsbedrijf Zuid-Holland (EZH).
6 In Dutch: Nederlandse Organisatie voor Energie en Milieu (NOVEM).
7 At the beginning of the experiment, the company was located in eastern Netherlands and had to transport the pallets to western Netherlands. The company's own calculations showed that producing and transporting the pallets only used 8% of the total energy content of the pallets. When the experiments proved successful, the company decided to construct a permanent processing plant near the power station.
8 In Dutch: Elektriciteits-Productiemaatschappij Oost- en Noord-Nederland (EPON).
research proved the technical feasibility of co-firing coal and wood, and EPON applied for a permit to co-fire 60,000 tons of demolition wood per year.

The EPZ production company followed a different strategy for combusting demolition wood, deciding to gasify the wood before adding it to the main boiler of a coal plant (EPZ, 1995).\(^9\) In 1993, PNEM distribution company (a shareholder of EPZ) and NUON (another distribution company) cooperated with BFI waste company in a research project on gasifying waste wood.\(^10\) The companies concluded that the construction and integration of a gasifier in an existing coal boiler was the most promising option for processing the demolition wood. EPZ joined the network in 1994 and began to explore the construction of a wood gasifier in Geertruidenberg, site of one of the company’s power plants. The preconditions for the project were similar to the conditions in other co-firing initiatives: normal operation of the plant, the composition of by-products (fly-ash, bottom ash and gypsum) and emissions to air and water were not to be affected. EPZ approached KEMA research institute for cooperation on further fundamental research activities and laboratory tests (Duursen, 1995; KEMA, 1996). In 1996, EPZ decided to stop the project. New data showed that large amounts of demolition wood were being exported to Scandinavia, resulting in a much higher wood price than EPZ had anticipated. The high fuel price would make the gasifier economically unfeasible (Willeboer, 2000:80).

EPZ also investigated another option for combusting biomass in existing coal plants, i.e. the direct co-firing of paper sludge. The Dutch paper industry produced large amounts of paper sludge (about 250,000 tons/yr). EPZ expected that they could co-fire half that amount in two of their plants. The company performed several tests, but did not modify the plant. The results were positive, and EPZ applied for permits to continue co-firing in 1996 (ECN, 1997:63).\(^11\)

### 4.1.2 Commercial application (1996-1999)

The successful experiments with co-firing stimulated the production companies to take the necessary steps for permanent co-firing. EZH moved the Biomass Nederland company to a permanent location near the coal plant at the Maasvlakte, and applied for an environmental permit to co-fire pallets. EPZ applied for a permit to co-fire paper sludge in 1997. UNA, the third company, received a permit to co-fire sewage sludge in 1998, but eventually postponed the project (Ree et al., 2001:7). In all cases, the production companies made no changes to the power plant (direct co-firing).

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\(^9\) In Dutch: Elektriciteits-Productie.maatschappij Zuid-Nederland (EZH).

\(^10\) In Dutch: Provinciale Noord-Brabantse Electriciteitsmaatschappij (PNEM), Energie-Onderneming voor Gelderland, Friesland en Flevoland (NUON), BFI Holding B.V. (BF).

\(^11\) During the 1990s, EPZ also experimented with co-firing gas from a phosphorus oven of a nearby company at the Borssele 12 Unit in southwestern Netherlands (van Ree et al., 2000a:33).
In two other cases, the production companies did change the existing plants. EPON established a wood processing facility at the coal plant in Nijmegen and equipped the power plant with wood burners (see Figure 4.1). Several Dutch waste companies collected waste wood throughout the Netherlands. These companies also shredded the wood and removed large pieces of plastic and metal by hand. Smaller fragments like rocks, sand and glass were removed automatically. After transportation to Nijmegen, a hammer mill crushed the wood particles into smaller parts. Steam dried the wood particles, and EPON stored them in silos. Engineers replaced four coal burners with four wood burners, a total capacity of 54 MWth. These burners combusted the wood particles separately from the coal, but in the same boiler. The total investment costs were over 13 million euros. EPON received 2.1 million euros from Dutch and European research programmes. The company projected the total payback time to be six years (Caddet, 2000; Loo and Koppejan, 1999). The technological experiences with the plant were satisfactory and in accordance with performance, emission and ash quality specifications (Rasmussen and Overgaard, 1996:160). Only minor adjustments to the processing equipment were necessary (Konings, 2003).

Figure 4.1. Layout of the EPON co-firing plant (Caddet, 2000:2)

EPZ was the second company that made technological changes to the power plant, more radical than EPON’s changes. EPZ decided to restart the gasification project. New prognoses about the waste market predicted better availability of waste wood. The company decided to scale-up the gasifier to a capacity of 150,000 tons per year to improve economic feasibility. In 1997, EPZ reached an agreement with a large Dutch waste company (Bowie) for the supply of biomass fuels, and in 1998, EPZ also contracted companies to supply different parts of the
gasifier. Together with Essent Energy Systems (a merger of PNEM and MEGA), EPZ established a joint venture for operating the gasifier, Amergas B.V.\textsuperscript{12} Public authorities granted the necessary permits in 1998, and EPZ began to construct the plant. The plant operated as illustrated in Figure 4.2. Amergas B.V. stored the wood chips in a large storage silo located at the Amer site. A screw feeder transported the chips into the gasifier, where they were mixed with sand (a heat carrier). Air was added to the mixture, but in such a ratio that the wood chips were only partially combusted.\textsuperscript{13} The remaining chips were converted into wood gas (a mixture of carbon monoxide, hydrogen and several contaminants). The wood gas exited the gasifier through a hot cyclone, with the cyclone returning unburned particles in the wood gas back into the boiler. The gas entered a cooling section – producing steam – which cooled the gas to 220-240°C. This was a necessary condition for the flue gas cleaning system. A fabric filter removed dust and large particles after cooling, while a wet scrubbing unit removed ammonia and condensable tar materials. The gas was then reheated and fed into the boiler of the coal plant. Total capacity of the gasifier was 83 MWth, about 5\% of total plant capacity (Loo and Koppejan, 2002: 183, Kok, Boudewijn and Lindeman, 2000).

\textsuperscript{12} In Dutch: Maatschappij voor Electriciteit en Gas Limburg (MEGA).

\textsuperscript{13} The process operated at temperatures between 850 and 950 °C and at atmospheric pressure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{gasifier_layout.png}
\caption{Layout of the gasifier at the Amer-9 (Konings, 2003)}
\end{figure}

From the beginning, EPZ experienced substantial problems with the gasifier. In November 1999, the company first began testing the plant without fuels, followed by hot commissioning...
and preheating the system with natural gas. In this phase, problems arose with the start-up burner of the gasifier; the burner had to be modified. Process parameters had not yet been fully optimised either. In the next phase, wood was introduced into the system, a step that required the commissioning of the wood handling system. This resulted in several small modifications, like changes in the ash discharge system. In the final phase of commissioning the complete plant was tested, including the introduction of wood gas into the existing power plant. The previous modifications had solved most problems involving the gasification process, but major problems arose with the gas cleaning. Particularly problematic was the combination of gas cooling and gas cleaning. Cooling the gas to the desired temperature resulted in the deposition of tars, causing blockage in the gas cooler and gas cleaning system. These problems were so severe that they prevented continuous operation. EPZ started reconstructing the plant after 2000, but the gasifier did not come into full operation until 2004 (Fernando, 2002:21; Voorter, 2003:4).

Most Dutch coal plants were now permanently co-fired with biomass up to 5% (energy input). Two plants used demolition wood (Gelderland-13, Amer-9), one plant paper sludge (Amer-8) and one plant biomass pallets from various sources (Maasvlakte). In two cases, the production companies did not in any way modify the coal plants (Maasvlakte, Amer-8), in one case the production company installed special processing equipment and burners for the biomass (Gelderland-13), and in one case the company constructed a gasifier (Amer-9). The technological experiences with most of the plants had been very positive. Integration of biomass into an existing coal plants caused only minor problems – except for the gasifier. There was, however, a major problem with the social acceptance of co-firing biomass as well as these plants’ embedding in the existing regulatory framework. Getting permission for co-firing biomass in coal plants often provoked neighbouring residents or environmental organisations to resist, resulting in long legal procedures to acquire permits and high costs for establishing co-firing units. I will come back to this problem in section 4.2.


After 2000, all production companies intensified their co-firing activities, the main reason being a covenant between the power producers and the Dutch Ministry of the Environment, signed in 2002. The covenant dictated that the power producers reduce carbon dioxide emissions from power production by 3 Mton before 2012. Power producers could replace coal with biomass to realise the reduction.\(^\text{14}\) The companies decided on the following goals per company:

\(^{14}\) Production companies could also choose other options to realise the 3 Mton CO\(_2\) emission reduction such as closing a power plant, converting a coal plant into a natural gas plant, or using alternative fuels like non-organic waste streams. Besides the reduction aim for the seven coal combustion plants, the Dutch government and the energy companies agreed on another reduction of 0.5 Mton in the large coal gasifier in southern Netherlands (see section 4.5).
Table 4.1. Reduction aims for CO\textsubscript{2} in the Dutch coal covenant. Most production companies were taken over by other (foreign) companies in the early 2000s. Electrabel (Belgium) took over EPON, Reliant (USA) took over UNA, E.ON (Germany) took over EZH. Essent (Netherlands) partly took over EPZ (Anonymous, 2002).

<table>
<thead>
<tr>
<th>Company</th>
<th>CO\textsubscript{2} reduction (Mton)</th>
<th>Expected biomass capacity (MWe)</th>
<th>Coal plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrabel</td>
<td>0.466</td>
<td>73.8</td>
<td>Gelderland 13</td>
</tr>
<tr>
<td>Reliant</td>
<td>0.488</td>
<td>77.2</td>
<td>Hemweg 8</td>
</tr>
<tr>
<td>E.ON</td>
<td>0.805</td>
<td>127.5</td>
<td>Maasvlakte 1 + 2</td>
</tr>
<tr>
<td>EPZ</td>
<td>0.310</td>
<td>49.13</td>
<td>Amer 8 + 9</td>
</tr>
<tr>
<td>Essent</td>
<td>0.931</td>
<td>147.37</td>
<td>Borssele 12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3 Mton</strong></td>
<td><strong>475 MWe</strong></td>
<td><strong>7 plants</strong></td>
</tr>
</tbody>
</table>

The production companies began to expand their co-firing activities. Electrabel (previously EPON) asked for a permit to expand wood co-firing from 3% to 10%; E.ON (previously EZH) investigated co-firing of biomass pallets up to 10% or more (Ree, et al., 2001:7). Essent (previously EPZ) converted the direct co-firing facilities in the Amer 8 and Amer 9 into indirect co-firing facilities (Voorter, 2003). Essent began to co-fire vegetable oil in a natural gas-fired power plant in Maasbracht, equivalent to a biomass capacity of 30 MWe. Energy companies also planned new projects with more advanced technologies. Electrabel investigated the construction and integration of a gasifier into the Gelderland-13 power plant (Ree, Korbee and Lange, 2000:6). Reliant (previously UNA) investigated the construction and integration of two pyrolysis units (with a total capacity of 120,000 tons biomass annually) into the Hemweg-8 power plant (Ree et al., 2001:14).\textsuperscript{15} Nuon energy company started experiments with adding several sources of biomass to a large existing coal gasifier in Buggenum (Damveld, 2001:3). The companies also searched for new sources of biomass including bone meal, animal fat, coffee ground, sunflower waste and olive and apricot kernels (Ree et al., 2001:7; Konings, 2003). They also started importing biomass on a large scale.\textsuperscript{16} All these plans resulted primarily in increased co-firing of (imported) biomass in the (in)direct co-firing units, despite the plans for advanced technologies like gasification and pyrolysis. Nevertheless, energy production from co-fired biomass increased significantly (see Figure 4.3), mainly through (in)direct co-firing. Within a few years’ time, co-firing in coal plants became the most important renewable energy technology in the Netherlands, after waste incineration.

\textsuperscript{15} In a pyrolysis plant, biomass (or other fuel) is heated and pressurised in the absence of oxygen. Under these circumstances, the fuel is converted into a mixture of gas, oil and char, which can be used as fuel in a combustion process.

\textsuperscript{16} In 1995, KEMA research institute had already investigated import; Novem had financed research on the import of wood from Estonia and Uruguay. In 1997, EPZ, EZH and SEP (Samenwerkende Electriciteitsproductie bedrijven) investigated the economic feasibility of importing wood from Estonia again (Voorter, 1996; Anonymous, 1997). These research projects had not led to a substantial import of biomass for co-firing activities. In 2002, research on the import of biomass continued and energy companies started importing biomass. Essent, for example, studied the import of wood from the Russian wood industry and initiated a broad discussion on the sustainability of wood import (Kroon, 2002:18).
Conclusion

Table 4.2 shows the co-firing units that existed in the Netherlands in 2002. The total co-firing capacity in the Netherlands represented a biomass capacity of 177 MWe, or 0.9% of total power capacity and 1.2% of total centralised power capacity in the Netherlands.\(^\text{17}\) Co-firing developed from a small niche into one of the largest renewable energy niches in a short period of time – ten years. In the early 1990s, the focus was on experimenting with direct and indirect co-firing of small amounts of biomass. In the late 1990s, the focus shifted towards larger amounts of biomass and permanent co-firing. After 2000, energy companies also investigated more advanced technologies like gasification and pyrolysis, while the size of the co-firing niche further increased, but mainly by increasing biomass amounts in existing (in)direct co-firing plants.

\(^{17}\) Total central capacity includes the plants owned by Electrabel (4690 MWe), Nuon (3669 MWe), E.ON (1770 MWe), Essent (3248 MWe) and EPZ 875 MWe). Source: http://www.energie.nl
Table 4.2. Co-firing activities in the Netherlands in 2002 (Dinkelbach, 1999:10; Ree, Korbee and Lange, 2000:4; Joosen et al., 2003)

<table>
<thead>
<tr>
<th>Year</th>
<th>Plant</th>
<th>Co-firing concept</th>
<th>Total capacity (MWe)</th>
<th>Biomass capacity (MWe)</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Gelderland-13 (Electrabel)</td>
<td>Indirect</td>
<td>600</td>
<td>9</td>
<td>Demolition wood + olive seeds</td>
</tr>
<tr>
<td>1998</td>
<td>Maasvlakte 1+2, (E.ON)</td>
<td>Direct</td>
<td>2x518</td>
<td>39</td>
<td>Biomass pallets, animal waste (bone meal)</td>
</tr>
<tr>
<td>1998</td>
<td>Amer-8 (Essent)</td>
<td>Indirect</td>
<td>645</td>
<td>50</td>
<td>Paper sludge, food industry waste</td>
</tr>
<tr>
<td>1999</td>
<td>Borssele –12 (Essent)</td>
<td>Direct</td>
<td>403</td>
<td>14</td>
<td>Various organic sources</td>
</tr>
<tr>
<td>2000</td>
<td>Amer-9 (Essent)</td>
<td>Thermal pre-processing (gasification)</td>
<td>600</td>
<td>30</td>
<td>Demolition wood</td>
</tr>
<tr>
<td>2001</td>
<td>Buggenum-7 (Nuon)18</td>
<td>Direct</td>
<td>253</td>
<td>5</td>
<td>Various organic sources</td>
</tr>
<tr>
<td>2002</td>
<td>Claus power plant (Essent)19</td>
<td>Direct</td>
<td>2x640</td>
<td>30</td>
<td>Vegetable oil</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>177</td>
</tr>
</tbody>
</table>

The most striking puzzle in this case is how energy from co-firing biomass became a relatively large renewable energy option in the Netherlands in only ten years’ time, while it took other renewable energy options (e.g. wind power) more than thirty years to develop into a substantial niche. I will address this question in my analysis below. However, other questions also emerge from the historical overview, the second puzzle being why production companies decided to begin co-firing in the first place. Why did these companies decide to risk the stable operation of large, expensive and sometimes new power plants? Third, why was it so difficult to get permits for co-firing plants? Why did environmental groups resist co-firing biomass and coal? Finally, why is it that energy companies did not develop new co-firing units using gasification and pyrolysis, despite governmental pressure to dramatically increase the share of biomass? Why did energy companies mainly opt to expand existing units and use direct and indirect co-firing technologies, despite the fact that they had plans for employing more advanced technologies? In the following section, to investigate these puzzles, I will examine internal niche processes. As in the previous chapter, I will sometimes refer to regime dynamics, but not yet include them in the analysis.

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18 Coal gasifier
19 Natural gas plant
4.2 Analysis of niche dynamics

4.2.1 Visions and expectations

In the early 1990s, visions about co-firing mainly related to the availability of organic waste and possible reductions in fuel costs. In particular, wood and sewage sludge were promising fuels for power generation in coal plants. Actors like energy companies and research institutes referred to an upcoming ban on the landfill of organic waste, including wood and sewage sludge (Staatsblad, 1995). The Netherlands Energy Research Foundation (ECN) argued this point:

> Although forests are not abundant in the Netherlands, a considerable amount of wood is available for energy production. The wood comes from different sources, e.g. in the form of waste from wood processing industries (200 kton/year), demolition wood (500 kton/year) and wood from parks. Furthermore there is a large potential of thinning wood from forest (500 kton/year), which is at present not utilized. Therefore, wood is seriously considered as a potential fuel. […] In the case of sewage sludge, a disposal problem has arisen in the Netherlands due to changing legislation, which will ban the landfill of organic material in the near future and the fact that the use of sewage sludge for soil improvement in agricultural applications is prohibited. […] It seems inevitable that thermal conversion of sewage sludge, either gasification or combustion, will play an important role in coming years (Doorn et al., 1994:2).

Production company UNA argued at an international symposium for co-firing in 1995:

> Co-combustion of sewage sludge, considered as a waste disposal option, has an economically competitive outlook, mainly due to the savings on fossil fuel, combining economic benefits with environmental advantages (Dijkman, Geurts and Van der Valk, 1995).

Furthermore, EPON supported the view that co-firing contributed to solving the waste disposal problem:

> Waste wood from primary wood processing and demolition presents both a problem and a potential. If disposed of in landfills, it consumes large volumes and decays, producing CH₄, CO₂ and other greenhouse gases. As an energy source used in a coal-fired power plant, it reduces the consumption of fossil fuels, reducing the greenhouse effect significantly (Penninks, 1995:2).

The Dutch government supported the vision to use waste for energy generation (waste-to-energy). In environmental policy papers, the Dutch government identified waste-to-energy as an important route for utilising waste streams (see section 4.5). An example of the Ministry of Economic Affairs’ vision is found in the follow-up policy paper on energy conservation:
Besides large-scale waste incineration there are also very good possibilities for the combustion or gasification of specific waste streams. With respect to energy, the most important waste stream at this time is waste wood. [...] The EPON, for example, will experiment with co-firing pulverised wood at its power plant in Nijmegen. [...] If well aligned, these initiatives may eventually provide an important impulse for utilising agricultural materials for power production (Ministry of Economic Affairs, 1993:116-118).

Waste reduction and savings in fuel were thus the main reasons to investigate co-firing technology. The power companies motivated their choices with references to the disposal problem for specific types of waste (i.e. wood and sludge). Their main expectation was that replacing coal with waste would result in lower fuel expenditures, without any distortion of normal plant operation. The experiments in the early 1990s made these expectations more robust.

After 1996, visions and ideas about co-firing changed. Renewable energy production became a more important element in the vision on co-firing, linked to an emerging green electricity market. This is illustrated in documents on co-firing published during in the late 1990s. One of the major consequences was that actors increasingly talked about biomass rather than referring to specific waste streams. Energy companies applied for permits for co-firing biomass in general. EPON, which had applied for a permit to combust wood in 1996, started a new procedure to increase the amounts of biomass by co-firing wood, sewage sludge and biomass in 1999 (Commissie voor de MER, 2001). EPZ applied for a license for the co-firing of biomass (Commissie voor de MER, 1999a). The difference with previous permits was that the term ‘biomass’ referred to all kinds of organic sources rather than one or two specific waste streams. Energy companies increasingly emphasised the importance of producing electricity in an environmentally friendly manner, by replacing coal with biomass. In 2000, EPON made the following argument at the 1st World Conference on Biomass for Energy and Industry:

The interest for co-firing as well as co-firing itself is increasing. Co-combustion itself is not new. The basis for co-combustion is an economic one. Either inexpensive fuels are used, so-called opportunity fuels such as old tires, Refuse Derived Fuel (RDF) and petroleum coke or so called ‘green’ or ‘sustainable’ heat and power are produced by using biomass as fuel. This green or sustainable heat and power yield higher prices per GJth or kWh, compared to heat and power produced from fossil fuels. [...] The co-combustion of biomass in a coal-fired power plant makes this power plant more ‘green’ (Dijen, 2000:2124).

Original text: Naast grootschalig afvalverbranding zijn er ook goede mogelijkheden voor de verbranding of vergassing van specifieke afvalstromen. De energetisch belangrijkste afvalstroom op dit moment betreft afvalhout. [...] Zo zal de EPON in haar elektriciteitscentrale te Nijmegen een praktijkexperiment uitvoeren met de bijstook van verpoederd houtafval. [...] Mits goed afgestemd, kunnen deze initiatieven een belangrijke impuls geven aan de inzet op termijn van agrarische grondstoffen ten behoeve van elektriciteitsopwekking.
‘Being green’ gained importance in the strategies of power producers. Moreover, research institutes emphasised the importance of renewable energy production from biomass. The ECN research institute identified co-firing of biomass as being very promising and important for the Dutch renewable energy policy at the same conference:

Biomass, i.e. organic waste streams and energy crops, is expected to play a major role concerning the avoidance of fossil fuel use in the future in power, heat and transportation fuel production processes. For the time being, however, in the Netherlands the use of biomass is mainly restricted to a limited amount of small-scale thermochemical and biochemical conversion processes for heat and/or power production. Large-scale, stand-alone, biomass conversion processes, for the production of CHP and/or transportation fuels (ethanol, methanol, FT-fuels), are still unattractive from an economic point of view, whereas these technologies are also not fully technically mature. To accelerate the introduction of biomass into the Dutch energy supply system, to meet a significant part of the Dutch renewable energy policy, co-firing of biomass in already existing coal and natural gas fired power plants, and industrial natural gas fired combined-cycles is identified as a very promising option (Ree et al., 2000:787).

The changing vision towards green energy production stimulated energy companies to further increase the amounts of biomass. The companies expected co-firing to be an attractive route for the production of large amounts of inexpensive green electricity and relatively easy to implement in the short term, in particular as compared to other renewable energy technologies. Increasing financial gains from renewable energy generation supported the expectations, and became at least as important for energy companies as cutting fuel costs had been in the early 1990s (Broek et al., 2002:46). Because of the expectations, production companies further increased the share of biomass in coal plants. The results from direct and indirect co-firing turned out to be especially successful in terms of these expectations, both technologically as well as economically.

After 2000, the covenant between the Dutch Ministry of the Environment and the coal plant owners dominated the visions and expectations. Climate protection and reduction of carbon dioxide emissions became the main arguments for developing co-firing technologies. Rob Remmers (Essent) argued as follows:

You can divide the co-firing experiments into three phases. In the first phase, the early 1990s, the experiments’ primary aim was to reduce fuel costs. In the second phase, approximately as of late 1995, a new market for green electricity emerged and this became the main motive. It was not a strong motive, however, because a coal plant is designed to combust coal. It is extremely difficult to start adding other materials. The final phase is the current one; the climate covenant is the main driver for the experiments (Remmers, 2002).\(^{21}\)

\(^{21}\) Je kunt de mee- en bijstook projecten in drie fasen onderverdeelen. In de eerste fase, begin jaren 90, hadden de experimenten voornamelijk kostenreductie van de brandstoffen tot doel. In de tweede fase, vanaf ongeveer eind 1995, ontstaat er een markt voor groene stroom en wordt dat de drijfveer. Dit was echter geen sterke drijfveer, omdat een kolencentrale ontworpen is om kolen te verbranden. Het is erg lastig om andere materialen toe te voegen. De laatste fase is de huidige, waarin het kolenconvenant dé drijfveer is.
The covenant changed expectations about the future of co-firing. Energy companies and research institutes now expected that the share of biomass in coal plants would have to rise to 30% or even to more than 40% (Ree et al., 2000a). As a result, production companies further expanded their activities and also investigated many different sources of biomass, more radical interventions in the traditional coal combustion processes (thermal pre-processing) and the large scale importation of biomass.

Conclusion

The vision of production companies, research institutes and the Dutch government regarding co-firing changed in the 1993-2003 period. In the early 1990s, the potential benefits from co-firing were expected to be related to waste disposal problems and fuel cost reductions. The experiments with co-firing proved the feasibility of waste combustion in power plants. After the initial testing phase, renewable energy production became a more important part of the vision. The main expectation was that co-firing biomass would be the most inexpensive option to produce renewable energy. As a result, energy companies strengthened their activities in the field of co-firing, constructed permanent co-firing equipment and increased capacity. The shift in vision was accompanied by an increasing emphasis on biomass rather than waste. Although reduction of carbon-dioxide emissions had always been part of the expectations for co-firing, it became the primary incentive for co-firing after 2000. New expectations about co-firing up to 40% biomass resulted in increased investigation into different biomass and waste fuels, the importation of biomass, and advanced technologies like thermal pre-treatment of biomass.

4.2.2 Network formation

Production companies

The four production companies EPZ, EZH, EPON and UNA have been the dominant actors in co-firing since the early 1990s. They initiated projects, developed technological concepts and used the technologies when implemented. There are two reasons for their dominant position. First, co-firing technology requires integration into the existing infrastructure for coal combustion and on-site installation. Production companies were therefore involved in the projects from the beginning. They often started with laboratory tests in cooperation with research institutes (KEMA, ECN). After initial tests, most companies decided on actual implementation for real-life experimentation. Second, production companies were closely involved in the innovation process in the electricity sector through participation in SEP and cooperation with KEMA, both companies being responsible for planning and innovation in

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22 In Dutch: Energieonderzoek Centrum Nederland (ECN).
the power sector (see section 4.4). This position enabled the production companies to do much of the testing, experimentation and even construction of co-firing technology within established networks, independently or in cooperation with the KEMA. In the case of a more radical innovation (the gasifier at the Amer), the production company approached a supplier of gasification technologies, although EPZ still controlled the integration of components into a single system (Willeboer, 2000:80). The production companies’ dominant role in niche development is also illustrated by their participation (presentations and publications) in international workshops and research programmes on co-firing (Sulilatu, 1995; Loo and Koppejan, 2000:8; European Commission, 2000; Novem and TNO-Mep, 2000:2, 21). Participation in these networks enabled the companies to put several issues on the international research agenda (see also section 4.2.3 on learning).

**Public authorities**

Several ministries and regional public authorities were involved in the niche for co-firing. In particular the Ministry of the Environment was closely involved, because it was responsible for determining emission standards for coal plants. In 1994, the Ministry published a guideline for co-firing biomass in coal plants (Ministry of Spatial Planning, Housing and Environment, 1994). The guideline outlined procedures for granting permits in the construction of co-firing plants. Local public authorities (provinces) were responsible for granting permits, but no clear emission framework existed at the time. Two ministerial orders existed, one for waste combustion (BLA) and one for energy generation (BEES A). The former order dictated emission standards for waste incinerators, while the latter dictated emission standards for energy plants. A third standard (NER) dictated the emission standards in any other case. The standard for waste incineration was strict and included limits for mercury, heavy metals and dioxins (Table 4.3). Standards for energy generation only included limits for NOₓ, SO₂ and dust. When waste was co-fired in a coal plant, these standards conflicted, because waste (subject to the BLA standard) was now combusted in plants subject to the BEES-A standard.

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23 In Dutch: Samenwerkende Electriciteitsproductiebedrijven (SEP).
24 For waste incinerators this was the Order for Emissions to Air from Waste Combustion (Besluit luchtemissies afvalverbranding, BLA) and for energy generation this was the Order for Emissions Standards for Boilers A (Besluit emissie-eisen stookinstallaties milieubeheer A, BEES A).
25 Nederlandse Emissie Richtlijnen
Table 4.3. Emission standards for energy generation (Bees-A) and waste incineration (BLA) in the early 1990s

<table>
<thead>
<tr>
<th></th>
<th>Bees-A</th>
<th>BLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen oxide (NO(_x))</td>
<td>200</td>
<td>70</td>
</tr>
<tr>
<td>Sulphide dioxide (SO(_2))</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>Dust</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Cadmium (Cd) and thallium (Tl)</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Mercury (HG)</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Sum of heavy metals</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Hydrogen chloride (HCl)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Hydrogen fluoride (HF)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Dioxins and furans</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Volatile organic compounds (VOS)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

The Minister suggested the following rule for granting permits for co-firing: provinces were to use the order for energy generation if the total input of biomass was less than 10%; however, the provinces were allowed to set additional emission standards under the BLA order. If the total input was larger than 10%, they were to use the NER emission standards. The Minister thus constructed a new rule in the niche, based on existing rules from the electricity and waste regimes.

The new rule had a major influence on the emerging co-firing niche. No project exceeded the 10% limit. EPZ, for example, used this limit explicitly as a design choice for the gasifier (EPZ, 1995:7). Furthermore, provinces began to exploit the option to enforce additional standards from the BLA. The coal plants were each located in different regions and were therefore forced to apply for permits in different provinces. EPON applied in Gelderland, EPZ in Noord-Brabant and Zeeland, EZH in Zuid-Holland and UNA in Noord-Holland. Different provinces used different emission standards. For mercury emissions, the provinces of Zuid-Holland (Maasvlakte plant), Zeeland (Borssele plant) and Noord-Holland (Hemweg plant) each required different standards (ECN, 2002:66; Kok, Boudewijn and Lindeman, 2000:22). In some cases the provinces also enforced additional research obligations for transport and by-products (the Amer plant) or obliged the power company to construct closed systems for storage and internal transport (the Hemweg plant) (Kok, Boudewijn and Lindeman, 2000:25).

The different rules for emission standards frustrated production companies. They could not predict the outcome of a permission procedure, and procedures often took very long (Table 4.4.; 4.5). Embedding the co-firing projects in the existing regulatory framework became the dominant problem in the co-firing niche after 1996 (see also section 4.2.3).
Table 4.4. Experiences with permits and emission standards at the Dutch co-firing plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Owner</th>
<th>Province</th>
<th>Experiences with permits and emissions standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gelderland-13</td>
<td>EPON</td>
<td>Gelderland</td>
<td>EPON received a permit to co-fire wood in 1994. Neighbouring residents challenged the permit, however, until the authority had to rescind the permit on behalf of the European court. The main reason was that in the original permit, wood had not been classified as waste, as it should have been, according to the court. EPON applied for a new permit in 1999 for co-firing biomass (including wood) in general (Anonymous, 2000; Commissie voor de Mer, 1999a; Commissie voor de Mer, 2001).</td>
</tr>
<tr>
<td>Amer 8, 9</td>
<td>EPZ</td>
<td>Noord-Brabant</td>
<td>EPZ applied for a permit for the gasification of demolition wood (classified as waste) in 1995, which was granted in 1998. No appeals were made against the permit. In 1996 EPZ applied for a permit for co-firing paper sludge (classified as waste). No appeal was made against the permit (Commissie voor de MER, 1997; Commissie voor de MER, 1995; Kok, Boudewijn and Lindeman, 2000).</td>
</tr>
<tr>
<td>Maasvlakte 1+2</td>
<td>EZH</td>
<td>Zuid-Holland</td>
<td>In 1996 EZH applied for a permit for co-firing biomass pallets at the Maasvlakte power station. After intensive discussions with local and national authorities it was decided that this initiative should fall under the waste legislation (Beekes et al., 1998).</td>
</tr>
<tr>
<td>Hemweg plant</td>
<td>UNA</td>
<td>Noord-Holland</td>
<td>UNA applied for a permit for co-firing sewage sludge in 1996, which was granted in 1998. The project suffered from an appeal against the permit based on mercury emissions. The sewage sludge is classified as waste (Commissie voor de MER, 1998; Kok, Boudewijn and Lindeman, 2000).</td>
</tr>
</tbody>
</table>

Table 4.5. Periods for permit procedures and environmental reports for some of the co-firing initiatives (Kok, Boudewijn and Lindeman, 2000:11)

<table>
<thead>
<tr>
<th>Project</th>
<th>Period of procedure (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-firing wood in Gelderland-13 (EPON)</td>
<td>Permit 12, Environmental report (MER) + permit (no environmental report in first application)</td>
</tr>
<tr>
<td>Co-firing paper sludge in Amer (EPZ)</td>
<td>Permit 10, Environmental report (MER) + permit 16</td>
</tr>
<tr>
<td>Co-firing sewage sludge in Hemweg plant (UNA)</td>
<td>Permit 10, Environmental report (MER) + permit 28</td>
</tr>
<tr>
<td>Gasification and co-firing wood in Amer-9 (EPZ)</td>
<td>Permit 6, Environmental report (MER) + permit 27</td>
</tr>
</tbody>
</table>

After 2000, the production companies discussed with the Dutch government the difficulties involved in obtaining permits. This discussion was part of negotiations on climate protection. The companies agreed to reduce carbon dioxide emissions if the Minister of Environment came up with a clear emission framework (Brand, 2001; Brand 2002). He complied, and attached the new framework to the 2002 covenant on co-firing biomass. This framework was
based on a distinction between clean organic material – called ‘the white list’ – and polluted organic material – called ‘the yellow list’. The combustion of materials from the white list was subject to emission limits for NO$_x$, SO$_2$ and dust. Combustion of materials on the yellow list was also subject to limits for other toxins (Table 4.6). These emission standards were applicable independent of the type of plant in which the waste was combusted.

<table>
<thead>
<tr>
<th>Co-firing clean streams (mg/Nm$^3$)</th>
<th>Co-firing polluted streams mg/Nm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen oxide (NO$_x$)</td>
<td>NO$_x$ trading system$^{27}$</td>
</tr>
<tr>
<td>Sulphur dioxide (SO$_2$)</td>
<td>200</td>
</tr>
<tr>
<td>Dust</td>
<td>20</td>
</tr>
<tr>
<td>Cadmium (Cd) and thallium (Tl)</td>
<td>0.015</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>Input requirement$^{28}$</td>
</tr>
<tr>
<td>Sum of heavy metals</td>
<td>0.15</td>
</tr>
<tr>
<td>Hydrogen chloride (HCl)</td>
<td>10</td>
</tr>
<tr>
<td>Hydrogen fluorine (HF)</td>
<td>1</td>
</tr>
<tr>
<td>Dioxin and furane</td>
<td>0.1</td>
</tr>
<tr>
<td>Volatile organic compounds (VOC)</td>
<td>10</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>50</td>
</tr>
</tbody>
</table>

These emission standards provided a clear framework, though it was not yet definitive and needed to be embedded in upcoming European regulations (see section 4.4). Nevertheless, the Dutch government promised as part of the 2002 covenant that it would not deviate from the upcoming European regulations on emissions, an important precondition for the production companies to engage in the covenant, because similar regulations throughout Europe created a level playing field for the companies. This framework created stability in the emission standards for co-firing.

The problems, however, were not solved with this framework. New co-firing projects – and biomass combustion projects in general – continued to suffer from long procedures and legal fights in court. Why? One clue is provided by the distinction between the white and yellow lists. The Dutch government had not yet defined what organic flows should appear on which list. They wanted to await European definitions on biomass and waste. I will come back to the European definitions in section 4.4.

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$^{26}$ The limits for clean substances are similar to the limits for coal combustion. When combusting mixtures of polluted substances and coal, or clean substances, polluted substances and coal, the emission standards are based on weighted averages (Ministry of Spatial Planning, Housing and Environment, 2002:10).

$^{27}$ The system for trading NO$_x$ certificates was still being developed at the time of writing (2003).

$^{28}$ Under 10% co-firing on a mass basis, the input requirement for mercury is 0.5 mg/kg (dry material). Above 10% the standard for mercury is calculated with a specific formula.
Research institutes

In the early 1990s, the research institutes KEMA, ECN and Delft University investigated co-firing in their laboratories. Researchers from Delft Technical University constructed a small test unit (1.6 MWth) to investigate different technological aspects of co-firing (Andries, Vegelin and Verloop, 1994). Researchers from ECN focussed on co-firing biomass, municipal sewage sludge and coal in a small experimental plant (Doorn et al., 1994). KEMA carried out experiments in a so-called ‘drop tube furnace’ to investigate emissions, flue gas cleaning and the composition of the solid residues left from co-firing coal and wood (Gast and Visser, 1994; Doorn, Bruyn and Vermeij, 1996). The production companies had commissioned these projects in order to avoid any damage to the plant. In particular the KEMA acted as an institutional link between different projects in the early 1990s and contributed to producing basic knowledge about the fundamental processes in co-firing.

Relations between research institutes and production companies changed in the late 1990s and early 2000s. Research institutes began to investigate the advantages and disadvantages of complete co-firing plants, instead of basic process conditions. Simultaneously, however, energy companies became more reserved in providing plant data. ECN complained about the lack of data in one of their research projects:

To provide a more detailed picture on the real environmental and techno-economic co-firing potential of biomass and waste in Dutch coal fired and natural gas fired power plants, a specific analysis for each plant is necessary. In these analyses it is necessary to use, instead of general data, plant-specific data […]. Consequently, this means that the plant owner should provide (confidential) plant data. Such an analysis, performed by the research institute together with the plant owner, as well as the party providing financial aid, will provide the best result. Whether the energy companies will agree to such an analysis is highly doubtful (Ree et al., 2000:13).

Participation in international research networks solved part of the problem. In 1998, Sjaak van Loo (TNO) became task leader in the Bioenergy Task 19 on biomass combustion, one of the International Energy Agency (IEA) projects. Other countries also participated: Austria, Denmark, Sweden, the USA, Canada, New Zealand and Brazil (Tustin, 1999:69). The researchers aimed to stimulate the use of biomass combustion for the production of heat and power on a wider scale. Soon they concluded that “...it was highly desirable to include co-firing in the activities of Task 19” (Tustin, 2000:38). Experiences with co-firing in the USA

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29 Original text (Dutch): Om meer duidelijkheid te kunnen verschaffen over het daadwerkelijke praktische milieutechnische en financieel-economische mee-/bijstookpotentieel van biomassa- en afvalstromen in Nederlandse steenkoolgestookte centrales en aardgasgestookte installaties dient i.p.v. algemene uitgangspunten […] centrale/installatie-specifieke data te worden gebruikt. Dit houdt in dat voor de uitvoering van deze analyses de inbreng van (vertrouwelijke) data door de eigenaar/bedrijver van de beschouwde centrale/installatie onontbeerlijk is. Uitvoering van de analyse door een onderzoeksinstelling tezamen met de eigenaar/bedrijver van een centrale/installatie zal voor alle betrokken partijen, inclusief de subsidieverlenende instantie, het beste resultaat opleveren. Of de E-bedrijven tot zo’n gemeenschappelijke analyse bereid zijn valt ten zeerste te betwijfelen.
and the Netherlands hinted that research on NO\textsubscript{x} emissions, ash deposition and utilisation, char burnout and the preparation and feeding of biomass were the most urgent topics. The Task coordinators also signed an agreement with the IEA Clean Coal Science Group to exchange information related to co-firing.

In 2000, the groups organised a joint workshop at the world biomass conference in Seville, Spain (Tustin, 2001:34). A Dutch participant (Novem) presented an overview of non-technical barriers related to co-firing. The list mentioned uncertainty about tax exemptions, the lack of a level playing field in Europe, and local authorities’ enforcement of different emission standards within individual countries (Loo and Koppejan, 2000:9). Uncertainty about tax exemptions (see section 4.4) and local emission standards were typical Dutch problems. The European Commission later used this list in a publication on the constraints of successfully replicating co-firing experiments (European Commission, 2000:7).

After 2001, Task 19 was continued as ‘Task 32: Biomass Combustion and Co-firing’. The list of participants had hardly changed. Dutch participants continued to be heavily represented in the project. The results from Task 32 were published in a handbook for biomass combustion and co-firing, of which one chapter was devoted to co-firing. Dutch co-firing experiments represented several of the possible co-firing concepts. In the book, the researchers described extended guidelines for many (technical) issues involved in co-firing, such as fuel characteristics, fuel preparation and handling, and fly ash utilisation. They based the guidelines on the comparison of co-firing experiences in different countries and locations. In addition, in publications of the IEA Clean Coal Research programme, Dutch plants showed up as examples of co-firing plants (Morrison, 1996; Davidson, 1999; Fernando, 2002). The Dutch researchers in international research networks played a major role in stabilising design choices and in problem-solving heuristics at the niche level; they collected and published their experiences in the book (see also section 4.2.3).

Technology suppliers

Technology suppliers played a minor role in co-firing experiments. In most experiments there was no (or only minor) technological development. Rob Remmers of Essent explained the situation:

In general, technological developments in these initiatives is much less of an issue than system choice and adjustments to the existing system. From a technological view, only the mill is important. Theoretically, direct co-firing initiatives are thus easy to fit into the existing infrastructure, although you do need space for conveyor belts, storage silos and new burners. Moreover, on the whole this is relatively easy, as they are all proven technologies (Rob Remmers, 2002).\textsuperscript{30}

\textsuperscript{30} Orginal text (Dutch): Op zich gaat het bij deze initiatieven veel minder om technologie ontwikkelingen en veel meer om systeemkeuze en aanpassingen aan het bestaande systeem. In technologisch opzicht gaat het eigenlijk alleen om de molen. In theorie zijn meestook initiatieven dus redelijk inpasbaar in de bestaande infrastructuur,
More important were changing process conditions:

The story is different from a process point of view – there are, for instance, different fuel characteristics, chemical composition, consequences for ashes, consequences for boiler pollution as well as for boiler availability (Remmers, 2002).  

Traditional technology suppliers (e.g. Siemens, Stork, Babcock) could supply the necessary equipment – such as conveyor belts for fuel transport and storage equipment – because these technologies were nearly identical to the technologies for processing coal. The companies also helped optimise process conditions, with their knowledge of coal combustion. In the case of the gasifier, the role of the technology supplier was more important. The coal boiler supplier (Schelde Ketelbouw) investigated the integration of gasifier into the existing boiler (EPZ, 1995:13). The Lurgi company supplied the gasifier. Lurgi was familiar with gasifying fossil fuels, but had only constructed a few biomass gasification plants of the size in the Amer plant (see Table 4.7). EPZ further contracted the Dutch company Heijmans to construct the logistical system, and Siemens to adjust the control equipment. EPZ assembled the parts into one system, in cooperation with the companies. Previous experiences with a large coal gasifier enabled them to participate actively in the optimisation of process conditions (Willeboer, 1999; Willeboer, 2000:80). In general, innovation for co-firing occurred mainly within established social networks, with an important role for the production companies and the KEMA. The experiments with co-firing hardly changed these roles.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year of start-up</th>
<th>Capacity</th>
<th>Plant Description</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pöls, Austria</td>
<td>1987</td>
<td>27 MWth</td>
<td>Dryer, gasifier, air pre-heater</td>
<td>Tree bark</td>
</tr>
<tr>
<td>Rüdersdorf, Germany</td>
<td>1996</td>
<td>100 MWth</td>
<td>Gasifier</td>
<td>Wood</td>
</tr>
<tr>
<td>Bioeletristica, Pisa, Italy</td>
<td>2000</td>
<td>12 Mwe</td>
<td>Dryer, gasifier, gas cooling/cleaning, compression, water treatment</td>
<td>Wood</td>
</tr>
<tr>
<td>N.V. EOZ Geertruidenberg, the Netherlands</td>
<td>2000</td>
<td>85 MWth</td>
<td>Gasifier, gas cooling/cleaning, water treatment</td>
<td>Waste wood</td>
</tr>
</tbody>
</table>

**Fuel suppliers**

In the early 1990s, power companies combusted specific fuel types, in particular demolition wood and sewage sludge, because there was a surplus of these fuels rather than because there

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31 Procestechnisch is het echter een ander verhaal, bijvoorbeeld de brandstofeigenschappen, chemische samenstelling, effecten op verbrandingsassen, effecten op vervuiling van de ketel en beschikbaarheid van de ketel.
was a demand for renewable energy. UNA decided to start co-firing on the basis of available quantities of sewage sludge from local sewage treatment plants; EPON began co-firing on the basis of a surplus of demolition wood. When production companies began to increase the share of biomass in co-firing in the late 1990s, they needed much larger amounts of fuel. EZH established a new company called Biomass Nederland B.V., which produced biomass pallets from different sources of organic waste. EPZ (and stakeholder Essent) focussed on importing biomass and producing biomass fuels from organic waste streams. Despite increasing efforts to secure the supply of domestic biomass and waste fuels, security of supply became an important topic in the Dutch co-firing niche after 2000. Projections for the near future showed that for co-firing the large amounts of biomass, biomass importation was necessary, in particular for the amounts needed to reduce the CO$_2$ emissions mentioned in the covenant. However, there was no clear market for biomass fuels (domestically and internationally), there were no product standards and the supply was often unpredictable (Weterings et al., 1999; Ministerie van Economische Zaken, 2003). Experienced fuel suppliers, important actors, were missing in the co-firing network.

Environmental groups and neighbouring residents

Several environmental groups and residents living near power plants have put up resistance to co-firing since the early 1990s. The indirect co-firing experiment in the EPON plant was especially hard hit by people challenging the permits. Initially, local environmental organisations challenged the permits because they expected emissions to increase to levels higher than defined in the permit (a combination of BEES-A and BLA standards). The experiments, however, showed that emissions stayed within the limits. The critique then shifted towards the definition of biomass and waste. The permit did not define the demolition wood as waste and the environmental groups tried to invalidate the permit by arguing that the wood should be classified as waste. They succeeded in 2001, when the European Court decided that the permit was illegal. EPON was now forced to apply for a permit for waste combustion, and comply with BLA standards. The company stopped co-firing waste wood in 2002 and was not able to continue until it received a new permit (Zoethout, 2001:4; Anonymous, 2000:12; AOO, 1998).

The Ecological Knowledge Centre (EKC) played a prominent role in the resistance to co-firing projects. This centre’s methods included contesting permissions in court, presenting scientific facts to underpin arguments, publishing arguments and findings on websites, and organising and aligning similar protests from other local groups like the Vrijwillige Milieurecherche (Voluntary Environmental Detective Force) and the Gelderlandse Miliefederatie (Environmental Federation of Gelderland). EKC not only accused the EPON

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32 In Dutch: Ecologisch Kennis Centrum
33 See websites of the Social Data Bank (http://www.sdnl.nl) and the A van Rooij website (http://www.biomassa.polie.nl).
company, but also waste companies, civil servants in several Ministries and local governments. The group contested the use of impregnated wood in general and public authorities’ approval of its usage. In a column for Twente University of Technology, Ad van Rooij (director of EKC) argued as follows:

For 12 years I have already been challenging the impregnation of wood. The Netherlands is already full full of such wood. It is used for garden sheds, fences, pergolas, wooden playground equipment, picnic tables, wooden building frames, barns […], etc. Impregnated wood contains high levels of arsenic acid and chromium trioxide. These are extremely dangerous carcinogenic substances, which also harm the fertility of men and women and cause genetic variations. After thousands of items of correspondence with the national and local authorities, after interminable discussions with members of the Lower House and local authorities, and after fighting hundreds of disputes in court, I can only conclude that there is no longer any independent administration of justice in the Netherlands. What we have is a dictatorship which stems from conflicts of interest, ignorance, collusion, abuse of power, corruption and so on (http://www.sdnl.nl).

EKC also organised local opposition to co-firing biomass in the coal gasifier in Buggenum. The province allowed potential buyers to experiment with gasifying sewage sludge, demolition wood and chicken manure. EKC assisted a local interest group (representing more than 400 neighbouring citizens) in challenging the experiments. Their actions included demonstrations, challenging decisions in court and demanding penalties of €100,000,000 per day. Public authorities eventually allowed continuation of co-firing experiments, but the opposition remained able to slow down and postpone the project through legal procedures (Anonymous, 2000a:35). Furthermore, UNA faced resistance from a local environmental group. The Noord-Hollandse Milieufederatie (Environmental Federation of North-Holland) opposed the local authority’s decision to allow UNA to co-fire sewage sludge. The environmental group’s main argument was that co-firing sewage sludge in the Hemweg plant increased the total national mercury emissions by 4%. The environmental movement, together with the municipality of Amsterdam (located near the UNA plant) tried to stop UNA from co-

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34 EKC referred to this group of people as the Green Power Mafia.

35 Original text (in Dutch): Al 12 jaar lang voer ik de strijd tegen het impregneren van hout met wolmanzouten. Geheel Nederland staat er intussen vol mee. Het wordt gebruikt voor tuinhuisjes, tuinschuttingen, pergola’s, kinderspeeltoestellen, picknicktafels, houten skeletwoningen, schuren, balklagen, raamkozijnen, oeverbeschoevingen, etc. Gewolmaniseerd hout bevat zeer hoge concentraties aan ‘arseenzuur’ en ‘chromium trioxide’. Dit zijn extreem gevaarlijke kankerverwekkende stoffen die ook de vruchtbaarheid van man en vrouw aantasten en genetische afwijkingen in het nageslacht veroorzaken. Na duizenden briefwisselingen met de landelijke en lokale overheden, na oeverloze besprekingen met leden van de Tweede Kamer, provinciale staten en gemeenteraden in samenhang met het voeren van honderden juridische geschillen staat voor mij vast dat er van onafhankelijke rechtspraak in Nederland geen sprake meer is. Er is sprake van een dictatuur die voortvloeit uit belangenverstrengeling, onkunde, collusie, machtsmisbruik, corruptie e.d.

36 See website http://www.biomassa.polie.nl.
firing (Anonymous, 2001c). In 2004, there was still no jurisdiction on the case (Brand, 2004).

Environmental groups and residents living near the plants continued to resist co-firing experiments in the Netherlands. They succeeded, and constructing new plants continued to be a large problem in 2004.

**Conclusion**

Traditional regime actors dominate the development of the co-firing niche in the Netherlands. Initially, production companies cooperated with traditional research institutes to determine optimal process conditions, and with traditional technology suppliers to construct the necessary equipment. In the late 1990s, the composition of the network begins to change. The relationship between research institutes and production companies is frustrated, because production companies become more restricted in providing plant data. Research institutes intensify contacts within international networks to find clients and funding. The fact that traditional regime actors dominate the social network explains why there are only limited problems with technological optimisation and stabilisation. These networks can build upon a long history of cooperation, there is high alignment and much technical knowledge is available in these networks. Moreover, most technologies remain close to existing technological practices. The case of the gasifier is different, with more radical innovation within traditional networks; technological problems are much larger. The main problems, however, occur in the embedding of co-firing in the societal context. Environmental groups successfully resist biomass combustion in coal plants, because no clear regulatory framework exists. Nevertheless, after the implementation of a clear emissions framework, problems continue. In addition, a growing demand for biomass increasingly becomes a problem, because there is no clear and defined market for biomass. To conclude, the traditional social network is able to deal with technological difficulties, but lacks sufficient ability and experience to deal with the societal embedding of plants.

**4.2.3 Learning processes**

In the early 1990s, production companies mainly learned about technical issues related to co-firing. In particular, the companies learned about the process conditions for co-firing biomass; about environmental issues like ash quality; about coal mill patterns; about the thermal behaviour of the boiler. Experiments showed that direct co-firing was the most inexpensive option, but only feasible with limited amounts of biomass. To increase the amounts of

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37 Not all co-firing initiatives faced local opposition. The Amer plant was mentioned in the accusation made by the Ecological Knowledge Centre, but it managed to avoid long-term legal battles or large-scale public discussions. EPZ attributed this to early participation on the part of the environmental movement in the discussions on co-firing in the Amer plant, and to the fact that many of the neighbouring residents (used to) work at the Amer plant.
biomass, it was necessary to rebuild plants into indirect co-firing units. Rob Remmers (Essent) argued as follows in 2002:

The current activity, constructing storage and transport capacity, separate burners and millers for the biomass actually started when we saw that the capacity of directly co-firing biomass with coal is extremely limited. The reason is that the existing coal mills can only handle a limited percentage of other substances (Remmers, 2002).38

The quotation illustrates the general conclusion drawn from direct co-firing experiments in the late 1990s. Direct co-firing was possible with small amounts of biomass, but for larger amounts power plants had to be adjusted. Problems with the gasifier in the Amer plant showed that co-firing with thermal pre-processing was also very difficult. In 2003, Amergas argued that further expansion of biomass combustion would definitely occur in the future, but not with a gasifier. Their strategy shifted towards indirect co-firing and combustion in circulating bed reactors (Voorter, 2003:4). The main lesson from the experiments in the Netherlands was that indirect co-firing was the most promising option to co-fire biomass and coal.

The participation of Dutch actors in international research networks contributed to the formulation of technical guidelines and principles. In 1992 the European Commission launched an international research programme on co-firing (APAS). Researchers, industries and universities investigated technical issues related to co-firing biomass and waste, and in particular wood, straw and sewage sludge.39 The researchers summarised many technological lessons and rules in the final report (Table 4.8).

38 Original text (Dutch): De huidige activiteit, het bouwen van opslag- en transport capaciteit, separate branders en molens voor de biomassa, is eigenlijk ontstaan op het moment dat we zagen dat de capaciteit om bij te mengen met de kolen heel beperkt is. De reden hiervoor is dat de kolenmolen maar een beperkt percentage vreemde stof kan verwerken.

39 The main areas considered in the project were: (a) best suitable fuel preparation and feed, and the subsequent effects of the combustion process, (b) full fuel utilization – complete burnout – under minimization of envisaged operational problems like fouling, slagging and corrosion, (c) emissions and control of gaseous species and solid by-products (ashes), (d) scale considerations and scale-up criteria for industrial/utility application including retrofit aspects, (e) large-scale demonstration and the determination of special fuel/process dependent requirements and restrictions, and (f) economics, also in relation to single fuel firing systems (Hein and Bemtgen, 1998:161).
<table>
<thead>
<tr>
<th>Topic</th>
<th>Lesson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel characterization</td>
<td>Biomass offers important advantages due to high volatility of the fuel and high reactivity of both the fuel and resulting char.</td>
</tr>
<tr>
<td></td>
<td>Generally the sulphur content of biomass is lower than that of coal, while sewage sludge generally has a higher content.</td>
</tr>
<tr>
<td></td>
<td>Biomass is much less carbon and more oxygen and as a consequence has a low heating value.</td>
</tr>
<tr>
<td></td>
<td>Chlorine contents of certain biofuels, like straw, can exceed the level of coal.</td>
</tr>
<tr>
<td></td>
<td>Ash contents of biomass are generally much lower than those of coal, while sewage sludge can have a very high ash content.</td>
</tr>
<tr>
<td>Fuel Preparation</td>
<td>In general bituminous coal mills are not suitable for biomass. Therefore, biomass co-combustion requires separate milling and feeding devices.</td>
</tr>
<tr>
<td></td>
<td>The optimum particle size for straw and miscanthus ranged between 4-8 mm in diameter and 1-2 cm in length on a pilot scale, while for large-scale tests a length of 20 cm was sufficient. Wood has to be milled to less than 1 mm.</td>
</tr>
<tr>
<td>Co-firing of biomass</td>
<td>Ignition of the fuel does not cause any problems because of the high volatile content of biomass, compared with coal, favours a rapid ignition. Generally combustion of biomass is complete (no burnout).</td>
</tr>
<tr>
<td>in pulverized fuel mode</td>
<td>Entering the fuel with the central gun on the inside results in low NO\textsubscript{x} emissions. Fuel added through the annular clearance leads to increased conversion to NO\textsubscript{x}. Therefore, the fuel with a higher N-content should be injected at the centre.</td>
</tr>
<tr>
<td></td>
<td>With an increasing biomass share, the NO\textsubscript{x} emissions decrease in all burner arrangements.</td>
</tr>
<tr>
<td></td>
<td>In re-burning, biomass as reduction fuel is superior to bituminous coal with regard to both emissions and burnout.</td>
</tr>
<tr>
<td></td>
<td>Generally, SO\textsubscript{2} emissions decrease by an increasing percentage of biomass because the added fuel’s sulphur content is low.</td>
</tr>
<tr>
<td></td>
<td>Chlorine (e.g. in straw) is problematic because of corrosion in the boiler.</td>
</tr>
<tr>
<td>Co-firing of sewage sludge</td>
<td>In general, co-firing sewage sludge has a sufficiently high burnout and low CO emissions.</td>
</tr>
<tr>
<td>in pulverized fuel mode</td>
<td>NO\textsubscript{x} emission levels are extremely sensitive (with respect to the co-firing ration, injection mode, primary and re-burn zone, stoichiometry and flame ignition).</td>
</tr>
<tr>
<td></td>
<td>SO\textsubscript{2} emissions are strongly related to the fuel-S input and are lower compared with biomass co-firing.</td>
</tr>
<tr>
<td></td>
<td>Heavy metal emissions remain within the limits of legislation.</td>
</tr>
</tbody>
</table>

The participants concluded that combusting wood, straw and sewage sludge was technically feasible, provided that a fuel-dependent feed and preparation system was installed. They also concluded that no major changes in normal plant operation (e.g. emissions, fuel conversion) were expected. Tasks 19 and 32 of the IEA Bioenergy programme followed up the APAS programme. In 2000, the European Commission published a brochure on the constraints
concerning replication of co-firing demonstration plants (the data was based on the work in Task 19). The programmes contributed to a much more detailed insight into technological barriers and how to deal with them (see Tables 4.12, 4.13, 4.14, and 4.15, in Appendix 4.1). The conclusion from the programme was that although some technical problems had not been solved sufficiently (foremost were problems related to corrosion), most technical problems that had occurred in the past had been solved partially or completely. The researchers from Task 19 and Task 32 concluded the same, two years later, in a handbook on biomass and co-firing. They stated as follows:

> Overall, [..], it is clear that progress in this area over the past 5-10 years has been very encouraging. A number of the more important technical options for the co-utilisation of biomass materials have been successfully demonstrated, and are in a position to be replicated elsewhere (Loo and Koppejan, 2002:187).

The experiments and research programmes contributed to stabilisation in technological designs and yielded heuristics about dealing with technological problems. Most obstacles facing the diffusion of co-firing technologies were non-technical in nature. The researchers from Task 19 and Task 32 argued thus:

> The barriers to replication are essentially non-technical (Loo and Koppejan, 2002:187).

The European Commission shared this conclusion in a publication, and gave an extended list of possible non-technical barriers to co-firing. The international research project did not result in general guiding principles for dealing with the non-technical issues. Dutch actors succeeded in dealing with some of them, with an emphasis on discussing existing emission standards. Standards for the reuse of ashes were also in the process of revision, in order to enable residues of co-firing in cement production (Loo, Babu and Baxter, 2000). Another example of attempts to deal with the problems was a research project – carried out by Essent and Utrecht University – on learning about sustainability standards for the large scale import of biomass. Essent organised workshops and set up a website for discussing and questioning

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40 First, fuel handling and logistics were problematic, in particular for large installations, because of a lack of experience with fuel handling, logistics, sampling, and trading. In particular the different company cultures of traditional biomass traders and the power companies caused problems. Second, cost cutting through staff reduction created problems, because co-firing installations required more operating staff than fossil fired power plants. Third, fly-ash marketability was problematic, because the existing building material standards restricted the use of fly ash to that of coal only. Fourth, long-term government support was uncertain compared to the long lifetime of the plants. Fifth, existing emission standards caused problems because of a lack of a level playing field between technologies and between regions; local authorities could enact different emission limits. Sixth, obtaining local permits was problematic due to local resistance from neighbouring residents or local authorities. Seventh, fuel acceptance criteria were often unclear and could result in high sampling and analysis costs. Finally, the immature biomass market created barriers for co-firing because the financial feasibility was heavily influenced by instability in biomass prices and insecure supply (European Commission, 2000:7).
the sustainability of biomass in general, and the large scale import of biomass for co-firing in particular (Damen and Faaij, 2003; Faaij, Minnesma and Wieczorek, 2003).  

However, the main lesson was that the societal embedding of co-firing projects remained problematic and required steady effort. The project manager of the EPON plant argued as follows:

Although co-combustion itself is not new, the request for permits and the environmental impact studies on this technology are. In this way, the process is lengthy, but we are learning a lot, which speeds up future requests for permits and environmental impact studies. The costs for permits and environmental impact studies may vary between about 100,000 and 250,000 euro. The costs will be especially high when laws and regulations are not clear, when life cycle analyses have to be made and when know-how is limited […]. The time needed from the start of the environmental impact study to the reception of the permits will be between 1 and 3 years […]. It is strongly advised to agree in advance with the civil servants involved on the main goals and issues of the project, the environmental impact study and the permits. It is also strongly advised to establish a good working relation with the civil servants involved. This not only speeds up the process but also enhances the quality of the project, at least to our experiences. Besides, the process for obtaining permits becomes more agreeable to all parties involved (Novem and TNO-Mep, 2000:22).

Furthermore, the experiences at the EPON plant resulted in explicit ideas about laws and regulation in general:

EPON feels that a level playing field is important in a liberalised and competitive market. With this many laws and regulations concerning emissions, EPON feels that the civil servants expect companies like EPON to be a better Catholic than the pope himself! Besides, even lawyers specialised in this subject discuss about the right interpretation and execution of the laws and regulations (Novem and TNO-Mep, 2000:23).

The Dutch actors learned that the societal embedding of co-firing plants remained the most important barrier after 2000, but this realization was not able to prevent the issue from continuing to be a large problem despite several attempts to deal with it.

**Conclusion**

Actors in the co-firing niche generally learned about technological issues in the beginning. Dutch experiments contributed to stabilisation at the niche level, through the participation of Dutch actors in international research networks. Within these networks, technological lessons contributed to stabilisation in technical designs and heuristics. The most important lesson, however, was that non-technical issues prevented the quick replication or diffusion of co-firing experiments elsewhere. Despite these lessons, the problems could not be solved easily. Dutch actors did learn about the requirements for societal embedding, primarily from the

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41 See website [http://www.verantwoordgroen.nl](http://www.verantwoordgroen.nl)
opposition of local interest groups. These lessons can be identified as second-order learning lessons, because they resulted in a more reflective attitude towards emissions in biomass combustion and towards the sustainability of import. In general actors learned and dealt with technical problems, in contrast to their inability to solve societal embedding problems effectively.

### 4.3 Interaction between niche processes

I have divided the development of co-firing technologies into three periods. In Table 4.9 I have combined the previous analysis on niche processes per period to explain the niche development. I conclude that, in general, the niche processes were of high quality, with one of the reasons being that co-firing developed within established networks, which enabled actors to build upon established relations and use existing knowledge. Although this resulted mostly in incremental niche formation, the gasifier project shows that more radical options were also considered within these networks. In general, niche actors (research institutes, power companies) were able to learn from experiments and to compare these experiments in an international context, which enabled them to develop specific rules of thumb and design specifications for new plants. In addition, the fact that the niche actors were able to discuss emission standards with the public authorities enabled a rapid increase in market share. However, the development of the co-firing niche is complicated by regime dynamics, as I will show in sections 4.5 and 4.6.
Table 4.9. Main characteristics of niche processes in the case of co-firing in the Netherlands

<table>
<thead>
<tr>
<th>Period</th>
<th>Main characteristics of niche processes</th>
<th>Results in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993-1995</td>
<td>Waste producers increasingly have problems removing organic waste, and they cooperate with energy companies to co-fire the waste in power plants. Energy companies expect to reduce fuel costs, but their vision is that waste combustion should not affect normal plant operation. The experiments are successful, because they remain close to the power companies’ existing practices, and power companies can use established relations (research, technology suppliers) from the past. The companies mainly learn about (changes in) the process conditions of the power plants and how to handle the (limited) changes. The Ministry of the Environment solves initial regulatory problems ad-hoc, by implementing a new guiding rule based on a combination of existing rules.</td>
<td>Successful experiments with minor adjustments to existing practices in energy generation</td>
</tr>
<tr>
<td>1996-2000</td>
<td>Successful experiments stimulate power companies to continue co-firing on a permanent basis. A new vision on waste as a renewable energy source emerges in the co-firing niche, supported by the companies because it increases the income from waste combustion. Visions and expectations about being green and green energy markets stimulate the companies to increase the amount of biomass and to implement permanent equipment. The participation of research institutes and energy companies in international networks results in the increasing stabilisation of technological designs and technological problem solving. Actors that have not participated in the niche (environmental organisations, neighbouring residents) are able to frustrate the granting of permits on the basis of the unclear emission framework. This stimulates energy companies and policy makers to compare experiences from different locations, in particular the emission standards.</td>
<td>Construction of permanent co-firing plants with limited technological problems, but problematic embedding in existing frameworks for emissions</td>
</tr>
<tr>
<td>2001-2003</td>
<td>The coal covenant creates high expectations about the future application of co-firing, and is accompanied by further emission stabilisation frameworks. Energy companies increase their activities. The companies can build upon their previous experiences with co-firing, but need much more biomass and advanced technologies to combust the large amounts. The companies import biomass and investigate gasification and pyrolysis technologies. The construction of new plants remains problematic because of societal resistance.</td>
<td>Large increase in amounts of (imported) biomass in existing co-firing units</td>
</tr>
</tbody>
</table>
The analysis provides insight into some of the puzzles I mentioned in section 4.1.3. The main puzzle was how to understand the quick growth of co-firing within a limited period of time. From the analyses I conclude that several factors were important. First, the niche developed within existing social networks and close to existing practices, resulting in limited (technological) problems and the quick emergence of stabilised designs for co-firing plants, as well as heuristics for problem solving. Furthermore, the technological and economic risks associated with co-firing were limited. Dutch research institutes' and energy companies’ participation in international networks contributed to rapid stabilisation in the co-firing niche. Another explanation for the rapid development of co-firing lies in the changing visions and expectations – i.e. that energy companies increasingly recognised co-firing as a technology with different purposes: to reduce fuel costs (waste processing), to gain financially from funds for renewable energy sources, and to reduce carbon dioxide emissions. However, as I mentioned, for this to happen these purposes were linked to several niche-external dynamics, in particular the emergence of a green market and the dynamics in waste policies. A further investigation of these issues is therefore necessary (see next section).

The second question centred on why production companies began to co-fire in the first place. The reduction of fuel expenditures was one reason, but this incentive was not strong enough to prompt risking normal operation in large coal plants. The UNA company, for example, experimented with co-firing sewage sludge in a coal plant that was only one year old. The analysis of niche processes does not provide a sufficient answer to this question and I will address it again after the regime analysis.

The third question was why it was so difficult to get a permit for a co-firing unit. The niche analysis only reveals part of the answer. When the co-firing experiments began, there was no clear emission framework, and the Ministry of the Environment implemented a temporary framework on the basis of existing emission rules from the waste and electricity regime. Yet this framework was not enough to clear up the problems, because it allowed provinces to define their own emission standards based on existing standards from the waste and electricity regime. The lack of clarity in the emission framework enabled environmental groups and neighbouring residents to effectively resist the co-firing experiments. The Ministry of the Environment tried to solve the problems by publishing a national emission framework for co-firing in 2002, but the problems of acquiring a permit continued. Other factors were also important. I already hinted at unclear definitions for biomass and waste and I will continue to investigate this factor in the regime analysis.

The fourth question was why no new thermal pre-processing plants were implemented after 2000, despite the existence of several plans. One explanation lies in the internal niche processes. The experiences with indirect co-firing were positive, and energy companies learned that they could still increase the amount of biomass with this option. Negative experiments with the gasifier emphasised the problems associated with this type of technology, resulting in less support for this option among energy companies. However, other
factors related to the liberalisation process were also at stake after 2000. I will discuss them in the regime analysis.

4.4 Dutch regime dynamics

4.4.1 Competition and environmental considerations (1993-1995)

Electricity regime
In the early 1990s, the electricity regime was in the process of changing (see also Chapter 3). The Dutch government had implemented a new electricity law in 1989 to regulate the separation of electricity production and distribution. Energy companies had anticipated the law and they had begun merging in the late 1980s. In 1986, production company EPON was established, EPZ in 1987, UNA in 1988 and EZH in 1990. The number of distribution companies decreased from sixty-nine in 1985 to forty-three in 1990. The four production companies cooperated in the SEP, the institution that controlled electricity production, transport and import in the Netherlands and was involved in planning new power plants. Distribution companies cooperated with gas companies in EnergieNed. Another institution was the KEMA, responsible for research and development in the electricity sector. The new law stimulated reorganisations and takeovers and allowed distribution companies to establish decentralised production units, independently or in collaboration with industries. Decentralised power production increased rapidly, from 2,060 GWh in 1989 to 8,505 GWh in 1995, an increase from 2.8% to 9.9% in total final electricity demand in the Netherlands (Arnhemse Instellingen van de Electriciteitsbedrijven, 1970-1998). This resulted in decreased stability in the electricity regime, in particular because of the risk of overcapacity. In a joint publication put out by the SEP and EnergieNed, the institutions decided on a standstill in CHP construction. A large number of projects were discontinued or postponed. Several existing units were taken out of operation (ECN, 1996). The competition with distribution companies encouraged production companies to search for more competitive ways of energy generation.

In a 1993 publication, they acknowledged that competition within Europe was inevitable in the future and that it would determine most dynamics in electricity generation until 2000 (Anderson Consulting, 1993).

Increasing attention for the environmental consequences of energy generation also stimulated changes. Under Dutch governmental pressure, production companies had searched for ways to improve the environmental efficiencies of power plants. SEP and KEMA had investigated and implemented technologies to reduce emissions of sulphur dioxide and nitrogen oxides in the 1980s. Furthermore, SEP decided to construct an experimental coal-gasifier in 1988. They expected this plant to produce energy more efficiently than traditional

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42 EZH existed for a longer time, but in 1990 two other companies merged with EPZ.
coalfired in the Netherlands coalfired plants, with lower emissions (Arnhemse Instellingen, 1970-1998). Environmental efficiency became a more generally accepted argument in the construction of new power plants in the late 1980s. The emerging attention for carbon dioxide emissions and climate change also began emphasising the necessity for more focus on environmental issues in electricity production. A number of national and international publications in the late 1980s comprised a discussion on sustainable development. The prevention of climate change fit into this discussion and more firmly emphasised the use of fuels that could reduce carbon dioxide emissions, such as biomass and waste.

Waste regime
The increasing attention for waste combustion in the electricity regime was accompanied and influenced by changes in the Dutch waste regime. Until the late 1960s, the Dutch waste regime had been decentralised with limited regulations from the national government. Local and regional public authorities dominated waste processing supervision. The standards for air and water emissions were low and little purification technology was applied. This situation began to change in the late 1960s. An emerging environmental movement and mounting evidence of pollution from uncontrolled waste dumping prompted the government to introduce several new environmental laws. Especially strict regulations were introduced for dumping waste (1980, 1985) and for waste incinerator emissions (1985, 1989), both provoked by large environmental scandals. The strictest guidelines in the world were introduced and most incinerators were completely renovated, while some had to close. The developments stimulated a process of reorganisation in the waste sector. Both local public authorities (municipalities, provinces) and waste processing companies established institutes for consultation and planning. The Dutch government implemented a research programme called the National Research Programme for Reusing Waste (NOH) in 1984. The aim of the programme was to take an integral approach to waste management by taking into account environmental issues in the whole chain, from production of goods to end-use, including waste processing. This fitted a more general guiding principle that had emerged in waste regime in the 1980s, namely the ranking of different waste processing methods. Preventing the production of waste was most preferable, followed by recycling and waste incineration. Dumping in landfill sites was least preferable. In practice, the NOH programme focused on

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44 This part is based on Raven and Verbong (forthcoming) and Raven and Verbong (2001).
45 Most Dutch municipalities owned their own landfill sites; about three-quarters of all solid waste was dumped on landfills. There were also ten incineration plants, which reduced urban waste via combustion.
46 The Waste Management Council (Afval Overleg Organisatie, AOO) and the Dutch Waste Processing Association (Vereniging van Afval Verwerkers, VVAV), respectively.
47 In Dutch: Nationaal Onderzoeksprogramma Hergebruik van Afvalstoffen (NOH).
technologies that could process the waste at the end of the chain – in particular waste incineration – but later the focus shifted towards waste prevention and recycling.

From the NOH emerged another research programme in 1989, called ‘Energy from Waste and Biomass’ (EWAB). This programme, established by the Dutch Ministry of Economic Affairs, was part of renewed attention for energy savings in the electricity regime. The Ministry aimed to stimulate the use of waste and biomass as an energy source such that it would result in a maximum reduction of fossil fuel usage, but without changing existing waste policies and practices. To align the programme with the NOH programme, it was decided that all projects related to energy generation were to fall under the EWAB programme, while projects related to recycling and prevention were to fall under the NOH programme. In 1990, the EWAB programme was followed by the first 1990 policy document on energy savings. In the policy paper, the Ministry aimed for a total saving of 150 PJ of fossil fuels in 2000; two-thirds was to be realised with chain management and energy generation from waste and biomass. With this policy, the Ministry aimed at saving energy by optimising the existing waste processing infrastructure, and in particular by increasing the efficiencies of waste incinerators. This resulted in increased energy generation in waste incinerators, from 4 PJ in 1985 to 7 PJ in 1990 (Raven and Verbong, 2001; Novem, 1993; Novem, 1997).

In 1993, the Ministry of Economic Affairs published a second policy document on energy savings (Ministry of Economic Affairs, 1993). The basic assumptions were similar to those in the first policy document, but with one major difference. The Ministry now also stimulated the combustion of specific waste streams outside the established infrastructure for waste processing. A major contribution was expected to come from waste wood (10 PJ), as was well illustrated in the overview report of the EWAB programme for 1993: the first research line was waste incineration, but the second research lines aimed to investigate alternatives to waste incineration like combustion, co-firing and gasification of specific waste streams. An important reason for stimulating separate waste combustion was the expectation of higher efficiencies compared to traditional combustion in waste incinerators. Energy companies were particularly eager to investigate the options; production companies were thus offered a way of improving coal plants’ economic and environmental efficiencies.

**Conclusion**

Competition with distribution companies and the emerging notion of sustainable development and climate change protection created limited instability and triggered interest in waste combustion on the part of production companies. The companies became interested in ways to reduce fuel costs and further improve the environmental efficiency of power production. The combustion of organic waste streams fitted both conditions. Developments in the waste regime (in particular in waste policy) increasingly emphasised the need for higher energy

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48 In Dutch: Energiewinning uit Afval en Biomassa (EWAB).
49 This includes energy generation from the non-organic part of the waste.
generation efficiency from waste. The Ministry of Economic Affairs supported the investigation of specific waste streams outside the existing waste infrastructure. These policies created overlap between the waste and electricity regimes (in terms of fuels, research, regulations) and provided the basis for the co-firing experiments of the early 1990s.

4.4.2 Full competition and increasing overlap between energy and waste (1996-2000)

**Electricity regime**

The second half of the 1990s was characterised by the implementation of full competition in the electricity sector. The problems with overcapacity in the early 1990s had shown the inconsistency between centralised planning on the one hand and competition in production on the other. Moreover, the European Union was moving towards liberalising traditional utility sectors like mail delivery and telecom, but also energy generation and supply. The Dutch situation, in which electricity production and distribution were still highly restricted, could not be sustained in the 1990s. In 1995, the Dutch Ministry of Economic Affairs published the third policy plan on energy. The government formulated policies to transform the electricity and the gas market in liberalised markets – to transform the markets into demand-driven markets. The end-users would determine the amount and type of electricity produced, not the production companies. Any company was to be able to produce, supply, import and export energy. The Ministry also emphasised the need for renewable energy sources in the policy plan. The most important instrument was the tax exemption for electricity from renewable sources (REB). The REB exemption and the development of green electricity concepts created a large market for renewable electricity in the Netherlands between 1996-2000, and stimulated energy companies to expand renewable energy production (see section 3.4.3). This market formed a strong motivation for power companies to intensify their co-firing activities. The emerging market changed their expectations about the future sale of renewable energy in the Dutch market.

The process of liberalisation was accompanied by managerial reorganisations in the electricity regime. The number of distribution companies decreased from forty-three in 1990 to twenty-one in 1998. In 1999, five of these companies supplied electricity for up to 80% of the domestic market.\(^{50}\) The enactment of a new electricity law in 1998 resulted in more change and instability in the electricity regime. The law removed the distinction between distribution and production companies; production, supply and demand of electricity was liberalised in several phases in the following years. New institutions were established (TenneT, DtE) to guarantee equal access to the national transport network.\(^{51}\) Former distribution companies (Essent, Nuon) began to dominate electricity production, through

\(^{50}\) These companies were: Nuon (36%), Essent (17%), Eneco (17%), Remu (7%), Delta (3%).

\(^{51}\) In Dutch: Dienst Uitvoering en Toezicht Energie (DtE). DtE supervises the Dutch energy sector; TenneT is the Dutch grid operator.
reorganisations, takeovers and mergers with former production companies. In addition, foreign companies (Electrabel, E.ON, Reliant) bought Dutch production facilities and tried to buy distribution companies as well. The (traditional) large power of provinces and some municipalities in the electricity regime decreased, due primarily to mergers.

Liberalisation in the electricity sector and institutional changes resulted in the emergence of a new type of energy company, with a much broader scope than electricity generation alone. Companies like Essent and Nuon tried to diversify their products by increasingly promoting renewable electricity as a product alongside traditional grey electricity. Diversification and marketing enabled the companies to distinguish their activities from other companies and to anticipate the demand-driven markets for electricity and natural gas. Vertical integration of energy production and supply in some companies brought ideas and visions about renewable energy into organisations that used to be strongly fossil fuel orientated (former production companies), enabling a more pro-active stance towards biomass combustion in coal-fired power plants.

The new type of energy companies also increased their activities in other utility sectors, including gas, water and media (cable), but also waste processing. Distribution companies had already participated in waste incineration since the early 1990s, but now the companies extended their activities to all parts of the waste chain, including collection, recycling and end-disposal. Particularly the distribution companies that later merged into Essent bought or participated in waste companies (ECN, 1998, Graffhorst, 2002). Foreign companies such as E.ON also focussed increasingly on the (Dutch and European) waste market (Lomme and Buist, 2001:24). By integrating waste processing with renewable energy generation, energy companies could differentiate their products (important in a competitive market), lower their business costs through synergetic effects and profit financially from renewable energy funds. Emergence of this new type of (multi-utility) energy company benefited the expansion of the co-firing niche, because waste combustion became one of the core activities of (some of the) energy companies.

Waste regime
Waste companies resisted energy companies’ invasion of the waste regime for reasons of competition, but supported the vision on waste as a renewable energy source. Waste incineration companies lobbied for tax exemptions from the renewable energy tax and receiving a production bonus for renewable energy generation. The national government also supported the vision that organic waste streams – including domestic waste, demolition wood and other specific streams – could be used for renewable energy generation. In 1997, the government agreed on an amendment which stipulated that 50% of the electricity produced in incineration plants could be considered renewable energy and therefore be exempted from energy taxes. In 1999, the government accepted a protocol for measuring the production of renewable energy in the Netherlands. It included the energy from organic waste in waste
incinerators as a renewable energy source. The protocol also defined energy generation from contaminated organic sources (e.g. demolition wood) as renewable (Ministry of Economic Affairs, 1999; Novem, 1999:28). The protocol enabled a detailed calculation of renewable energy generation in the Netherlands, but also legitimised the account of contaminated biomass in national renewable energy statistics.

In general, developments in the waste regime moved increasingly towards the removal of waste outside the traditional options of waste incineration and waste dumping. In 1995, the government enacted a ban on the dumping of organic waste in landfill sites, in order to stimulate energy generation from organic waste. In addition, in 1995 the Waste Management Council (AOO) published its second long-term waste policy plan for the 1995-2005 period, in which the council addressed the question of what kind of processing routes were best suited for specific waste streams. In the following years, the waste dumping decreased from 12,140 kton in 1994 to 7,100 kton in 1998, while incineration increased from 2,600 kton to 4,550 kton in the same period (Werkgroep Afvalregistratie, 1999). After 2000, the national government strengthened the focus on processing waste outside the traditional waste regime with the publication of a new policy plan on waste management (LAP).52

Conclusion
The liberalisation and privatisation processes in the electricity sector resulted in a new type of energy company, with a much broader view on products and markets. Furthermore, linkages between the electricity regime and waste regime increased further in terms of organisations, technologies and regulations and policies. On the one hand, this was the result of deliberate policies to merge waste processing and energy generation. On the other hand, it was the result of the energy companies’ diversification strategies. Combusting waste for renewable energy generation enabled waste companies to receive financial support from the government, enabled the government to meet targets on renewable energy generation, and enabled energy companies to diversify their products. These regime dynamics enabled and stimulated further orientation on and extension of the co-firing experiments in the Netherlands.

4.4.3 Uncertainty in innovation and biomass definitions (2001-2003)

Electricity regime and waste regime
The electricity regime as it existed after 2000 was very different from the electricity regime of the 1970s. The SEP, one of the dominant institutions in electricity generation, was discontinued in 2001. The role and core activities of energy companies were changing through vertical and horizontal integration. Owned by provinces and municipalities in the past, energy companies were now part of internationally operating companies. With the

52 The ‘Landelijk Afvalbeheer Plan’ (LAP) also focussed on liberalisation and internationalisation in the waste regime, a development pushed by the European integration of internal markets.
enactment of the two electricity laws in 1989 and 1998 and the ongoing liberalisation process in Europe, the regime was changing from a production-driven market to a demand-driven, international market. National and international agreements on climate protection and carbon dioxide reductions (Kyoto, coal covenant) were also increasingly affecting decision making in the electricity regime. Carbon dioxide emissions became the dominant criteria to assess the environmental efficiency of power plants, and regime actors were forced to deal with these emissions. The technological setting of electricity production was also in flux. After the electricity market was liberalised in 1998, the market share of central production units decreased from 60% to 50% in 2000, in particular due to the increasing import of electricity. The market share of decentralised production of electricity increased to 30% in 2000 (ECN, 2002).

These dynamics created high instability in the electricity regime after 2000. One of the consequences was uncertainty about different actors’ roles in the electricity regime, and in particular in the innovation processes. The liberalisation of energy markets resulted in increasing (international) competition, a stronger focus on cost reductions and a concentration process among R&D departments because of mergers and take-overs. A 2000 research project showed that private R&D expenditures were decreasing in the European energy sector. The R&D that was still carried out focussed on the short term, with a fast return on investment. Although the actors did not always consider this focus a problem, they observed that in areas with collective benefits, R&D expenditures were often too low. These areas included renewable energy technologies and efficiency improvements (Graaff et al., 2000). Energy companies began to postpone closure of power plants and focus more on short term survival in a liberalised market (Boonekamp et al., 2001:25). The role of KEMA as traditional R&D institute in the Dutch electricity regime was no longer self-evident. The KEMA became an internationally oriented consultancy company; it no longer acted as a natural institutional link between different energy companies, although cooperation still continued on the basis of contract research. The market orientation of energy companies and research institutes helps explain the increasing focus on indirect co-firing in the Netherlands despite earlier plans for more radical solutions (gasification, pyrolysis). Indirect co-firing enabled energy companies to make a fast return on their investments and still allowed large amounts of biomass co-firing. Research and investment in thermal pre-processing technologies like gasification did not fit the increasing emphasis on short term return on investments.

Instability was also the case in biomass and waste definitions, which were influenced by European developments. In the late 1990s, the European Commission worked on several guidelines related to the combustion of waste and biomass. In 2000, the European Commission enacted a directive for the combustion of waste and in 2001 a directive on the

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53 The decreasing share of centralised production did not result from closing power plants. Most of the new capacity brought online in the 1990s was decentralised capacity. The changes in the technological system thus mainly resulted from the construction of new capacity; the old system was still in place, but did not expand.
limitation of emissions from large combustion plants and a directive on the promotion of electricity produced from renewable energy sources (ECN, 2002). These directives were to become a part of the Dutch electricity regime. A key issue in the discussions towards the final directives was the definition of biomass. The Dutch government lobbied for a broad definition of biomass including organic household waste, demolition wood, manure and sewage sludge, similar to the definitions they already applied in the Netherlands. The lobby was successful – in the final versions of the directive, the European Commission indeed used a broad definition of biomass:

The biodegradable fraction of products, waste and residues from agriculture (including vegetable and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste (Directive 2001/77/EG, 2001).

The directives provided European legitimisation of the Dutch situation with respect to biomass combustion, and created clear rules for emissions from biomass combustion and waste incineration. However, the rules did not solve the problem of getting permits. In general, actors from the electricity and waste regime supported the definition and directives as did the government and Dutch research institutes. However, environmental groups did not support the definitions (Wijland, 2002). Although they supported energy generation from waste in general, several groups (EKC, Milieudefensie, World Nature Fund) contested the use of sources like demolition wood, sludge and manure for renewable energy generation. These organizations argued that several organic sources defined as biomass could still contain many contaminants. Moreover, unrestricted use of these sources complicated the focus on recycling for other purposes. Finally, they argued that the emission standards in the directives did not represent the state-of-the-art Dutch waste incinerators, and referred to general guiding principles in the waste regime, like the ALARA principle (As Low As Reasonable Achievable) and scientific methods like Life Cycle Analysis (LCA). Environmental groups continued to contest biomass plants (including co-firing units) on the basis of these considerations (guiding principles in the waste regime) and often succeeded in delaying or canceling the construction of plants. Another problem was that the biomass definition did not point out any specific organic streams that could be used for renewable energy generation. The Dutch government tried to solve the problems by discussing white and yellow lists for biomass and waste streams, but the lists were not yet complete at the time of this writing. The lack of an elaborated list of biomass sources, supported by all actors, continued to create uncertainty in local decision making, e.g. for granting permits and making investment decisions.
Conclusion
The electricity regime continued to change after 2000. Instability in regulations and definitions, the disintegration of former regime institutions (SEP), and the changing roles of energy companies and research institutes created uncertainty for actors investing in (radical) technological solutions. They developed a preference for more incremental solutions with a short term return on investment. Moreover, the overlap between the waste and electricity regimes continued to create uncertainty, due to limited support from the environmental movement and limited elaboration of the definitions for practical use.

4.5 Conclusions

In this section, I first discuss the remaining puzzles and questions and see how the regime analyses contribute to understanding them. Then I construct the niche development pattern in terms of protection and stabilisation. In the last part, I discuss niche-regime interaction.

Regime dynamics
Utilizing the regime analysis, I can now give a more detailed explanation of the puzzles that remained after the analysis of niche processes (section 4.3). The main puzzle was how energy from co-firing could grow more rapidly as compared to other renewable energy options. From the analysis of niche processes, I concluded that the technologies and the social network remained close to the existing regime, enabling rapid learning on technological issues. From the regime analysis, I conclude that not only niche processes enabled rapid growth, but also the ongoing changes in the electricity and waste regime. Energy from waste emerged as an important topic in both regimes already in the late 1980s, stimulated by waste and energy policies. Electricity and waste regime actors both supported the new policies, as production/processing costs were lower. Later, additional revenues from the renewable energy market became important. The co-firing niche grew rapidly, because it fitted problem definitions in two regimes: how to increase combustion efficiency in the waste regime and how to increase renewable energy generation in the electricity regime. The overlap between waste and electricity regime also explains the second puzzle, i.e. why production companies began to co-fire in the first place. Although they risked losing normal power plant operation, the combustion of waste in power plants was part of an emerging strategy on the part of energy companies (product diversification and horizontal integration). The third puzzle was related to the problems in obtaining permits for co-firing units. Part of the explanation comes from the niche analyses (emission frameworks), but the regime analysis provides an additional explanation. National and international discussions on the definitions of biomass and waste finally resulted in the formal definition of a European directive, but the definitions were not widely supported by environmental groups. Although the directives created formal rules regarding emissions and definitions, opponents continued to resist the definitions and
emission standards by referring to guiding principles from the waste regime (prevention and recycling has a higher priority than combustion, ALARA, etc.). The final puzzle was why no new thermal pre-processing plants were installed after 2000. One explanation was the negative results with the gasifier in the Netherlands, but more important was the process towards liberalisation at the regime level, putting more emphasis on short term, low-cost investments and creating instability in the relations between research institutes and energy companies.

Construction of niche patterns
In this section I construct the niche development patterns in terms of stabilisation and protection. I use these patterns in Chapter 7 to discuss the main factors in the emergence of market niches and the role of internal niche processes in the emergence of market niches.

Figure 4.4 shows the niche development trajectory of co-firing in the Netherlands. In the early 1990s, several energy companies experimented with (direct and indirect) co-firing. These niches remained close to existing practices, with limited uncertainty and actors who could rely on existing knowledge and practices for coal combustion. There was some protection from renewable energy funds, but the reasons for niche creation were mainly local opportunities from waste residues. These were dedicated market niches in the early 1990s, because of limited protection in terms of expectations and tax exemptions. The gasifier was an exception. When research started in the early 1990s, there was only limited stability in the gasification niche, and no similar experiments from which the actors could learn. Expectations about gasification in terms of efficiency and cleaner production were high, however, which protected the project from strong market selection. Around 1998, when construction of the gasifier started, knowledge from R&D studies and from experiences abroad (Lurgi) increased. At the same time, there was more protection, primarily in the form of governmental subsidies and tax exemptions. This was also the case for the direct and indirect co-firing initiatives. The expansion of co-firing activities was complicated by resistance from environmental groups and neighbouring residents, provoking a discussion on the emission standards for co-firing and the sustainability of biomass. Around 2003, most technological problems related to direct and indirect co-firing were solved and there were now detailed rules of thumb to overcome specific problems (resulting from the comparison of local practices in international research programmes). There was also more stabilisation and certainty in the societal aspects of co-firing (regulatory framework, biomass definitions and perceptions), but this did not solve all problems (difficulties in obtaining permits, societal resistance). Direct and indirect co-firing became protected market niches, due to stabilisation in technological designs as well as heuristics for problem solving. Thermal pre-processing remained a technological niche. Operation of the gasifier was still problematic and there was uncertainty about roles and relations in general in the energy sector’s innovation practices in, which complicated the (experimental) R&D process and the construction of new experimental
plants. Indirect co-firing began emerging as the dominant niche for dealing the reducing carbon dioxide emissions, producing renewable energy and processing waste. Table 4.10 gives an indication of the size of the co-firing niche.

![Diagram of niche development pattern for co-firing in the Netherlands]

**Table 4.10. Indication of niche size for co-firing in the Netherlands**

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity in all niches</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>21</td>
<td>34</td>
<td>64</td>
<td>90</td>
<td>177</td>
</tr>
<tr>
<td>Total installed capacity in the Netherlands (MWe)</td>
<td>20752</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of coal capacity</td>
<td>4170</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Niche-regime interaction**

The regime analysis showed that regime dynamics contribute greatly to understanding the outcome of niche development. In this section I will focus on the interaction between regime dynamics and niche development. I have summarised the main developments at the regime level in Table 4.11, including the effects of regime dynamics on niche development and the effects of niche development on regime dynamics. I conclude that regime dynamics resulted in...
in an increased co-firing niche in the early 1990s. In particular, ongoing policies for processing waste outside the waste regime and inside the electricity resulted in an expanding co-firing niche. Furthermore, the emergence of a new actor in the electricity regime, with a much broader scope than the incumbent energy companies, resulted in increased scale. These companies were interested in horizontal and vertical integration, and looked for market share outside the electricity regime. Nevertheless, after 2000 regime changes begin to complicate niche development. Liberalisation of the electricity regime was a major complication in expanding the co-firing niche, due to uncertainties about investment returns and changes in research networks and practices.

The first period is characterised by an increasing overlap between the electricity and waste regimes, particularly in terms of policies and research programmes. Moreover, a new electricity law introduced competition into the electricity regime, created a new actor and resulted in the rapid growth of decentralised electricity generation. These developments created instability in the electricity regime as well as a sense of urgency on the part of the production companies regarding investigation of more competitive ways of generating electricity. These companies began to develop a new vision on the electricity regime, based on competition. Furthermore, energy policies increasingly leaned towards energy generation from waste products, while at the same time waste policies changed towards stimulating waste combustion outside the established waste infrastructure. These trends resulted in local

Table 4.11. Niche-regime interaction: the Dutch co-firing case

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability in electricity regime decreases because of new regulations for competition, new actors (distribution companies), increasing decentralised production.</td>
<td>Introduction of full competition in the electricity regime and increasing support for renewable energy (green energy market). Emergence of new type of energy company also focused on waste processing. Horizontal and vertical integration in electricity sector.</td>
<td>High instability in electricity regime because of disintegrating social networks, changing regulations (green energy market, emission standards, definition of biomass), climate change policies.</td>
<td></td>
</tr>
<tr>
<td>Emerging focus in waste policies on waste processing outside the waste regime.</td>
<td>Waste regime actors recognise their potential as producers of green electricity, because of financial benefits.</td>
<td>Biomass definition and emission framework not aligned with general guiding principles in the waste regime (resistance from environmental groups)</td>
<td></td>
</tr>
<tr>
<td><strong>Effect of regime dynamics on niche development</strong></td>
<td>Local opportunities for waste combustion to increase economic (and environmental) performance of coal plants.</td>
<td>Shift in vision of waste as a renewable energy source. Increasing expectations about future potential of co-firing for renewable energy generation.</td>
<td>Preference for low-risk, low cost co-firing solutions. Continuation of problematic societal embedding.</td>
</tr>
<tr>
<td><strong>Effect of niche development on regime dynamics</strong></td>
<td>None</td>
<td>Problems with societal embedding contribute to formulation of new emission standards for power generation and waste combustion.</td>
<td>Indirect co-firing niche becomes embedded in electricity regime as dominant solution to climate change.</td>
</tr>
</tbody>
</table>
opportunities at the niche level. The experiments in the early 1990s did not yet affect the electricity regime.

In the second period, the previous developments continued, but were reinforced vertical and horizontal integration and an emerging market for green electricity. The emerging green energy markets increased expectations about the potential of co-firing, resulting in further expansion of co-firing activities. In the waste regime, actors recognised their potential as renewable energy producers and suppliers of biomass sources, while regulations and perceptions of waste combustion outside the waste regime were discussed and established (emission standards, sustainability of biomass combustion). The successful development of the co-firing niches (increasing size) was an important trigger for this discussion; niche actors discussed their problems connected with societal embedding of co-firing units.

In the third period, policies on climate change created produced a sense of urgency among electricity regime actors. The public policies forced electricity regime actors to increase the size of the co-firing niche and to search for more radical solutions than direct and indirect co-firing. However, the liberalisation process increasingly emphasised low-risk and low-cost investments and increased uncertainty about actors’ roles in the electricity regime, in particular with respect to innovation, affecting niche development and stimulating the choice for indirect co-firing. In addition, the overlap between the electricity and waste regimes complicates further expansion of the co-firing niche. Despite stabilisation in formal rules (definitions, emission standards), there is still uncertainty for local decision makers, because societal groups do not support the rules.
## Appendix 4.1

Table 4.12. Technical constraints of co-firing related to biomass feedstock pre-processing (European Commission, 2000:5)

<table>
<thead>
<tr>
<th>Technical constraint</th>
<th>How to overcome the constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-processing of the biomass:</strong></td>
<td></td>
</tr>
<tr>
<td>• No equipment and space at the power plant</td>
<td>• Buy specified biomass from certified suppliers</td>
</tr>
<tr>
<td>for pre-processing</td>
<td></td>
</tr>
<tr>
<td><strong>Receiving and handling of the biomass:</strong></td>
<td></td>
</tr>
<tr>
<td>• Emissions of dust, methane or odours</td>
<td>• Do the receiving indoor with an increase of air exchange</td>
</tr>
<tr>
<td></td>
<td>• Protect your workers and take precautions against fires and explosions</td>
</tr>
<tr>
<td><strong>Fuel quality assurance:</strong></td>
<td></td>
</tr>
<tr>
<td>• Determination and surveillance of the</td>
<td>• Use standardised, certified and regularly analysed biomass</td>
</tr>
<tr>
<td>quality of the received biofuels</td>
<td>• Undertake visual inspection and regular sampling and testing in your own or independent</td>
</tr>
<tr>
<td></td>
<td>laboratories</td>
</tr>
<tr>
<td></td>
<td>• Install screening equipment to control size distribution</td>
</tr>
<tr>
<td><strong>Storage:</strong></td>
<td></td>
</tr>
<tr>
<td>• Problems with bridging, risk of fires and</td>
<td>• Compress bulk biomass to pellets or briquettes</td>
</tr>
<tr>
<td>dust or methane induced explosions in the</td>
<td>• Install prevention measurements (water or nitrogen inertia)</td>
</tr>
<tr>
<td>silos</td>
<td></td>
</tr>
<tr>
<td><strong>Conditioning:</strong></td>
<td></td>
</tr>
<tr>
<td>• Increased wear of shredder and mills</td>
<td>• Use a stone and sand remover or trap and a metal separation system</td>
</tr>
<tr>
<td>• Risk of spark ignition, explosion and fire</td>
<td>• Install a security system with spark detection and water or nitrogen fire protection</td>
</tr>
<tr>
<td><strong>Conveying:</strong></td>
<td></td>
</tr>
<tr>
<td>• Problems with bridging, blockages,</td>
<td>• Mix fresh biomass with dried biomass material</td>
</tr>
<tr>
<td>stickiness and back slipping of frozen</td>
<td>• Screen the material to exclude oversized material which causes blockages</td>
</tr>
<tr>
<td>biomass</td>
<td>• Use proved belt and vertical conveyor systems or other reliable systems</td>
</tr>
<tr>
<td>• Emissions of odours, dust and dire,</td>
<td>• Cover the conveyor belts</td>
</tr>
<tr>
<td>methane</td>
<td>• Avoid long transportation distances and junctions</td>
</tr>
<tr>
<td><strong>Feeding:</strong></td>
<td></td>
</tr>
<tr>
<td>• Tightness or blocking of the (duplex</td>
<td>• Use reliable feeding systems</td>
</tr>
<tr>
<td>rotary) feeders</td>
<td>• Install more than one feeding point</td>
</tr>
<tr>
<td></td>
<td>• Find the optimum for the location feeding point</td>
</tr>
<tr>
<td></td>
<td>• Adjust the feeding rates</td>
</tr>
</tbody>
</table>
Table 4.13. Technical constraints of co-firing related to combustion system and process (European Commission, 2000:5)

<table>
<thead>
<tr>
<th>Technical constraints</th>
<th>How to overcome the constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boiler design:</strong></td>
<td></td>
</tr>
<tr>
<td>• The gas volumes are increasing and also the</td>
<td>• The increase is manageable by the existing boiler equipment if only a small amount (5 to 10%) of</td>
</tr>
<tr>
<td>water content in the gas</td>
<td>biomass is co-fired</td>
</tr>
<tr>
<td><strong>Boiler and burner behaviour:</strong></td>
<td></td>
</tr>
<tr>
<td>• Melted metals (e.g. zinc, aluminium) found on the grate</td>
<td>• Special material coating with protection and deflection materials</td>
</tr>
<tr>
<td>(if demolition wood is used as supplementary fuel)</td>
<td>• Add more feeding points to guarantee a good biofuel distribution</td>
</tr>
<tr>
<td>• High temperature chlorine induced boiler corrosion</td>
<td>• Change circulation patterns and increase the central velocity</td>
</tr>
<tr>
<td>due to reduced oxygen layer</td>
<td>• Increased need for soot blowing</td>
</tr>
<tr>
<td>• Sintering in the boiler due to hot spots in the freeboard</td>
<td>• Adjust the maintenance requirements</td>
</tr>
<tr>
<td>• Increased risk of slagging, fouling in the boiler</td>
<td></td>
</tr>
<tr>
<td>(walls)</td>
<td></td>
</tr>
<tr>
<td>• Increasing risk of erosion and deposits at the burner</td>
<td></td>
</tr>
<tr>
<td>**Burn-out problems due to the insufficient residence</td>
<td></td>
</tr>
<tr>
<td>time for fine biofuel particles:**</td>
<td></td>
</tr>
<tr>
<td>• In CFBC: Significant freeboard combustion and also final</td>
<td>• Reduce share of fine materials</td>
</tr>
<tr>
<td>combustion of fines and unburned gases in the hot</td>
<td></td>
</tr>
<tr>
<td>cyclone</td>
<td></td>
</tr>
<tr>
<td>• High temperature before the super heater due to the</td>
<td></td>
</tr>
<tr>
<td>content of fine materials</td>
<td></td>
</tr>
<tr>
<td>**High temperature corrosion induced by the presence of</td>
<td></td>
</tr>
<tr>
<td>chlorine on tube surfaces:**</td>
<td></td>
</tr>
<tr>
<td>• Surfaces of the heat exchanger (and air pre-</td>
<td>• Special coating with protection and deflection materials</td>
</tr>
<tr>
<td>heater), super-heater and economiser: Increase of</td>
<td>• Change materials, e.g. use martensitic and austenitic steels instead of ferritic steel</td>
</tr>
<tr>
<td>condensation, chlorine induced corrosion and deposits</td>
<td>• Additional installation of a steam heated air pre-heater</td>
</tr>
<tr>
<td>• Reduction of superheated steam production due to the</td>
<td>• Sonic blowers to remove slag deposits</td>
</tr>
<tr>
<td>lower CFB bed temperature</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.14. Technical constraints of co-firing related to the flue gas clean-up systems (European Commission, 2000:5)

<table>
<thead>
<tr>
<th>Technical constraint</th>
<th>How to overcome the constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flue gas path:</strong></td>
<td></td>
</tr>
<tr>
<td>• Flue gas volume and flue gas temperature are increasing</td>
<td>• Substitute lignite with coal</td>
</tr>
<tr>
<td><strong>Catalysts:</strong></td>
<td></td>
</tr>
<tr>
<td>• Accelerated ageing and deactivation of the (high and low dust) SCR catalysts due to the higher content of alkaline</td>
<td>• Use biofuel with lower content of alkalines</td>
</tr>
<tr>
<td>• Use biofuel with lower content of alkalines</td>
<td>• Regenerate the catalyst</td>
</tr>
<tr>
<td>• Use catalysts which can operate under these circumstances</td>
<td>• Remove the catalyst poisons in the flue gases</td>
</tr>
<tr>
<td><strong>Flue gas desulphurisation:</strong></td>
<td></td>
</tr>
<tr>
<td>• Controlled limestone addition for desulphurisation is difficult due to relatively great variations in the ash composition of biomass wastes (e.g. limestone, sulphur)</td>
<td>• Purchase more homogeneous biomass</td>
</tr>
<tr>
<td>• Purchase more homogeneous biomass</td>
<td>• Install more advanced desulphurisation control systems</td>
</tr>
<tr>
<td><strong>Emission limit values for heavy metals</strong></td>
<td></td>
</tr>
<tr>
<td>• Use only small amount (and/or clean or only slightly contaminated) of biofuels to be able to keep the limits of the new EU mixing rule</td>
<td>• Add additional flue gas cleaning unit if necessary</td>
</tr>
</tbody>
</table>

Table 4.15. Technical constraints of co-firing related to the usability of solid by-products and residues (European Commission, 2000:5)

<table>
<thead>
<tr>
<th>Technical constraint</th>
<th>How to overcome the constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ashes:</strong></td>
<td></td>
</tr>
<tr>
<td>• Increase of the bottom and fly ash volumes</td>
<td>• Adjust ash handling systems</td>
</tr>
<tr>
<td><strong>Composition and quality of the bottom and fly ashes and the gypsum:</strong></td>
<td></td>
</tr>
<tr>
<td>• Modified chemical, physical and mineralogical ash properties (e.g. highest content of unburned carbon and of alkaline)</td>
<td>• Adjust type and amount of biomass to ensure that the variations in ash properties are within the range of coal ash</td>
</tr>
<tr>
<td>• Limit the share of co-fired biomass in order to meet the quality requirements of the bottom and fly ashes (European Code EN 450 for fly ash use in concrete production)</td>
<td>• Limit the share of co-fired biomass in order to meet the quality requirements of the bottom and fly ashes (European Code EN 450 for fly ash use in concrete production)</td>
</tr>
<tr>
<td>• Reduce the content of alkaline and chlorine in the biomass</td>
<td>• Reduce the content of alkaline and chlorine in the biomass</td>
</tr>
<tr>
<td>• Use separate pre-gasification system to separate ashes</td>
<td>• Use separate pre-gasification system to separate ashes</td>
</tr>
<tr>
<td>• Increase the air supply at the burners or the residence time for the biomass particles in the boiler</td>
<td>• Increase the air supply at the burners or the residence time for the biomass particles in the boiler</td>
</tr>
<tr>
<td>• Regularly clean the economiser and air pre-heater, e.g. using soot blowers</td>
<td>• Regularly clean the economiser and air pre-heater, e.g. using soot blowers</td>
</tr>
</tbody>
</table>
Chapter 5.
Manure digestion in Denmark

5.1 Historical overview

5.1.1 Farm-scale plants (1973-1983)

The first oil crisis in 1973 set off many renewable energy projects in Denmark, including biogas plants. The farmer Anders Lassen constructed the first plant in the town of Voel, near Silkeborg. It was a very small plant, made of fibreglass for only 3,000 Danish Kroner (DKK, about 400 euros). He used the biogas for heating purposes on his own farm. In 1974, Hans Aage Jespersen built a second plant, in cooperation with a local blacksmith. The two plants were the first of many farm-scale plants in the 1970s and 1980s (Beuse et al., 2000:261, Elmose, 2002). Most farmers had no prior experience with manure digestion. They constructed the plants alone or in cooperation with local craftsmen, and several Danish Folke High Schools assisted the farmers. One of them was the Brandbjerg Folke High School, and particularly the Energy Group.¹ In a 1979 report they published detailed experiences and technical data about ten biogas plants (see Table 5.7, Appendix 5.1). The group also reported on a number of other experimental plants, as well as plants under construction or in the planning phase. These plants showed wide variety in designs, plant components or operational results (Energigruppen, 1979).

In an attempt to combine experiences, the Danish Ministry of Trade established the Cooperation for Technological Development of Biogas Plants (STUB) in 1978.² An employee of the Danish Technological Institute chaired the group.³ The group further existed of ten to twelve engineers and agricultural specialists. The Carls Bro engineering firm coordinated the activities, while the National Agricultural Economic Institute (JSI) was responsible for economic monitoring.⁴ The goal was ambitious: to develop advanced technologies for manure digestion, inspired by technologies from the Nordic countries, Thailand and the USA. The participants constructed three plants, financed by the Ministry of Trade with a DKK 3.6 million grant (about one-half million euros). In 1981 the programme was updated and the Ministry of Energy financed the programme with another DKK 3.2 million (Beuse et al., 2000:263, Groen, 1981:1).⁵ The three plants were erected in Gråsten,

¹ In Danish: Energigruppen
² Samarbejdsgruppen for Teknologisk Udvikling af Biogasanlæg (STUB)
³ Danish Technological Institute is a partly government financed research institute. Establishment dates back to 1906.
⁴ In Danish: Statens Jordbrugsøkonomiske Institut (JSI)
⁵ From the beginning farmers criticised the STUB programme. Their main argument was that the STUB researchers did not want to learn from the existing plants. The biogas plant at the Højbjerg Folke High School
Manure digestion in Denmark

Gadebjerggård and Assendrup (see Table 5.8, Appendix 5.1). Besides the three pilot plants, the STUB programme also monitored technical and economic performance of four existing biogas plants. A STUB service engineer visited the plants monthly to collect the information and to report analysis results back to the farmers. The results were also published in a magazine called *Biogas Nyt* (Groen, 1981:2-5).

The Gråsten plant was located at a training farm near the Gråsten Agricultural School, in southern Jutland. The design was based on a prefabricated concrete wall system, a common system used in agricultural buildings. A centrifugal pump fed the manure into a pre-heater. After eight hours the manure was pumped into the first reactor, while a similar volume flowed through a pipe to the second reactor. From the second reactor, the manure overflowed into a sludge storage tank. Total residence time was 20-30 days at a temperature of 30-35°C. In order to prevent a scum layer, the plant supplier installed time-controlled propellers in all tanks. The two flexible covers in the reactors, with a capacity of 160 m³, collected the biogas. A gas blower extracted the gas from the cover and transported it to two gas-fired boilers. The heat was used for maintaining the temperature inside the digester and for heating the agricultural school. Flow-switches, thermo-switches and timers automated the whole process (Groen, 1981).

The Gråsten plant faced several technical problems, mainly related to the gas system and the manure handling system. The supplier of the gas system claimed that the blower, originally designed for operation with town gas, met the specifications. However, the blower broke down several times and needed replacing. More problems occurred with the mixing system inside the digester. Straw prevented a continuous flow of manure. Replacing the system with a propeller system solved the problems. The main problem, however, was that the farmer had no experience with the process conditions. The biogas yields never met the expected yields in the first year (Groen, 1981).

A private farmer (a producer of bacon pigs) owned the Gadebjerggård plant, located in northern Jutland. He relied on common practice in agro-construction and several general standards, e.g. for gas installations. The system operated like the Gråsten plant at a temperature of 30-35°C and residence time was 20-30 days. The digester tank was not made of concrete, however, but fibreglass. Furthermore, the plant had only one reactor instead of two. The farmer experienced extraordinary problems with the plant. The supplier had neglected safety measures. The first accident with the plant occurred in 1977, shortly after the farmer had filled the plant with manure. The digester tank completely collapsed, causing a flow of 300 m³ manure over his yard. In 1980, a second accident happened when the floating cover for the gas storage flew off in a hurricane.

A foundation for the promotion of a Danish cattle race owned the third plant in Assendrup, seventy-five kilometres south of Copenhagen. This plant also operated at 30-35°C with a retention time of about 20-30 days. The digester consisted of two tanks made of reinforced concrete. Other design choices included a feeding system by means of a centrifugal

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6 Initially they installed a pump circulation system, but that failed to prevent the scum layer.

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pump, a heating system divided into three parts, a gas storage system based on flexible covers and an energy system based on a dual-fuel engine of 35 kWe.\footnote{A dual-fuel engine uses a small amount of diesel.} Despite some technical problems with the engine (a number of cylinder heads broke down), the plant operated satisfactorily. However, biogas yields only met half of the expected yields (Groen, 1981).

Generally, the STUB programme demonstrated that biogas technology was by no means trouble-free. An inventory among twenty-one Danish biogas plants in 1981 showed that all plants had encountered severe technical problems (see Table 5.9, Appendix 5.1). Five plants were completely out of operation without any plans for reinstatement. Three plants were not working, but the participants still searched for technical solutions. Four plants actually were in operation or in the start-up phase, but problems prevented stable operation. Finally, nine plants were more or less in stable operation. The prospects were not promising (Operations Analysis Centre, 1982).

### 5.1.2 Centralised plants (1984-1994)

In the mid-1980s, several Danish villages decided to establish centralised biogas plants. The North Jutland County Council implemented the ‘Village Energy Project’ (Danish Energy Agency, 1992:8). This project included the construction of four biogas plants throughout North Jutland (although only two were constructed), the first in Vester Hjermitslev in 1984. The objective was to demonstrate the autarky of the town regarding energy (Seadi, 2000:8, Danish Energy Agency, 1992:8). The Vester Hjermitslev Energy Association, an independent institution, owned the plant.\footnote{In Danish: Vester Hjermitslev Energiselskab} Its board of directors consisted of four members appointed by local inhabitants and three appointed by the directors of the local district heating company.\footnote{The ‘Vester Hjermitslev Heating’ company.}

The North Jutland County Council lent DKK 8.4 million (about 1.2 million euros) and the national government granted the remaining DKK 4 million (over one-half million euros).\footnote{The total costs of 12.4 million DKK (1.7 million euro) also included the costs for a wind turbine as well as a slurry storage tank.} The Krüger-Bigadan company, also involved in the construction of some of the farm-scale plants, supplied and constructed the plant.

The layout of the plant is presented in Figure 5.1. The manure from six farms was stored in a pre-storage tank, together with organic waste from a slaughterhouse. The mixture was pasteurised at 55°C for three days in a 200 m$^3$ tank (to prevent the spread of disease). Three 500 m$^3$ tanks digested the manure at 37°C. Fish offal could also be added into the digester. This so-called codigestion of manure with organic waste was invented at some of the farm-scale plants, but was never exploited on a large scale. In centralised biogas plants codigestion became more common. Adding a little amount of waste could double or even triple the biogas yields. A gas engine with generator combusted (part of) the biogas and produced heat for the local district heating system and for a heat pump; electricity was also produced and supplied to the grid. A gas furnace combusted the remaining part of the biogas. The digested manure...
Manure digestion in Denmark was stored in a storage tank and used as fertilizer on the supplying farmers’ fields (Danish Energy Agency, 1992:8, Haskoning, 1988:5).

![Diagram of biogas plant](image)

Figure 5.1. Process layout of the biogas plant in Vester Hjermitslev (Danish Energy Agency, 1992:8)

In 1985, the Vegger Energy Association commissioned the construction of the second centralised biogas plant. The design of the plant, the second in the ‘Village Energy Project’, was similar to the first plant, except that it operated at a thermophilic temperature of 55°C. An extra pasteurisation step could therefore be left out. The W.W. Engineering company supplied the plant. Experiences with both the Vester Hjermitslev and the Vegger plant were not very good; the plants had to be reconstructed several times, supported financially and politically by a special committee called the 'Styregruppe for Vedvarende Energi' (Committee for Renewable Energy). After reconstruction work, however, the plants operated satisfactorily. Throughout the 1990s, the Vegger plant was used for demonstration purposes, in particular for the demonstration of codigestion with organic household waste. The owners established a small laboratory to continuously analyse the digestion process (Danish Energy Agency, 1992:9).

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11 In Danish: Vegger Energiselskab
The Krüger-Bigadan company constructed the third centralised biogas plant in Skovsgård in 1986. The commissioner of the plant was an independent institution, with a board of directors comprised of seven members. The Skovsgård District Heating Station appointed three members, the District Council appointed one, and the ‘Society for Energy in Skovsgård’, a local citizens’ association, appointed another three. The original design (the plant was reconstructed in 1990) was similar to the original design of the Vester Hjermitslev plant (also supplied by Krüger-Bigadan). The plant processed forty tons of manure and an additional fifteen tons of industrial waste per day (Danish Energy Agency, 1992:10).

After 1986 a new type of ownership emerged in the Danish biogas niche. Farmers began to establish biogas plant cooperatives. The first plant for which farmers established a cooperative was the biogas plant in Davinde in 1987. Eleven farmers cooperated; six of them supplied the manure. The plant also combusted farmers’ straw in a boiler. The heat from this and the biogas-fired boiler was supplied to the local district heating network. The plant produced no electricity. The digested manure was stored in a central manure tank and used by the farmers for fertilizing. The plant produced high yields of biogas due to the addition of fish offal. Overall, the experiences were positive (Danish Energy Agency, 1992:11).

Between 1987 and 1992 five new centralised biogas plants were constructed (see Table 5.10, Appendix 5.1). All plants were constructed within the framework of a national Biogas Action Programme. This programme was a cooperation between three ministries, i.e. the Ministry of Energy, the Ministry of the Environment and the Ministry of Agriculture. The Biogas Action Programme focussed on the construction and monitoring of biogas plants, informational activities, and research and development work. Also included was an investment grant for centralised biogas plants with a maximum of 40% and a financing scheme with long term, low-interest loans (Danish Energy Agency, 1992:4; Danish Energy Agency, 1995:9). The five new and the four previously constructed plants were monitored for five years. The plants had different layouts technically as well as organisationally, allowing a comparison of the advantages (and disadvantages) of the concepts.

In Sinding, the municipality owned the plant (instead of a cooperation of farmers), but farmers formed an organisation for delivering manure. In 1993, the municipality equipped the plant with a trial unit for processing organic household waste. In Fangel, the Fangel Environment and Energy Association (a cooperative of twenty-eight farmers) owned the plant. The cooperative also established twenty-three decentralised storage tanks near the farmers’ fields, which it rented to the farmers. In Revninge, the Revninge Energy Association (a local consumer cooperative for energy supply) commissioned a centralised biogas plant with a gas mixer unit. This unit mixed natural gas with air so that it was degraded to the quality of biogas (60% methane and 40% carbon dioxide). A gas system then supplied the mixture of natural gas and biogas to the energy consumers. At the Ribe plant, farmers combined insights from previous plants into the largest centralised biogas plant of the time.

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12 In Danish: Skovsgård Energiforening
14 In Danish: Fangel Miljø- & Energiselskab
15 In Danish: Revninge Energiselskab
The owner of the plant, Ribe Biogas A/S, was a private organisation instead of a cooperative. In the Lintrup biogas plant, sixty-six farmers cooperated to establish a technologically advanced plant, including a pasteurisation tank at 70°C, and a ‘Reverse Osmosis’ unit for separation purposes. The pasteurisation tank enabled the farmers to process sewage sludge together with manure, and still use the digested substance as fertilizer. The Reverse Osmosis unit, installed to filter the degassed liquid manure into 40% concentrate and 60% clean water, never operated satisfactorily (Danish Energy Agency, 1992:12-16).

The first Biogas Action Programme ended in 1991. The cooperating ministries decided in March 1992 to continue the programme for another 2 years, from 1992 to 1994. The aims were to construct four biogas plants and monitor their technological and economic performance as well as environmental and agricultural aspects. The plants were located in Lemvig, Hodsager, Hashøj and Thorsø (see Table 5.11, Appendix 5.1). At the Lemvig plant, the supplier of the plant mainly used familiar technology from previous plants. However, he applied a new low pressure gas transport system to transport the gas to a nearby combined heat and power station. Furthermore, the owner of the plant, a cooperative of farmers, implemented a new feature called Operational Service Management Agreement. The cooperative agreed with the supplier of the plant, Burmeister & Wain Scandinavian Contractor (BWSC), that the latter was responsible for operation and maintenance for five years. At the plant in Hodsager, constructed in 1993, a system for analysing the composition of the manure (minerals, dry matter content) was installed. Farmers used the information to improve mineral dosing to the crops. The Hasjøj plant cooperative also implemented a service agreement with the supplier and provided farmers with detailed information on manure composition. The cooperative also experimented with the combined combustion of biogas and natural gas. The plant in Thørso combined insights from the previous plants. The plant was equipped with a low-pressure transmission pipe and a gas engine, which could combust natural gas, biogas or a mixture of both (Seadi, 2000:15-18).

Generally, plant operation improved, both economically and technically. However, all plants still depended on favourable economic conditions (investment grants, low-interest loans). The ministries involved decided to continue the programme after 1994. The focus shifted from technological optimisation (which could be left to the commercial sector) to social-economic functions, i.e. integrated waste treatment and the distribution and use of manure (Danish Energy Agency, 1995:32).

5.1.3 Organic household waste and farm-scale plants (1995-2003)

The number of plants increased by one or two plants per year as of the late 1980s. After 1994, eight new plants were constructed (see Table 5.12, Appendix 5.1). The plants were located in Århus Nord (1995), Filskov (1995), Studsgaard (1996), Blåbjerg (1996), Snertinge (1996), Blåhøj (1997), Vaarst/Fjellerad (1997) and Nysted (1998). A total of twenty centralised biogas plants were now in operation in Denmark (see Figure 5.2); only one plant was taken out of operation (Skovsgaard). In general, the techno-economic operation of these plants
improved over the years (Seadi, 2000). After 1998 no new plants were constructed in Denmark.

Two new developments occurred after 1995, i.e. digestion of organic household waste with manure and the reintroduction of farm-scale plants. In the early 1990s, some of the biogas plant cooperatives had experimented with the digestion of organic household waste (without manure). Within the Biogas Action Programme, four cooperatives installed systems to codigest organic household waste with manure, i.e. in Århus Nord, Studsgaard, Vaarst/Fjellerad and Nysted. The Herning Municipality took a leading position with the establishment of the biogas plant near Studsgaard. In 1993 the municipality implemented separation of waste in parts of the town and constructed a small-scale pilot plant for the treatment of the waste. In 1994, a full scale plant was constructed at the Sinding biogas plant and another was constructed in Studsgaard in 1996.

The plant in Studsgaard operated as follows. The municipality collected, supplied and pre-processed the waste in a plant called ‘Knudmoseværket’. The Knudmoseværket crushed the bags and separated the organic waste from the plastic. In Studsgaard (see Figure 5.3), a pasteurisation tank (70°C) destroyed pathogenic bacteria and infectious germs in a pre-sanitation tank. The waste was then mixed with liquid manure and digested at a temperature of 55°C for a period of sixteen days (digester 2). A separation process after digestion finalised the first process line. Another line processed manure, together with organic industrial waste (Caddet, 1998; Escobar and Heikkilä, 1999; Nedergaard and Ørtenblad, 1997).

The municipalities Elsinore and Helsingør experimented with the separation of household waste at home and the digestion of that waste, but the experiments were unsuccessful due to problems with the removal of plastics (Danish Energy Agency, 1992:18; Centre of Biomass Technology, 2000:39). Both plants used the same technological concept. For further information on the technologies used at Helsingør and Elsinore, see Danish Energy Agency (1992), Verma (2002) and Rise-AT (1998). The Municipality of Grindsted installed a third plant for the digestion of organic household waste in Grindsted in 1997. This plant only codigested sewage sludge with organic household waste after an early initiative with cooperation with farmers had failed (Bro, 2000).
In addition, the municipalities of Århus, Aalborg (near Vaarst and Fjellerad) and Nysted experimented with household waste. The process at the Århus Nord plant was divided into two flow-lines. The main line digested manure and industrial organic waste (38°C). The second line processed manure, household waste and several types of organic industrial waste (52°C). Both lines also applied pasteurisation to reduce the risk of disease. The digested biomass from both lines was stored in a silo until farmers used it as fertilizer (Seadi, 2000:19). The plant in Vaarst/Fjellerad combined manure, industrial waste, fatty waste and household waste digestion. Household waste and manure were digested in two separate lines. The line for household waste digested about 10-15 tons per day, collected from about 2,600 families in Aalborg. A machine called the ‘de-waster’, normally used for the industrial de-boning of fish and chicken, separated the plastic bags from the organic waste. The biomass from both lines was stored in a silo before being returned to the farmers’ fields (Caddet, 2000a). The cooperative in Nysted did not install equipment for processing the waste; they used pre-processed waste (Seadi, 2000:25). Most of the plants using household waste suffered from an unsatisfactory system for the separation of plastic bags. The digestion process does not affect plastic bags. If they are not separated from the waste, they end up on the fields, making the biomass unsuitable for fertilizing purposes (Centre for Biomass Technology, 2000:40).
The second development after 1994 was the reintroduction of farm-scale biogas plants. Three types of farm-scale plants were implemented. There were two types of a plant called the *Smedemester* (Blacksmith) biogas plant, developed by employees of the Folkecenter for Renewable Energy, and supported by the Committee for Renewable Energy. The first Smedemester plant was a horizontal steel tank with a capacity of 50-300 m$^3$, manufactured in industrial workshops (see Figure 5.4). The manure was added on one side of the digester, while a horizontal stirrer transported the manure slowly in about 15-25 days to the other side of the tank. The second Smedemester plant was a vertical steel tank built on-site in sizes of 400 m$^3$ and larger. For power production, the plant was equipped with an Otto-type motor, produced by the Valmet/Frichs, a German company. Later, these motors were replaced with dual-fuel engines. These engines use 5 to 15% diesel mixed with the biogas. The advantage of the engine was that it was economically attractive for smaller biogas plants and could easily be used for starting up the process. The Folkecenter also developed a computing programme for controlling the process and optimising biogas yields (Fisher and Krieg, 2000; Maegaard, 2000; Hjort-Gregersen, 1998; Köberle, 1988; Wellinger, 1997).

A third type of farm-scale biogas plant was developed by the Bigadan company during the 1970s and 1980s, and consisted of a low concrete digester inside a storage tank. When the digester was full, the manure could overflow into the storage tank. A membrane sealed on the...
storage tanker (either soft or hard) collected the biogas (Wellinger, 1997; Hjort-Gregersen, 1998).

These designs were at the basis of the development of farm-scale plants in Denmark in the early 1990s. Initially, the number of plants implemented increased slowly. However, in the mid-1990s the number of plants suddenly increased (see Figure 5.5).

![Figure 5.5. Increase in the number of farm-scale plants in Denmark (Elmose, 1997; Elmose, 2002)](image)

**Conclusion**

Danish niche development of biogas plants is a success compared to other countries in Europe. This is shown by the number of plants installed: twenty centralised biogas plants and over 35 farm-scale plants. Only Germany surpasses Denmark in the number of plants constructed.\(^1\) Nevertheless, the absolute amount of renewable energy production from biogas plants is still small compared to total Danish renewable energy production (see Figure 5.6). In total, the plants produced about 1.4 PJ per year (about 0.6% of total final energy use) and processed about 2-3% of the animal manure in Denmark Holm-Nielsen and Seadi, 2001:47; Birkmose, 2000:3; Andreasen, 2001:107).\(^2\)

\(^1\) The total number of plants in Germany exceeds 1500, but the number gives a distorted view regarding the processing capacity installed. The plants differ greatly in size. In Germany almost all plants are small-scale farm-plants, producing about 3.7 PJ per year in total (Holm-Nielsen and Seadi, 2001).

\(^2\) Data on energy production is from 2000 and counts the biogas production from 20 centralised plants (1.3 PJ) and 25 farm-scale plants (0.1 PJ). Date on the amount of manure is from 2000 and only counts the manure processed in the centralised plants.
Several puzzles and questions emerge from the historical overview. The main puzzle is: why was the introduction of manure digestion plants successful in Denmark? Though other European countries also investigated manure digestion, Denmark was one of the few countries that were able to implement a sufficient number of plants. How can we understand this? Second: why did farmers suddenly become interested in participating in the organisation of centralised plants after 1985? Before 1985, the farmers did not participate in biogas plant organisations. The third question is: why did the development of centralised biogas plants stop after 1998? This is striking, since plant operation was steadily improving. Fourth: what were the reasons for the emergence of two new niches after 1994? The final question is: how could the number of farm-scale plants increase so quickly after 1994? In the following section I will try to answer these questions through analysis of the niche processes. In section 5.4 I discuss the influence of regime dynamics.

5.2 Analysis of niche dynamics

5.2.1 Visions and expectations

As in the Netherlands, in the early 1980s the Danish vision on biogas plants was based on energy generation. Danish farmers were facing high energy prices due to the oil crisis. Some of them were active in the Danish grassroots movement, which was also involved in the construction of wind turbines. Together with schools, craftsmen and researchers, this group tried to develop decentralised, small-scale energy systems, including biogas plants (see also section 5.2.2). In general, their expectations about biogas yields and the market potential of farm-scale biogas plants were high. Researchers in the STUB programme anticipated in 1981 the following:
A suitable technology is fully adapted in the agricultural sector [by 1985]. Based on analysis of the present development in the animal-based farm operations concerning numbers and sizes, it is calculated that by the year 2000 almost 50% of the dairy and swine production will take place on approximately 10,000 farms. These 10,000 farm operations with the average size of either 70 dairy cows with breeding or 125 sows with breeding comprise the future potential market for biogas plants. […] [A 100 m$^3$] plant shall produce approximately 140 m$^3$ biogas per day (Groen, 1981:2).

These expectations legitimised support for farm-scale biogas plants. A calculation based on data from a European research programme, however, shows that expected (calculated) biogas yields were very high compared to actual production in 1982 (see Table 5.1).

Table 5.1. In 1981, STUB engineers calculated an average production of 140 m$^3$ biogas per 100 m$^3$ reactor tank. In most cases the real production was much lower (in 1982). Data from Operations Analysis Centre (1982:82) and Groen (1981:2)

<table>
<thead>
<tr>
<th>Location</th>
<th>Digester size (m$^3$)</th>
<th>Calculated biogas production (m$^3$/day)</th>
<th>Real production (m$^3$/day)</th>
<th>Real production / calculated production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stenderup</td>
<td>45</td>
<td>63</td>
<td>45</td>
<td>71.4%</td>
</tr>
<tr>
<td>Elsted</td>
<td>4x220</td>
<td>1232</td>
<td>17</td>
<td>1.3%</td>
</tr>
<tr>
<td>Vilstrup</td>
<td>2x150</td>
<td>435</td>
<td>160</td>
<td>36.4%</td>
</tr>
<tr>
<td>Sjoulundgård</td>
<td>6x60</td>
<td>504</td>
<td>180</td>
<td>35.7%</td>
</tr>
<tr>
<td>Hjelmerup</td>
<td>100</td>
<td>140</td>
<td>80</td>
<td>57.1%</td>
</tr>
<tr>
<td>Brested</td>
<td>100</td>
<td>140</td>
<td>85</td>
<td>60.7%</td>
</tr>
<tr>
<td>Assendrup</td>
<td>2x200</td>
<td>560</td>
<td>150-200</td>
<td>26.3-35.7%</td>
</tr>
<tr>
<td>Grasten</td>
<td>2x180</td>
<td>504</td>
<td>350</td>
<td>69.4%</td>
</tr>
<tr>
<td>Gadebjergård</td>
<td>360</td>
<td>504</td>
<td>200</td>
<td>39.7%</td>
</tr>
<tr>
<td>Lejre</td>
<td>20</td>
<td>28</td>
<td>6</td>
<td>21.4%</td>
</tr>
</tbody>
</table>

Results in the early 1980s were poor; the real energy yields (the main motive for the construction of the plants), never met the expected yields. In Denmark, the disappointing results of farm-scale biogas plants triggered a shift towards centralised plants (Operations Analysis Centre, 1983). Larger plants were expected to improve economic feasibility due to economy of scale. This expectation was taken up by the county of North Jutland, who initiated the first centralised biogas plants in Denmark. The plants were constructed as part of local renewable energy projects and suffered from severe technical problems due to a lack of experience with centralised digestion (in Denmark as well as internationally these plants were the first of its kind). The problems were so severe, that the North Jutland county withdrew as an important supporter of centralised biogas plants (Mæng, Lund and Hvelplund, 1999). The future of centralised plants would have been in a critical situation, if not without the support of the Committee for Renewable Energy, which continued to support these first centralised biogas plants with a strong vision on a decentralised and renewable energy industry in Denmark (see also next section).

The Biogas Action Programme built upon this development, but broadened the vision on biogas plants. Agricultural and environmental advantages became a part of the vision on
manure digestion, stimulated by learning processes (see section 5.2.3) and an emerging perception of the environmental problems in agriculture (see section 5.4). The Danish Energy Agency described the vision as follows in one of the programme publications:

The centralized biogas plant plays an important environmental role. It can help farmers distribute animal manure and at the same time help towns dispose of and recycle organic waste. This reduces pollution by nutrient salts, as the material is turned into valuable fertilizer. The improved utilization of organic material permits a reduction in the use of artificial fertilizers. Finally, the biogas produced (a renewable energy source) displaces coal and oil, with all the associated environmental benefits (Danish Energy Agency, 1992:3).

The broadening of the vision resulted from and stimulated research on improving the utilisation of minerals in the manure, pathogen kill-off, odour reduction, pasteurisation of waste and waste recycling. Expectations about the market potential of centralised plants were more moderate than they were for farm-scale plants. The Danish Energy Agency argued that despite a large potential (about 22-25 PJ per year), the full utilization of this resource would be a very long-term project (Danish Energy Agency, 1992:30). Therefore, the Agency anticipated a long development trajectory.

The codigestion of organic waste with manure turned out to increase biogas yields enormously and exceeded all expectations on biogas yields. This was the gist of the Danish Energy Agency’s comments in 1995:

Operation experiences since the late 1980s show a considerable increase in the volume of gas produced. This is primarily due to increased codigestion of the manure with different kinds of organic waste containing easily digestible organic matter. The attainable levels of gas production have proved to be considerably higher than was generally expected some years ago (Danish Energy Agency, 1995:10).

The high yields of biogas plants contributed to a positive perception of the plants. A downside of codigestion was that biogas plants became increasingly dependent on the supply of industrial waste to maintain economic profitability. Programme participants expected that it would become a serious problem in the near future, when the number of plants increased. The availability of useful industrial waste was limited and increasing demand would result in lower revenues from gate fees for the biogas plants. This prospect stimulated a search for other organic sources for codigestion. At the same time, some municipalities became involved in the programme because of expectations about a national obligation to separate household waste at home – which was ultimately never implemented. Later, municipalities referred to the implementation of a ban on the landfill of combustible waste (implemented in 1997). In the case of the Sinding plant, the argument was stated as follows:

In 1993, in accordance with Danish national policy, the municipality of Herning decided to introduce the separation of waste at source. To verify the technology and gain valuable experience, a small-scale pilot plant for the special treatment of organic household waste was retrofitted to the biogas plant (Caddet, 1998).
Expectations about environmental policy also played a dominant role in the case of Grindsted, a plant for the codigestion of sewage sludge and household waste:

When the time came, when Grindsted Kommune had to decide how to dispose and treat their sewage sludge from the planned sewage treatment plant they took a look in the crystal ball in order to foresee the development in waste treatment in general in Denmark. […] The background was some trends in political statements and some expectations in the administrations, which pointed in the direction of a high level of recycling of refuse, to re-use the components in the Danish society in general (Bro, 2000).

The roles of visions and expectations is less clear in the case of niche branching towards farm-scale plants in the late 1990s, although they did play a role. The Folkecenter for Renewable Energy continued to develop farm-scale plants, despite the negative results in the 1970s and 1980s. This organisation, coming from the grassroots movement, had strong ideals about decentralised energy generation and renewable energy.

Conclusions

Visions and expectations about biogas plants legitimised the development and construction of biogas plants. External developments like energy prices and environmental policies were important factors in creating and changing visions on niche level. However, experiments with biogas plant also contributed to changing visions and shifts in niche development. The results from farm-scale plant experiments resulted in a shift towards centralised plants, and experiences within the Biogas Action Programme resulted in changing regulations and practices (see section 5.2.3). Changing visions and expectations also explain the process of niche branching towards the digestion of household waste. In the case of farm-scale plants in the late 1990s, the vision and ideas of one actor were especially important (Folkecenter). I will come back to this in the next section.

5.2.2 Network formation

In this section I discuss the following social groups: farmers, the ‘grassroots movement’ (including The Organisation for Renewable Energy, Folkecenter for Renewable Energy and the Folke High schools), public authorities (including Committee for Renewable Energy, Danish Energy Agency, Ministry of Agriculture, Ministry of the Environment, municipalities), research institutes, energy companies and biogas plant suppliers.

Farmers

Pioneering farmers have played a crucial role in Denmark. In the 1970s, enthusiastic and idealistic farmers began to develop farm-scale plants, usually alone or in cooperation with local craftsmen. They relied on knowledge and experiences from existing agricultural and energy-related practices, e.g. the construction of silos and the operation of boilers. Coordination between the experiments occurred through participation of the grassroots movement (see below) and the STUB programme. Nevertheless, the pioneering farmers are the most important actors in the 1970s and early 1980s.
After 1986, farmers began to participate in centralised biogas plants. A key element in the development of centralised biogas plants is the cooperation between farmers in groups of five to 100 farmers. The cooperatives were not established to make profit. They were financed with inexpensive loans and grants from the government. Moreover, they received revenues from energy sales (electricity and heat) as well as from gate fees for receiving industrial waste. This enabled farmers to process their manure without paying, while in all other European countries farmers had to pay a processing fee (Danish Energy Agency and Kruger Bigadan, 1992:167). Some of these cooperatives constructed storage silos near the fields of farmers and rented the silos to the farmers. The rental cost and risks were lower than in the case of buying a silo. Economic benefits for the farmers also came from savings on artificial fertilizer purchases. The cooperative structure became the dominant organisational structure for biogas plants (see Figure 5.7). 19

The organisation of the Biogas Action Programme enabled an exchange of information between farmers, plant operators, technology suppliers and scientists. Farmers participated in workshops, learned from scientists about improving practices regarding fertilizing with animal manure, and could give feedback to researchers and cooperate in case studies. This resulted in alignment between the activities of different social groups, including farmers.

Figure 5.7. Ownership of 21 centralised biogas plants in Denmark. The ‘other’ category includes decentralised energy producers in cooperation with farmers or other actors. Data from Danish Energy Agency (1992) and Seadi (2000)

In the late 1990s, farmers became more traditional users of technology. Biogas plant companies like Krüger and Dansk Biogas (see below) developed standardised plant concepts. Farmers could purchase turn-key plant concepts including warranties, maintenance contracts, etc. Some of the farmers continued to participate in the network more actively by making

19 The biogas plant cooperatives were organised in the Dansk Biogasteknisk Forening (Danish Biogas Technical Association). The association never acted as an interest organisation for its members towards public authorities or other energy producers. However, for exchanging experiences between single plants, the biogas technical association played an important role. Later, in 1997, the Danish Biogas Plant Association was formed which acted more as an interest organisation towards other parties. For example, when the energy sector was liberalised in the late 1990s this organisation negotiated with the national authorities on the payback prices for electricity produced at the biogas plants (Danielsen and Halkier, 1995:110; Holm-Nielsen, 2002).
Manure digestion in Denmark

their plant available for monitoring within the biogas research programmes (Hjort-Gregersen, 2002).

Grassroots movement
A second social group in the biogas niche is the Danish grassroots movement. This movement emerged after the energy crisis in the early 1970s. Representatives of this movement are the Organisation for Renewable Energy (OVE), the Folkecenter for Renewable Energy and several Folke High Schools. These organisations participated in the development of many renewable energy technologies – like wind power – but also in the development of biogas plants. Their activities focussed on both (support for) the construction of experimental plants and political lobbying (together with several Danish universities).

The Organization for Renewable Energy was founded in 1975. This organisation was a typical grassroots movement. The participants were activists organised in local groups throughout Denmark. The strength of the organisation was that they provided information through publishing in journals and books, and through organising street demonstrations. OVE closely cooperated with Energy and Environment offices, a network of local offices, financed by the Danish Energy Agency. These offices provided free information and supported energy conservation and utilisation of renewable energy sources. At the political level, the OVE lobbied for financial support. Later the organisation turned into a more traditional organisation with registered members. They began to organise meetings for scientists, users and biogas plant suppliers, with the aim of assisting biogas plant cooperatives in improving plant operation and to assist biogas plant suppliers in improving technical designs; scientists were able to receive user and design feedback (Danielsen and Halkier, 1995:63, Beuse, 2003).

From the OVE came the Folkecenter for Renewable Energy. In 1982, OVE applied for financial support to set up a centre to support the development and implementation of renewable energy technologies and to coordinate and disseminate knowledge. The main goal of the centre was to bridge the gap between research and implementation by means of experimentation. The Folkecenter for Renewable Energy was established in 1982 and began to develop and test technologies at the institute itself (Danielsen and Halkier, 1995:67). The Folkecenter and OVE, and Folke High Schools like the Brandbjerg Folke High School, supported the development of farm-scale biogas plants in the early 1980s. They assisted farmers and technology suppliers in the development of biogas plants and facilitated exchange of information through meetings. The Folkecenter also developed new technological concepts. In the early 1980, the director of the centre Preben Maegaard, had close contacts with several private farmers (such as Paul Overgaard) who had developed farmscale biogas plants themselves. These plants, however, were not ready for mass production, for example, because they were made off second-hand materials. The first step to come to a more mature design was an investigation in 'best practice', to prevent the reinventing of the wheel. The second step was to construct new plants, to learn about making them suitable for mass

20 In Danish: Organisationen for Vedvarende Energi (OVE), Nordvestjysk Folkecenter for Vedvarende Energi, (Folkecenter)
21 See website http://www.sek.dk
production. Several plants were constructed on farms near the Folkecenter, financed by the Committee for Renewable Energy (sometimes up to 65% of investment costs were financed). Based on these experiences, the centre improved the design, first the horizontal steel tank, and later the vertical steel tank. Through international contacts, the centre imported knowledge from (in particular) Germany and could further improve the design. In the mid-1990s, employees of the Folkecenter began to commercialise their designs in the Dansk Biogas company, enabling the reintroduction of farm-scale plants in the late 1990s (Maegaard, 2005).

Public authorities

Several national and local public authorities have been active in the development of biogas plants in Denmark. In particular I will discuss the Committee for Renewable Energy, the Danish Energy Agency, the Ministry of Agriculture, the Ministry for the Environment and municipalities.22

The Committee for Renewable Energy (Styregruppe for Vedvarende Energi) was established by the Technology Council in the Ministry of Industry and Commerce in 1982 and lasted until 1991. The members of this committee were scientists and actors from medium and small businesses, experts in the field of renewable energy sources, and included, among others, Niels I. Meyer (Chairman and Professor in Physics from the Technical University of Denmark), Klaus Illum (Aalborg University) Jens Jensen (Danish Black Smith Society), Preben Maegaard (Danish Organisation for Renewable Energy), Helge Petersen (National Research Laboratory Risø), Karin Christiansen (Ministry of Industry and Commerce) and Finn Godtfredsen (observer from the Ministry of Energy). The group's annual budget increased from two million Danish crones (about 280,000 euros) in 1982 to 34 million Danish crones (about 4,7 million euros) in 1990. The budget was mainly used for financing demonstration projects, in particular to support medium and small companies, and advocating the use of renewable energy through informational activities. Several forms of renewable energy were part of the committee's portfolio (wind turbines, solar thermal energy, biomass combustion), but the committee also advocated the development of biogas plants. They financed several of the projects carried out by the Folkecenter for Renewable Energy, who published many reports about the plants, including handbooks on how to construct and operate biogas plants.23 Also members of the Committee published several reports on biogas plants (as well as other alternative energy plants).24 The financial support enabled the Folkecenter to initiate and maintain the development of farm-scale plants despite the (in general) negative perception of these plants in the early 1980s. The committee's support also turned out to be crucial in helping out the first centralised biogas plant in V. Hjermitslev. The committee provided financial support for solving technical problems and reconstructing the

23 See for example Christensen (1986); Folkecenter (1987); Møller (1989); Møller, Thulesen and Maegaard (1990); Hinge (1992); Mathiesen (1995)
24 See for example Sørensen and Mæng (1989); Meyer, Pedersen and Viegand (1990); Styregruppe for Vedvarende Energi (1991).
(poorly) designed plant, lobbied (successfully) for additional finance from the Danish Energy Agency, and contributed to a positive perception of centralised plants in the Danish political context. Due to the committee's efforts, the Danish ministries of Energy, Agriculture, and Environment, were later on positive about participation in the Biogas Action programme. In general, the committee has played the role of an alignment actor: they tied projects, actors, financial means, and political will together in a period when the future development of biogas plants was not at all certain (Illum, 2005; Meyer, 2005; Maegaard, 2004; Beuse et al., 2000).

The Danish Energy Agency (DEA) is a part of the Ministry of Energy, established in 1979. In 1980, this agency became responsible for the STUB programme. They supported the development of the farm-scale biogas plants and the first three centralised biogas plants. In 1987, the DEA implemented the Biogas Action Programme together with the Ministry of Agriculture and the Ministry of the Environment. The DEA administered the programme, published Danish and English booklets and reports, participated in meetings and lobbied with other ministries. The agency was responsible for choosing test and demonstration plants, for distributing investment grants, and for monitoring and publishing results. They were a key actor in the network, but stimulated bottom-up participation on the part of biogas producers, farmers, scientists and other actors (Danielsen and Halkier, 1995:106-109).

Two other ministries were active in the social network, i.e. the Ministry of Agriculture and the Ministry of the Environment. Both ministries supported implementation of the Biogas Action Programme and participated in the network. Their participation enabled a direct interaction between local experiments and policy making. Several new regulations affected the further development of the biogas niche. In particular, the Water Environment Action Plans I (1987) and II (1998), several statutory orders on manure storage and handling, a statutory order on the application of waste products for agricultural purposes, and in addition, 1990s legislation regarding landfill and incineration of waste (Seadi, 2002; Boo, 1993:5). In some cases, experiences from the Biogas Action Programme contributed to the formulation of new regulations and policy plans (see next section). The centralised biogas plant offered a solution to several environmental issues like carbon dioxide emissions from fossil fuels, environmental problems in farming and the production of organic waste streams, and the ministries supported the technology, both financially and politically.

Finally, municipalities participated in the network for biogas plants. The municipalities were responsible for implementing decentralised Combined Heat and Power (CHP) on natural gas and biomass (including centralised biogas plants) in the early 1990s (see section 5.4). Some municipalities participated in biogas plant boards and integrated the plants into local

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25 In particular Søren Tafdrup of the agency played a key role in the network. In 1983, he had joined the Højbogård as a plant manager where he experimented with the codigestion of different sources of waste (Beuse et al., 2000:265). In 1986 he joined the Danish Energy Agency, where he became responsible for the administration of Biogas Action programme. His practical experience combined with a position at the Danish Energy Agency enabled him to be an active participant in the network. He participated in meetings with plant operators, published reports on biogas plants in Denmark and attended international seminars on biomass and biogas (Tafdrup, 1997; Tafdrup, 1998; Tafdrup, 2000).

26 Later, the agency concluded that the active bottom-up participation was very successful for the implementation of new technologies. They used the same set-up for other technologies, e.g. for the monitoring of newly established farm-scale plants in 1994 (Hjort-Gregersen, 1998:1)
energy planning. In some cases, the involvement of municipalities led to the implementation of separation technologies for household waste, and codigestion of the organic portion with manure (Danielsen and Halkier, 1995:95,109).

Research institutes

In the 1970s and early 1980s there was no knowledge on issues like chemical processes, biogas combustion and digester tank construction. During the development of farm-scale plants in the 1970s and 1980s, several research institutes got involved, including the Technical University of Denmark (DTU, Energy Department) and The Royal Veterinary and Agricultural University (KVL, see Table 5.13, Appendix 5.1). These institutes carried out temporary projects in the biogas niche. The long duration of the Biogas Action Programme enabled research institutes to have employees continuously involved in the biogas community. One of the first institutes was the Danish Institute of Fisheries Economics (FOI), the research institute under the Ministry of Agriculture. The head of the Farm Management and Production Systems Division, Johannes Christensen, was appointed as the chairman of the Biogas Group, the working group for the implementation of the Biogas Action Programme. He had been involved in developing and implementing biogas plants since 1978. FOI, and in particular Johannes Christensen, continued to participate in the network throughout the 1990s.

A second group of institutes was involved in research on veterinary aspects of biogas plants in the late 1980s and early 1990s. The three cooperating ministries implemented a research programme in 1988 to research veterinary aspects, because processing and transporting manure from several sources increased the risk of spreading disease. A steering committee – including nine members from veterinary institutes as well as a medical jurist, two technologists and a representative of the Ministry of Energy – gave direction to the programme between 1988 and 1992. Several agricultural research institutes worked on a total of four projects (Bendixen, 1994; Bendixen, 1996).

A third important research institute, established in the early 1990s, was the Bioenergy Department of the Southern University of Denmark. The Bioenergy Department employed three researchers, i.e. Jens Bo Holm-Nielsen, who had been involved in the planning and implementation of the Ribe Biogas Plant; Teodorita Al Seadi, an MSc in Agronomy; and Kurt

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27 In Danish: Danmarks Tekniske Universitet (DTU), Den Kgl. Veterinær- og Landbohøjskole (KVL)
28 In Danish: Fødevareøkonomisk Institut (FOI)
29 In Danish: Afdeling for Jordbrugets Driftsøkonomi
30 The first project was a laboratory research programme at the Danish Veterinary Laboratory (Danmarks Fødevare- og Veterinærforsknings). The second project was carried out by the Institute for Hygienics and Microbiology at the Royal Veterinary High School and included measurement at several centralised biogas plants. The Institute for Epidemiology at the same high school carried out the third project. They researched the chances on spreading animal diseases, but also investigated regulatory aspects of collective manure digestion. Finally, the fourth project was directed by the Danish Veterinary Service and focussed on hygienic aspects and preventive measures concerning the design, location and daily routines at biogas plants (Boo, 1993:59). The research programme has been regarded as successful and, for example, resulted in the development of a standardised measurement method for determining the sanitation effect as well as the implementation of regulatory guidelines on hygienic operation of biogas plants.
31 In Danish: Syddansk Universitet
Manure digestion in Denmark

Hjort-Gregersen, appointed by the Danish Institute of Agriculture and Fisheries Economics for his knowledge of agricultural economics. This small group of scientists represented the biogas research community in and outside Denmark. Their activities included coordinating activities from Danish institutes and companies in the field of biogas; publishing reports about Danish centralised biogas plants; producing knowledge on agricultural advantages, technological issues and energy generation; monitoring biogas plants; organising meetings between biogas plant operators; and chairing workshops on biogas. Internationally, the Bioenergy Department acted as the Danish representative in several European research networks such as the Altener Waste for Energy Network and IEA Bioenergy tasks. Participation in these programmes also provided the institute with financial resources for research. When in 2002 the Danish Biogas Action Programme ended, the institute was able to continue on the basis of international projects.

Energy companies

The energy companies involved in biogas plants were mainly local district heating companies. These companies were often closely involved in establishing the biogas plants; they integrated heat production from the biogas plant into local energy planning. The large energy associations ELSAM and ELKRAFT were marginally involved. They bought electricity produced in the biogas plants, but in general had no active role in the biogas network. An obligation to buy electricity from decentralised production units for fixed minimum prices enabled the biogas plant companies to sell electricity at favourable prices to the utilities (Danielsen and Halkier, 1995:99).

Technology companies

The establishment of biogas plant suppliers was closely linked to the development of the biogas niche. Farmers or craftsmen involved in the early development of farm-scale plants established new companies to commercialise their design. The Krüger-Bigadan company (market leader in centralised biogas plants in the 1990s) emerged from a cooperation between the farmer from the Højborgård biogas plant and a Danish marzipan factory (Marcia). The resulting company Højborgård Biogas A/S cooperated with the Hans Jørgensen & Søn

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32 In the Waste for Energy network, established in 1995, Jens Bo Holm-Nielsen was the coordinator of the programme for biogas. The aim of the network was the dissemination of information, transfer of knowledge, know how and technology and promotion of business opportunities in the area of biogas in Europe by the means of study tours, biogas training actions, European biogas events, meetings and networking, dissemination of biogas knowledge and information by internet web pages, reports, leaflets and other informative materials. Waste for Energy merged into EUBIONET. The Bioenergy department coordinated the biogas research in this network and organised workshops and study tours. See website http://websrv5.sdu.dk/bio/eubinet and (Anonymous, 2003:6; Anonymous, 2003b). In the IEA Bioenergy task 24 ‘Energy from Biological Conversion of Organic Waste’ and its successor, task 37 ‘Energy from Biogas and Landfill Gas’, the Bioenergy Department participated as the Danish representative for biogas technologies. The work programme from this network, in which also Finland, Sweden, Switzerland and the U.K. (and for a short period of time also the Netherlands) participated, included research on biogas upgrading technologies, source separation technologies of organic wastes, quality management of digistate, the organisation of a sanitation workshop, setting up a plant database and investigating the potential of codigestion (Tustin, 2000; Tustin, 2002). The work of the Bioenergy Department focussed in particular on quality management of residues from biogas plants. See website http://www.novaenergie.ch/tea-bioenergy-task37/index.htm and (Seadi, 2001).
enterprise to form the Bigadan Biogas company in 1974. Finally, Marcia sold Bigadan to Krüger in 1990, a large Danish company that operated in the international market for (among other things) sewage treatment plants (Beuse et al., 2000). In the case of farm-scale plants, too, this pattern of bottom-up establishment of biogas companies can be found. A Folkecenter employee, for example, established the Dansk Biogas A/S company. This company was able to construct a large number of plants in the second half of the 1990s.

Development of the Danish biogas plant industry is characterised by a large number of companies, often existing for a limited time. Besides the Krüger company and the Dansk Biogas A/S company, the Danish biogas plant industry included at one time or another Burmeister and Wain Scandinavian contractors, NIRAS, Bioscan A/S, Herning Municipal Utilities, C.G. Jensen Ltd, Bruun & Sørensen, Jysk Biogas A/S, W.W. Engineering, Agro-Metan, Andersen & Fog and Hørlych & Kongsted (Seadi, 2000; Demuynck and Nyns, 1984). The precise role of these companies is hard to trace. Some of them only constructed one plant; other companies merged into larger companies. Generally, however, the bottom-up development of the industry is typical for Denmark. It was also observed in the case of wind power (Garud and Karsøe, 2003; Est, 1999). The participation of biogas plant suppliers in the Biogas Action Programme enabled feedback from users and input from scientists to further optimise plant design.

Conclusion

I conclude that the Danish biogas plant development was accompanied by the emergence of a strong social network, including many actors with intensive interaction between them. The Danish grassroots movement facilitated this interaction in the late 1970s and early 1980s, in the early and mid 1980s, the Committee for Renewable Energy was a decisive alignment actor, while after the mid-1980s, the Biogas Action Programme’s bottom-up approach stimulated interaction between different social groups. This resulted in a broad social network with high alignment between the actors’ activities, enabling the exchange of information between different locations and between different social groups, and thus contributing to a high quality learning process in the Danish biogas niche (see next section).

5.2.3 Learning processes

The learning process in Denmark was mainly a learning-by-doing process supported by input from scientific research projects. The experiments with biogas plants were crucial to this approach. Participants focussed on four aspects of biogas plants, i.e. improving biogas yields, improving technological components, learning about agro-environmental aspects and improving economic performance.

Energy generation was the dominant focus of research and experimentation in the 1970s and 1980s, and continued to be important after 1985. Codigestion has been crucial in increasing biogas yields. Codigestion was already discovered at some of the farm-scale plants in the 1970s and 1980s, but it was only widely applied in centralised biogas plants (Energigruppe, 1979:41; Beuse, 2000:262,265). Centralised biogas plants were well suited for
codigestion, because of plant size and the space for receiving waste from industrial sources. The Sinding Øre plant was the first centralised plant to use codigestion, but codigestion rapidly diffused among the other centralised plants (Anonymous, 2000:26). Figure 5.15 (Appendix 5.2) shows the type of biomass used by the centralised plants in 1998. On average, the plants use about three-quarters of manure and one-quarter of additional organic waste (see Figure 5.16, Appendix 5.2). The organic waste is very diverse, although intestinal content, fat, flotation sludge and fishery waste are most common. Besides codigestion, biogas yields also improved due to optimised plant design and operation through learning-by-doing. Overall, this led to increased biogas yields between 1991 and 1998 (Table 5.2).

Table 5.2. Change in biogas production in eight Danish centralised biogas plants (Danish Energy Agency, 1992; Hjort-Gregersen, 1999)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year of construction</th>
<th>Biogas production in 1991 (million m$^3$/year)</th>
<th>Biogas production in 1998 (million m$^3$/year)</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vester-Hjermitslev</td>
<td>1984</td>
<td>1.27</td>
<td>1.49</td>
<td>17.3%</td>
</tr>
<tr>
<td>Vegger</td>
<td>1986</td>
<td>1.46</td>
<td>2.00</td>
<td>37.0%</td>
</tr>
<tr>
<td>Sinding-Øre</td>
<td>1988</td>
<td>2.06</td>
<td>2.35</td>
<td>14.1%</td>
</tr>
<tr>
<td>Fangel</td>
<td>1989</td>
<td>2.09</td>
<td>2.28</td>
<td>9.1%</td>
</tr>
<tr>
<td>Revninge</td>
<td>1989</td>
<td>0.37</td>
<td>0.36</td>
<td>-2.7%</td>
</tr>
<tr>
<td>Ribe</td>
<td>1990</td>
<td>3.15</td>
<td>4.76</td>
<td>51.1%</td>
</tr>
<tr>
<td>Lintrup</td>
<td>1990</td>
<td>3.44</td>
<td>3.72</td>
<td>8.1%</td>
</tr>
<tr>
<td>Lemvig</td>
<td>1992</td>
<td>4.20</td>
<td>5.30</td>
<td>26.2%</td>
</tr>
</tbody>
</table>

Biogas plant suppliers and operators developed several innovations to improve the techno-economic operation of biogas plants. In the 1970s and 1980s, start-up of the digestion process was a major obstacle. The process runs on living microbes, which need to be present sufficiently in the digester in order to maintain the process. The plant operator of the Højbogård farm-scale plant found by coincidence that a clay mineral (ziolit) could do that. However, ziolit was very expensive and the operator searched for a similar but less expensive mineral. Through learning by doing, he found that bleach oil, a waste product from oil mills, was also very effective (Beuse et al., 2000:265).

After 1985, the Biogas Action Programme stimulated learning through the organisation of regular meetings. The Bioenergy Department chaired these meetings, where plant operators exchanged experiences and information on technological solutions. One of the main innovations was related to purifying the biogas. Biogas was mostly used in gas engines for combined heat and power generation. Engine suppliers restricted the content of hydrogen sulphide in the biogas, because this gas could seriously damage the engines. Biogas plant operators were forced to take (expensive) measures like adding ferric chloride to the biomass or installing gas cleaning systems (Danish Energy Agency, 1992:20). In 1993, information from the German biogas industry inspired operators at the Fangel biogas plant to experiment with adding air to the biogas. The hydrogen sulphide was biologically converted to sulphur.
This method was so successful that it diffused among all new biogas plants, while some of the older plants also turned to this method (Danish Energy Agency, 1995:10).

Many other technological improvements occurred in response to comparative experiences at different centralised plants. Several plants experimented with the design of gas transmission systems. The Sinding, Lintrup and Ribe plant implemented a system based on drying, compressing and transporting the gas at pressures up to four bar. This system turned out to be very expensive and later plants used systems with low pressure transmission (copied from landfill gas systems) (Danish Energy Agency, 1992:20; Hjort-Gregersen, 1999:14). In addition, the manure transport system improved through optimised loading and unloading equipment, and calculation methods for limiting transport distances. Many other parts of the plants improved (stirrers, pumping systems, odour reduction systems). In general, successful innovations from one plant diffused rapidly among other plants, or comparing experiences among different plants resulted in improved designs for new plants.

Another area of learning was the agricultural aspects of manure digestion, one of which was the fertilizing value of digested manure, investigated by researchers from the Bioenergy Department, the National Institute of Animal Science and the Agricultural Advisory Centre (Holm-Nielsen, Halberg and Huntingford, 1993). The Ribe Biogas plant and associated farmers were involved in field trials. The project showed that the distribution of nitrogen improved when digested slurry was sold to farmers without animals. The project also showed that participation in a centralised biogas plant reduced the purchase of artificial fertilizer (see Table 5.14, Appendix 5.1). Reduced use of artificial fertilizer was the result of three factors: first, the digestion process converts part of the nitrogen into a non-organic form, which crops can absorb more rapidly; second, the biogas plant provided farmers with a detailed analysis of the digested slurry contents, enabling improved planning for dosing manure to the crops; third, farmers changed the way they used the manure, improving nitrate utilisation. The research report formulated guidelines on several topics, including guidelines on the most optimal period for fertilisation and best practices to incorporate the manure into the soil (see Box 1 in Appendix 5.3).

Another learning process occurred in the field of sanitation. The Ministry of Agriculture implemented several sanitation research projects in the late 1980s and early 1990s to investigate the risk of spreading animal disease. These projects produced two important outcomes: first, the researchers developed a measurement method (FS), which could effectively determine the presence of pathogens in the digested manure. The method was so successful that in 1994 all biogas plants applied it (Bendixen, 1994:179). Secondly, the projects generated detailed knowledge on the interrelation between temperatures, residence time and pathogen kill-off in biogas plants. In the early 1990s, a Danish order regulated the application of organic waste in agriculture. The order enacted sanitation requirements for waste products, but was not very detailed: only one standard without distinctions for

33 Transport costs could be as high as 40% of total operational costs.
34 The method was based on the reduction of a specific micro-organism called *faecal enterococci streptococci* (FE).
temperature or residence time was allowed (see Table 5.15, Appendix 5.1). The research projects enabled specification of the process variables in relation to sanitation. In 1996, the Minister of Environment implemented a revision of the statutory order. The new order was based on the FS method to measure the presence of pathogens, and enacted more specific time limits on sanitation (Table 5.16, Appendix 5.1). The values created more flexibility in sanitation, facilitating lower sanitation costs and improved economic performance. This example clearly illustrates the interaction between different social groups in the Biogas Action Programme, and the transfer of knowledge and rules between them (Bendixen, 1997:56).

Finally, farmers learned about several advantages from participating in centralised biogas plants and in the Biogas Action Programme. One of the lessons learned was that digestion reduced manure odour problems. Participating farmers saw this as an important benefit of the digestion process, because it could reduce complaints from nearby urban areas (Knudsen and Birkmose, 1997:43; Tafdrup, 1995:306). A second benefit for farmers was the reduction of transport miles for distributing manure (Holm-Nielsen, Halberg and Huntingford, 1993). In the late 1980s the Danish government obliged farmers to have a nine-month storage capacity for manure (see section 5.4). Biogas plants often installed local storage capacity near the farmers’ fields. Farmers could rent the silos, which reduced the risk of long-term investments. The biogas plant company transported manure from the farm to the biogas plant and returned it to the local storage facilities. Farmers could limit their manure transport, because the facilities were located near the farmers’ fields (often a few kilometres away from the farms). A calculation based on the farmers’ experiences showed that on average, farmers reduced their transport time by 65%, and the transport distance by a striking 95%.

The improvements in biogas yields and technologies increased the economic performance of centralised biogas plants. Plants’ average income increased substantially between 1992 and 2000 (see Figure 5.8). An evaluation of centralised biogas plants in 1998 showed that the majority of plants operated at an acceptable level, or at least balanced, in particular the more recently constructed plants. Plants constructed in the late 1980s and plants that codigested organic household waste (Århus Nord, Vaarst-Fjellerad) still had financial problems (see Table 5.17, Appendix 5.1). Another evaluation in 2000 showed further improvement of the plants’ economic performance (see Table 5.18, Appendix 5.1). Moreover, the economic performance of several farm-scale biogas plants was monitored and showed similar results (Table 5.19; 5.20; 5.21, Appendix 5.1). Plants constructed in the 1980s achieved limited economic performance, while plants constructed in the late 1990s were able to reach satisfactory results. The economics of farm-scale plants, however, remained precarious, primarily due to the high investment costs of the plants (Hjort-Gregersen, 1999a; Hjort-Gregersen, 2002a).

In a recent socio-economic analysis the reduction of stench was calculated as an important externality of 0.7 euro/ton liquid manure, meaning that achieving the same reduction through alternative methods would cost 0.7 euro/ton. In the same study the savings from improved fertiliser value were calculated about equal (Nielsen, et al., 2002:36).
During the 1990s, the Danish government reduced the level of investment grants for new centralised biogas plants. Reduction of investment grants had been an important aim of the Biogas Action Programme (Danish Energy Agency, 1995:7). Figure 5.9 represents the relative investment grants of the twenty centralised biogas plants installed in Denmark, with the oldest plants at the left of the graph. The graph shows that in the mid-1990s investment grants decreased. Reduced investment grants resulted from, and stimulated optimisation of the centralised biogas plant concept. Economic viability maintained primarily by increasing the income from gate fees and by increasing biogas yields through codigestion (Hjort-Gregersen, 1999:18).
Conclusion
The learning process was well organised in Denmark, in particular within the Biogas Action Programme. Regular meetings with biogas plant operators, farmers, scientists, technology suppliers and public authorities enabled a broad and deep learning process. Farmers, biogas plant operators, biogas plant suppliers and policy makers learned about many technological, economic, regulatory and user issues, among other matters. Some learning processes can be described as second-order processes, e.g. when farmers adjusted fertiliser practices or when the ministerial order was adjusted for the use of organic waste in agriculture. These are second-order learning processes, because experiments resulted in changing existing rules and practices. The high quality of learning enabled a successful implementation of biogas plants in Denmark. Nevertheless, the plants’ economic situation remained unstable. Biogas plant construction still depended on investment grants and favourable loans.

5.3 Interaction between niche processes

Table 5.3 shows the main characteristics of niche development for manure digestion in Denmark. From the analysis, I conclude that in general the quality of niche processes was high in Denmark, in particular in the case of the niche for centralised biogas plants. This high quality was due to intensive interaction between many different social groups and many locations, and the ability of actors to learn from experiments and transform the lessons into new designs.
Table 5.3. Main characteristics of niche processes in the case of manure digestion in Denmark

<table>
<thead>
<tr>
<th>Period</th>
<th>Main characteristics of niche processes</th>
<th>Results in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973-1983</td>
<td>Farmers had high expectations about biogas yields from manure digestion, induced by high energy prices. The grassroots movement supported the farmers, with a strong vision on renewable and decentralised energy generation. This movement and later the STUB programme created alignment between the experiments, but plant performance remained poor due to limited experience with manure digestion. The main search objective was to improve the biogas yields, resulting in the invention of codigestion. The experiences with farm-scale plants were translated into a new development trajectory, i.e. the centralised biogas plants for energy generation.</td>
<td>The construction of a large number of farm-scale biogas plants, but poor operation prevented breakthrough</td>
</tr>
<tr>
<td>1984-1994</td>
<td>The vision on biogas plants broadened, and agricultural and environmental aspects were included. Furthermore, the social network broadened. Due to efforts from the Committee for Renewable Energy, several ministries were willing to support and participate in a long-term action programme on centralised biogas plants. This programme stimulated interaction between locations and between social groups, resulting in a broad and deep learning process. The Folkecenter continued to develop the farm-scale plant through local experimentation and international relations with Germany.</td>
<td>Increase in the number of centralised biogas plants and gradual improvement of technological and economic performance of the plants</td>
</tr>
<tr>
<td>1995-2003</td>
<td>Developments under the auspices of the Biogas Action Programme continued. Folkecenter’s strong visions propelled the continuing development of farm-scale plants. Folkecenter succeeded in commercialising the farm-scale plant concept through experimentation and the importation of knowledge from Germany. Some municipalities anticipated future waste policies and participated in the programme.</td>
<td>Process of niche branching towards codigestion of organic household waste and farm-scale plants, and improvement of the technological and economic performance of centralised plants</td>
</tr>
</tbody>
</table>

The developments at the niche level can explain some of the questions I addressed in section 5.1.3. The main question was why the Danish were successful in developing and implementing biogas plants. My conclusion is that this was the result of high quality niche processes, in particular in the case of developing centralised biogas plants. A broad social network supported these plants’ development, based on realistic expectations, but with a broad vision on the plants’ functions and applications. This broad social network was able to learn effectively about the plants’ feasibility, how to improve designs, how to compare the socio-technical concepts from different locations, and how to maintain niche development for a long time. The invention and implementation of codigestion was one of the most important outcomes of this learning process, because it enabled improvement of economic feasibility despite decreasing financial support from the government. However, other (regime) factors, too, were crucial for success. I will investigate them in the next section. The second question
was why farmers participated in the centralised plants. The niche analysis showed that farmers benefited economically from participating in centralised plants. However, this does not explain why farmers established cooperatives only after 1986, while they did not in the three centralised plants constructed prior to 1986. I have referred to emerging agro-environmental legislation, and I will investigate this topic further in the following section. The third question was why the development of centralised biogas plants stopped after 1998, which cannot be explained by the niche processes. I will investigate this question in the regime analysis. The fourth question was related to the reasons for niche branching after 1994. The niche analysis gave insight: some municipalities tried to anticipate waste legislation and began to participate in the niche. In the next section I investigate what kind of legislation this was and how it affected niche development. Folkecenter’s continued efforts as well as the financial and political support from the Committee for Renewable Energy were essential for the emergence of farm-scale. However, other factors were also important in the case of farm-scale plants, which I will discuss in the next section, thereby also answering my fifth question, i.e. why the number of farm-scale plants increased so quickly after 1994.

5.4 Danish regime dynamics

5.4.1 Reducing oil dependency (1973-1983)

*Electricity and heat regimes*

The 1973 oil crisis forced Denmark to deal with a high dependency on oil from the Middle East. Denmark produced no oil; it was fully imported. Oil represented 80% of the contribution to Danish power production. Nor was there a natural gas infrastructure like in the Netherlands. Electricity was mainly produced in large power plants, with heat being supplied either through district heating systems or individual stoves combusting oil or local resources (see below). The Danish government began to intervene in the electricity and heat regimes to reduce the dependency on foreign oil. In 1976, they published the first national White Paper on energy. The plan’s main goal was to safeguard Denmark from future fluctuations in oil prices, mainly by introducing nuclear power in Denmark.\(^{37}\) In general, these plans were supported by the Danish electricity sector.\(^ {38}\) Other goals of the White Paper were to increase efforts in energy savings and increase energy production from domestic fuels, in particular fossil fuel resources in the Danish North Sea. In the short term, the central power plants changed fuels from oil to coal. (Hadjilambrinos, 2000:1120, Vleuten, 2002:21).\(^ {39}\)

\(^{37}\) The government suggested five nuclear power plants to produce 23% of primary energy demand in Denmark.

\(^{38}\) Previously, the sector had been reluctant in fear of increasing interference of the government, but the high oil prices forced them to investigate new directions.

\(^{39}\) Historically, the Danish electricity regime was rooted in cooperative organisations. In the 1970s this led to the establishment of two associations, divided by the Great Belt between Sealand and Jutland. ELSAM coordinated power production in the West of Denmark and ELKRAFT in the East. Both associations were bottom-up organised. A large number of local distribution companies (cooperatives of consumers as well as municipal companies) chose the board of regional utilities, organised among eight central power stations. The regional institutions elected the board members for ELSAM and ELKRAFT. The two associations took care of planning of power production and operation of the transportation grid. Despite the bottom-up ownership, many of the
The decision whether to develop nuclear power in Denmark was embedded in a lively social discussion, accompanied by street demonstrations and publications of alternative energy plans, for the most part driven by the grassroots movement. This movement lobbied for the development of an alternative energy system based on wind power, solar power and biomass, including farm-scale biogas plants. In 1979, Denmark was confronted with the second energy crisis. The Ministry of Energy increased its participation in decision making in the energy sector and published a second White Paper in 1981. The policy plan was similar to the first White Paper, but put more emphasis on alternative energy technologies like biogas plants (although marginally): one of the scenarios anticipated the construction of 20,000 biogas plants. The White Paper was accompanied by the implementation of support schemes for renewable energy, including investment grants and the obligation that electricity companies buy surplus electricity from local power production. The grassroots movement judged the regulations as not progressive enough, and published an alternative energy plan in 1983. In this plan, the movement opted for an energy system without nuclear power, mainly based on alternative energy technologies (Danielsen and Halkier, 1995).

By 1983, the electricity regime had changed in many ways. The Danish government had gained a decisive role, as the implementation of an Electricity Act in 1976 provided the government with power, for example to reject the construction of a new power plant. Technologically, power production was still dominated by large-scale power plants, which accounted for 95% of total electricity production in 1983 (Energistyrelsen, 2002). Nevertheless, the number of alternative power plants (in particular wind turbines) had increased to a considerable level (Hadjilambrinos, 2000:1120).

In addition, the heat regime changed in the early 1980s, resulting in three different types of heating systems. First, in the 1960s a large number of district heating systems had been constructed, mainly fuelled by inexpensive oil. The district heating systems were owned by a large number of independent companies – the majority of these companies were consumer cooperatives, with the larger ones being owned by municipalities. When oil prices increased in the 1970s, many of the district heating companies turned to coal. In 1981, 40% of all households were connected to this type of district heating system. Second, a large number of consumers were still using individual heating systems in the early 1980s, fuelled by oil and local biomass resources such as wood and straw. Third, in 1979 the Danish government decided to introduce natural gas from the Danish North Sea in Denmark and commissioned the construction of a large natural gas network (Ministry of Energy, 1990:36). The Danish government implemented several laws to regulate the introduction of natural gas, including the Heat Act (1977) and the Natural Gas Act (1979). The former became one of the most important energy planning policy tools in Denmark. The Act’s official aim was to promote the best socio-economic use of energy for heating. However, the Act also secured the government with a market for natural gas. Large parts of Denmark were obliged to connect to the natural gas network, mostly through combined heat and power plants. The second act on new capacity and environmental decisions were taken centrally in these associations (Olesen and Lyck, 1996:25).

In 1981, over 1000 privately owned wind turbines were in operation.
determined that the state would build a national natural gas supply system from platforms in the North Sea to individual users. A state-owned company, DONG, exploited the system after construction was finished. Gas production began to rise rapidly in the mid-1980s (Vleuten, 2000:22; Lorenzen, 2001; Danielsen and Halkier, 1995).

Conclusion
The electricity and heat regimes began to change in the 1973-1984 period in Denmark, triggered by increasing oil prices in the 1970s and increasing governmental interference. This created flux in the electricity and heat regimes. Denmark was highly dependent on oil, both for electricity and heat production. The new policies’ main aim was to reduce the dependency on foreign oil. In the short term, coal replaced oil for electricity and heat production. Long term projections included the construction of nuclear power plants in Denmark, the construction of a natural gas network, and the exploitation of local resources, including biomass. The influential Danish grassroots movement strongly supported the introduction of renewable energy sources (including biogas plants) and objected to the introduction of nuclear power. The dominant actors in the electricity regime (ELSAM, ELKRAFT), however, were in favour of introducing nuclear power, while dominant actors in the heat regime (local district heating companies) switched to coal for heating the cities. In this period, biogas plants were a local niche activity, remaining invisible to regime actors.

5.4.2 Decentralised CHP and agro-environmental regulations (1984-1994)

Electricity and heat regimes
The circumstances for nuclear power changed in Denmark around the mid-1980s. The state effort to stimulate energy savings was successful; total final energy consumption decreased from 612 PJ in 1980 to 556 PJ in 1983. The construction of new large power plants was no longer necessary. Moreover, opposition from the grassroots movement, well represented in the Danish left-wing parliament, slowed down decisions on nuclear power. In 1985, the government rejected nuclear power in favour of small scale systems, use of domestic fossil fuels (oil and natural gas) and alternative sources, in particular wind and biomass (Hadjilambrinos, 2000:1120). In 1986, the price of oil dropped on the world market. Danish dependency on the foreign oil supply had decreased from 92% in 1972 to 38% in 1985. Oil was hardly used in power production anymore (replaced by coal) and was only used for 30% of total heat production (Danielsen and Halkier, 1995:45; Energistyrelsen, 2002:10). To prevent the reintroduction of oil in the electricity and heat regimes, the Danish government decided to raise taxes on energy and fuels.\footnote{Energy tax on oil and electricity was introduced in 1977 and on coal in 1982 (Ministry of Energy, 1990:30)} The energy tax included high taxes on oil products, taxes on coal, and relatively high taxes on electricity. Renewable energy sources and natural gas were both tax-exempt (Ministry of Energy, 1990:30). In general, this resulted in the same electricity price for households before and after the decrease in oil global prices (IEA, 1998).\footnote{The government transformed the energy tax into a carbon dioxide tax in the early 1990s.}
Two forces drove Danish energy policy after 1985: environmental protection, and the exploitation of domestic natural gas resources. Environmental concerns were reinforced by the Brundtland Report (1987) and were soon followed by emerging notions on the greenhouse effect and carbon dioxide emissions. In 1990, the government published a new White Paper, in which they elaborated their vision on the electricity and heat regimes until 2000 (‘Energy 2000’). The policy plan anticipated three trajectories. First, the plan aimed to increase the environmental performance of the existing energy systems, mainly by stimulating the use of natural gas in power production (Danielsen and Halkier, 1995). Second, the production of renewable energy was expected to increase. In particular the development of windmills was anticipated, not only by private producers, but also by ELSAM and ELKRAFT (Hadjilambrinos, 2000:1121). Third, the plan anticipated the large scale introduction of combined heat and power plants. In 1986, the main political parties agreed that ELSAM and ELKRAFT had to establish 450 MW of decentralised CHP plants with natural gas, biomass and waste before 1995. In 1990, the political parties made a second agreement, determining that decentralised heat producers should convert district heating plants to decentralised CHP on natural gas, or to district heating on biomass in locations outside the natural gas area, as defined in the Heating Act (Ministry of Energy, 1993:3; Danielsen and Halkier, 1995:91).

Transformation of the district heating sector was closely linked to expansion of the natural gas market in Denmark. The 1990 heating agreement favoured natural gas over biomass, because biomass was only allowed at locations outside the natural gas area (Danielsen and Halkier, 1995:92). Overall, the conversion of district heating plants into CHP plants was very successful in Denmark. In 1993, seventy-three CHP plants had been commissioned and forty-seven had been approved but not yet commissioned. Fifty-one of the forty-seven plants used natural gas, eleven plants used biogas and the other plants used waste, wood or straw (see Table 5.22, Appendix 5.1). Decentralised electricity production increased in the 1990s, from 270 GWh in 1990 to 6,126 in 2002. The development of CHP plants and the general energy policies in Denmark improved conditions for centralised biogas plants, especially in the early 1990s. Although the political agreements favoured natural gas, there were still enough locations for biogas plants outside the natural gas area. Moreover, tax exemptions for renewable energy sources improved the competition with fossil fuels (oil and coal). Too, the presence of district heating systems enabled the sale of both electricity and heat (see Figure 5.10), improving the financial performance of centralised biogas plants.

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43 In the 1980s, the Danish government had enacted several regulations for the reduction of SO₂ and NOₓ emissions, which began to take effect.

44 Source: Danish Energy Authority
Agricultural regime

In the late 1980s, many European countries were forced to deal with growing environmental problems in agriculture, a legacy from intensive farming, the use of artificial fertilizer and a large number of animals. The European Commission introduced several regulations to improve the environmental conditions in agriculture – the first in 1985 – followed by regulations in 1991 and 1992, on organic agriculture and agricultural production methods.\footnote{These regulations included the obligation for farmers to set aside farming land so that overproduction was decreased.} In 1991, the EU implemented a directive on water pollution from nitrates. This directive defined strict limits for nitrate emissions from chemical fertilizer and manure, to be implemented by the member states prior to 1999 (McCormick, 2001:202, 253).\footnote{In 1999, Denmark and Luxembourg were the only two countries that met the limits defined in the directive.} In Denmark, agriculture was not considered to be an environmental problem before 1984, at which time the Danish Environmental Protection Agency (EPA) published a report on pollution caused by nitrate leaching from agricultural land (Miljøstyrelsen, 1984). The report triggered a debate about the environmental circumstances in agriculture and resulted in a number of agro-environmental regulations.\footnote{The report also led to the first joined investigation of the Ministry of Agriculture, the Ministry of the Environment and the Ministry of Energy into centralised biogas plants (Miljøstyrelsen, Energistyrelsen and Landbrugsministeriet, 1986)} These regulations included an obligation for farmers to have sufficient manure storage capacity for six to nine months. Storage capacity would enable farmers to spread manure only in specific periods (spring), when the risk of nitrate leaching was low, and store it for the rest of the year. In 1986, a serious environmental pollution problem (due to oxygen depletion in marine waters) received considerable media attention. The Danish EPA reacted by publishing the Water Environment Action Plan I in 1987, which included a major reduction goal for nitrate leaching in agriculture. It regulated the number of animals per hectare as well as the maximum input of nitrogen per hectare. Later, in 1992, the Danish Ministry of Agriculture implemented a plan for ‘sustainable agriculture’ in which also the European legislation was implemented, including an obligation for farmers to maintain a fertilizer bookkeeping (Mogens, 1995).

These changes in agro-environmental regulations were a strong incentive for farmers to cooperate in centralised biogas plants. First, the introduction of emission limits for nitrogen...
created distribution problems for Danish farmers. Manure production on individual farms often exceeded the maximum limits allowed by law. Farmers were forced to look for alternatives. Danish agriculture was not as intensive and concentrated as agriculture was in many other European regions, and most farmers could solve the problem by transporting the manure over a short distance (five to ten kilometres). A centralised biogas plant, however, could manage the distribution of manure for the farmers. Second, the storage obligation for manure stimulated farmers to participate in biogas cooperatives. The construction of storage capacity required a large investment (approximately 35,000 euros for a 1,000 m$^3$ tank). The government made grants available, covering 25-40% of the investment, but the investment was still large for individual farmers. Participation in biogas plants enabled farmers to reduce investment risks by renting the storage capacity from the biogas plant company.

The cooperative also suited a general preference among Danish farmers, who often established cooperatives, for example for buying fertilisers. A Danish cooperative had no private capital; the members owned the association and not a private institution (e.g. a company with private capital). Danish farmers were often free to frame association rules as they wished, because of a lack of special cooperative legislation. This enabled the establishment of cooperatives solely for the benefit of their members (Pedersen, 1977).

Conclusion

After 1984, the electricity regime began to become more decentralised, with increasing linkages with the heat regime. The expansion of CHP and natural gas was accompanied by new policies and regulations, improving the competitive position of natural gas, but also the position of centralised biogas plants. The stimulation and introduction of CHP was important for creating a market for natural gas, but also benefited the implementation of centralised biogas plants. Biogas plants linked up with the development of CHP on natural gas in terms of tax exemptions, feed-in tariffs and policy goals. Also the fact that CHP combined electricity and heat sales improved the conditions for centralised plants. Finally, environmental problems in the agricultural regime created a sense of urgency among politicians, resulting in the implementation of several agro-environmental regulations. These regulations stimulated farmers to support the development of centralised biogas plants.

5.4.3 Increasing competition, climate change policy and waste policy (1995-2003)

Electricity and heat regime

The expansion of the natural gas network, the expansion of decentralised CHP systems and the increase in renewable energy production continued after 1994. No new, large scale power plants were constructed, with the exception of one advanced multi-fuel power plant near Copenhagen (see Chapter 6). The majority of new capacity brought on line in the 1990s

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48 In the case of artificial fertilizers for example, the cooperative structure enabled farmers to set out much stronger demands on prices and quality than in other European countries. This has contributed to a relatively strong position for farmers in Denmark (Holm-Nielsen, 2002).
Manure digestion in Denmark (77.3%) was in the form of decentralised CHP and wind (Figure 5.11). Actors outside the electricity regime developed most of these technologies, although ELSAM and ELKRAFT participated in establishing a few decentralised CHP plants (Hadjilambrinos, 2000:1121). A large number of new, decentralised power producers came into the power market. The share of natural gas increased, both in power generation and heat production (see Figure 5.12; 5.13).

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The remaining part of new capacity was in the form of wind power.
The market shares of ELSAM and ELKRAFT decreased in the 1990s.50 Their (former) monopolistic position in the electricity regime came under further pressure with the introduction of competition in the electricity regime. In 1996, the EU had reached agreement on the directive for liberalising the internal electricity market. The Danish government published a new White Paper (‘Energy 21’) in the same year. Energy 21 outlined the government’s vision on introducing competition in the Danish electricity regime. In May 1996, the government approved an amendment that allowed private companies and distribution companies of sufficient size to buy power from third parties (IEA, 1998:9).51 In 1999, the parliament enacted a new law, the Danish Energy Reform. The reform aimed to transform the Danish electricity regime after 2000. The reform broke with traditional power company non-profit principles and the companies began to reorganise into market-oriented organisations.

The liberalisation process had consequences for the development of renewable energy technologies in Denmark. The Danish government used to stimulate the production of renewable energy through a feed-in model. In such a model, a long term, fixed price is guaranteed, on top of the market price for electricity. The Danish government decided to replace this model with a new model, which they expected to be fare better in a liberalised electricity market, i.e. a certificates trading model. In such a model, producers of renewable energy receive a total payment consisting of the market price of conventional electricity

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50 The power associations ELSAM and ELKRAFT had been monopolistic on public concession for a very long time. Monopolistic behaviour, however, was prevented due to the construction of ownership through bottom-up participation of consumers and the organisation of ELSAM and ELKRAFT as non-profit institutions. They were obliged to either reimburse any profits to consumers by lowering electricity prices or to invest it into new capital. When the new group of power producers emerged, ELSAM and ELKRAFT resisted. On the one hand, because they feared loosing market share. On the other hand, because decentralised power production broke with their principles regarding economic advantages of scale and centralised control-systems (Danielsen and Halkier, 1995:98).

51 The amendment was originally planned to become fully implemented from 1998. However, uncertainties rising from possible acquisitions by foreign companies resulted in a postponement to 2001 (IEA, 1998:12; Meyer and Koefoed, 2003:600)
supplemented with the market price of a green certificate (Meyr, 2003; Meyer and Koefoed, 2003).

The transition towards the new model created uncertainty for investments in biogas plants. The Danish Energy Agency sent the amendment on the new model to a large number of actors for review, including the Industry Association for Biogas, The Danish Farmers’ Union and the Biogas Group (Folketinget, 1999). Traditionally, the fixed price for electricity from biogas was between €0.06 and €0.075 per kWh. The bill would replace this fixed price with an uncertain price, because both the conventional electricity price and the price for green certificates could fluctuate. The Biogas Plant Association negotiated with the DEA, focusing on specific transition rules that would guarantee the prices until the green certificate market was fully operational (not before 2005). Nevertheless, the uncertainty created by the new scheme stopped all investments in new centralised plants after 1998 (Christensen, 2000).

Another development affected the implementation of biogas plants. In November 2001, the Danish people elected a new government, a liberal/conservative coalition, which enacted a shift in environmental and energy policies in Denmark. In general, the new government focused less on environmental issues in energy generation and more on a cost efficient energy supply. Renewable energy technologies were forced to survive in harsher market conditions; several established grants, funds and R&D support mechanisms were dropped (see Table 5.4). The government’s strategy shift also increased uncertainty about new policies, and actors like investors, research institutes and companies waited for new policy documents. The direct consequence for the biogas niche was that the Biogas Action Programme was discontinued in 2002 (Knoppers, 2002:4; Evald and Jakobsen, 2003).

Table 5.4. Programme reductions in Denmark after new government (Evald and Jakobsen, 2003)

<table>
<thead>
<tr>
<th>Programme</th>
<th>Previous government support (million euros)</th>
<th>New government support (million euros)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of and information about renewable energy</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Energy research</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Utilities energy research</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Energy savings and fuels switch in industry</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>Investment grants for biomass CHP</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Joint Implementation and Clean Development Mechanism</td>
<td>0</td>
<td>17</td>
</tr>
</tbody>
</table>

Consumers are obliged to buy a specific amount of green certificate, which creates a market for these certificates. The revenues from this certificates replace the fixed price from the previous model.

Also the organisation of Danish energy policies changed. The Danish Ministry of Energy was turned into the Danish Energy Authority, a part of the ministry of Economic and Business Affairs. The Ministry of the Environment and Energy became the Ministry of the Environment.
Agricultural regime

Two changes in the agricultural regime affected the development of the manure digestion niche in Denmark after 1995. First, agriculture was increasingly recognised as one of the sectors responsible for large emissions of greenhouse gases. The agricultural sector emitted approximately 18% of all greenhouse gases in Denmark in 2000, which made the sector the second largest emitter of greenhouse gases (Danish Environmental Protection Agency, 2000). Moreover, the majority of gases in agriculture are methane and nitrous oxide. These gases received increasing attention after the 1997 Kyoto Protocol, which emphasised the effects on climate change. In 1998, the Danish government implemented the second Action Plan on the Aquatic Environment, which increased several standards for emissions from agriculture. The new standards included reductions in amounts of manure and fertilizer to be spread on farming land and improvements in the utilisation of minerals in manure. Both regulations increased the need for manure distribution methods in agriculture. The emission reductions in agriculture (and in other sectors) were also stimulated by the ‘green tax package’, a carbon dioxide tax on energy consumption implemented in 1995. Along with the green tax package, a new subsidy scheme was established for energy savings in business enterprises. In 2000, similar schemes became available for the agricultural sector and could be used for investments in farm-scale plants. The support included investment grants up to 40%, comparable to the level of grants in the early 1980s for centralised biogas plants. Thus the economic viability of farm-scale biogas plants was improved; the poor economic performance of farm-scale plants had mainly been caused by relatively high investment requirements (see section 5.2.3).

The second change in agriculture was of a structural nature. Average farm size increased in Denmark. In the first half of the 20th century there were about 200,000 farms with an average area of about 16 hectares. After 1950, the numbers began declining slowly. During the 1960s an average of 5,000 farms disappeared each year. After the 1970s, the decline rate slowed down, but persisted in the 1990s at about 2,600 farms per year. In 1997, a total of 60,900 farms remained, but with an average area of 43.6 hectares. At the same time changes took place in agricultural practice. Farmers increasingly concentrated their efforts on one type of animal. Specialisation in animal production led to fewer types of farms, but larger numbers of livestock. The growing farm size improved conditions for farm-scale plants due to economies of scale. The combination of more emphasis on methane reductions in agriculture, growing financial support and increasing average farm size facilitated a rapid increase of farm-scale plants in the late 1990s and early 2000s.

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54 Denmark had already begun to develop climate change policies in the late 1980s, but the emphasis had been on carbon dioxide reduction.

55 The background to the changes in both the farm structures and methods of working were the demands for a steady improvement in productivity to compensate for deteriorating terms of trade and profitability trends (http://www.danishembassy.ro/page.php?id=38).
Waste regime
The Danish policy on waste treatment and management was rooted in the mid-1980s, when considerable problems arose with finding new landfill sites. A dioxin debate also focused attention on waste incineration plants as a large source of pollution. In 1986, the Danish Ministry of the Environment implemented the Environmental Protection Act (Andersen, Dengsøe and Brendstrup, 1997:22). From that time on, Danish environmental policy reflected a similar thrust as that of the Netherlands and Germany. Prevention of waste production was of the highest priority, followed by recycling and incineration. Dumping waste was considered as the least desirable route for waste disposal (Mogens, 1995). A specific instrument in waste policy was taxation of dumping waste as well as incineration. Taxation on dumping waste and incineration was implemented in 1987, followed by a tax increase in 1990. In 1992, the government implemented tax differentiation to favour incineration over dumping waste. Throughout the 1990s, both taxes were further raised, resulting in a tax increase of 5.6 euros (DKK 40) per ton in 1987 on landfill and incineration to 36 euros (DKK 260) per ton on incineration and 47 euros (DKK 335) per ton on landfill. In 1997, the government also implemented a ban on dumping organic waste. Instead of developing a new infrastructure for composting (like in the Netherlands), the Danish actors decided to focus on centralised biogas plants. Waste producers (industries, municipalities and sewage treatment plants) were stimulated to search for alternative waste processing methods, while the high prices for landfill and incineration increased the competitive position for centralised biogas plants in the waste processing sector. Due to higher biogas yields from codigestion, biogas plant companies could acquire large amounts of organic waste, raise gate fees and increase economic performance.

Conclusion
In the late 1990s, the Danish electricity regime was characterised by high instability due to the liberalisation process. In particular the changes in support mechanisms and a shift in energy and environmental policies created uncertainty for investment and research in centralised biogas plants. No new plants were implemented after 1998. Climate change policies resulted in rapidly increasing numbers of farm-scale plants, but also structural changes in agriculture was an important factor. Finally, structural change in the waste regime (increasing taxes) created chances for biogas plants as the competitive position of plants in the waste sector continued to improve.

5.5 Conclusions
In this section, I first discuss the remaining puzzles and questions and see how the regime analyses contributed to understanding them. Then I construct the niche development pattern

---

56 On the European level, policies for waste treatment and management began in 1975 with the implementation of the Directive on Waste. The aim was to harmonize national waste measures and oblige member states to ensure that waste was disposed without harm to human health and the environment. The directive was followed by a large number of directives regulating specific waste streams and waste treatment methods, including directives for chemical and hazardous waste and for waste incinerators (McCormick, 2000:169)
in terms of protection and stabilisation. In the final section, I discuss niche-regime interaction in the case of Danish manure digestion.

**Regime dynamics**
In section 5.3 I argued that not all questions and puzzles derived from the historical overview could be answered by looking at niche processes. The first question was why Denmark succeeded in developing and implementing biogas plants. I concluded that a high quality of niche processes was important for understanding the outcome. From the regime analysis I conclude that several changes at the regime level also played important roles, in particular the emergence of decentralised CHP after the mid-1980s, the introduction of taxes on fossil fuels, the implementation of several agro-environmental regulations, and the emerging vision within the waste regime on recycling organic waste, combined with taxation on dumping and waste incineration. The second puzzle was why farmers suddenly became interested in participating in centralised biogas plants. The regime analysis shows that this was mostly due to the aftermath of regulations for storage capacity and manure distribution, as well as a more general preference among farmers to participate in non-profit cooperatives. The third question was why the development of farm-scale plants stopped after 1998. This question could not be answered by looking at niche processes. From the regime analysis I conclude that in particular the liberalisation processes, the changing support mechanisms and the shifts in energy and environmental policies in the late 1990s caused a stop in the construction of new plants. The fourth question was related to niche branching towards farm-scale plants and codigestion of organic household waste. The regime analysis showed that the rapid increase in the numbers of farm-scale plants was the result of decisions in climate change policies regarding agriculture, combined with structural changes in the agricultural regime (larger farms). Waste policies improved the competitive position of biogas plants as organic waste processors.

**Construction of niche patterns**
In Figure 5.14 I have represented the development of manure digestion in Denmark. This niche trajectory begins in the early 1980s, with the establishment of farm-scale plants. The design shows very limited stabilisation, but some stabilisation and comparison between projects occurs within the STUB programme and through grassroots participation. High energy prices and high expectations about future markets were the main forms of protection guarding the development of the farm-scale biogas niche. Around 1983, niche branching towards centralised digestion took place, initiated by the North Jutland county and supported by the Committee for Renewable Energy. In 1988, the Biogas Action Programme began, contributing to stabilisation in plant designs, and functionalities (energy generation, manure distribution, waste processing) and providing financial support for further experimentation and development. The programme built upon the centralised plants that had emerged after poor results with farm-scale plants. Within ten years’ time, the centralised biogas plant concept was further optimised, with much interaction between different experiments. Technological designs, solutions, functions and regulations stabilised and increasingly provided structuration for new experiments. Protection in the form of investments grants was
reduced in this decade, but remained necessary to stimulate new experiments. The technological niche became a protected market niche. The Biogas Action Programme benefited two other trajectories. The first was the emergence of a niche for codigestion of household waste, protected by investment grants and expectations from municipalities about new waste policies. Municipalities had no experience with this technology – especially the separation of plastic bags and organic waste was problematic, nor were there many examples to build upon. The number of plants remained small, with much uncertainty about the feasibility of this technology and only limited resources dedicated to optimisation. The second trajectory that benefited from the Biogas Action Programme is the sudden growth of the niche for farm-scale plants. Dedicated actors developed this niche in the absence of major Danish government support. Employees of the Folkecenter were able to optimise the concept through international linkages and local experiments. After 2000, all three niches were experiencing a reduction in protection, because of large shifts in energy and environmental policies. Moreover, ongoing liberalisation processes create uncertainty in the future of manure digestion plants, no new plants are installed and the Biogas Action Programme is stopped. Table 5.5 gives an indication of the size of the niches.

![Figure 5.14. Niche development pattern for manure digestion in Denmark](image-url)
Table 5.5. Indication of size of niches for manure digestion in Denmark and total annual manure production

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm-scale plants</td>
<td>58</td>
<td>13</td>
<td>71</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>Centralised plants + household waste separation/codigestion</td>
<td>0</td>
<td>30</td>
<td>293</td>
<td>862</td>
<td>862</td>
</tr>
</tbody>
</table>

1993

Annual Danish manure production (kton) 44,000

Niche-regime interaction

In this section I discuss how regime dynamics interacted with niche development in the case of manure digestion in Denmark. Table 5.6 shows the main developments in regimes, the effect of regime dynamics on niche development and the effect of niche development at the regime level. My general conclusion is that regime dynamics have been very important in realizing the successful development of biogas plants in Denmark, largely due to decreasing stability in the electricity regime, overlap between the electricity and heat regime, and the alignment of problems and solutions with the agricultural and waste regime.

Table 5.6. Niche-regime interaction in the biogas case in Denmark.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Instability in electricity and heat regime due to high oil prices and high dependency on foreign oil. Solutions are found in regime optimisation (fuel replacement, energy savings)</td>
<td>Instability in electricity regime due to emerging actor (decentralised producers), and introduction of natural gas and CHP.</td>
<td>High instability in electricity regime due to liberalisation, and new energy and environmental policies create uncertainty.</td>
</tr>
<tr>
<td></td>
<td>Implementation of energy taxes</td>
<td>Construction of natural gas network and stimulation of CHP create overlap between electricity and heat regime.</td>
<td>Structural change in agriculture results in larger farms. Climate change policies emphasise reduction of methane emissions.</td>
</tr>
<tr>
<td></td>
<td>Instability in agriculture regime due to environmental problems results in implementation of several agro-environmental regulations.</td>
<td>Emphasis on organic waste recycling in waste regime</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Local opportunities for manure digestion due to high energy prices and (limited) stimulation of renewable sources</td>
<td>Regulations and policies stimulate farmers to participate in centralised plants.</td>
<td>Halted development of centralised plants because of uncertainty about returns on investments and about energy and environmental policies.</td>
<td></td>
</tr>
<tr>
<td>Centralised plants benefit from the favourable conditions created for natural gas CHP.</td>
<td>Municipalities and other waste producers interested in participation in centralised plants or in supplying waste.</td>
<td>Rapid increase in number of farm-scale plants</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Niche experiments result in new guidelines for manure spreading and sanitation requirements in agricultural policy.</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

57 Data on annual manure production from Holm-Nielsen and Seadi (1999). Annual production in early 2000 was lower and between 33000-40000 kton (Tijmensen et al., 2003:15).
In the first period, the manure digestion niche mainly developed against the backdrop of the electricity and heat regimes. The oil crisis created instability in the regimes, and most emphasis was on reducing the dependency on foreign oil. Regime actors found solutions primarily in replacing oil with coal. However, the instability also resulted in the creation of local opportunities for biogas plants and a small biogas niche. The regime level reveals no discernable effects caused by development of the manure digestion niche; the niche is highly invisible.

In the second period, there was much more interaction between the manure digestion niche and relevant regimes. The electricity and heat regimes were both affected by the implementation of new policies and the introduction of natural gas. The regime became more decentralised and there were increasing linkages with the heat regime, resulting in a larger manure digestion niche: centralised manure digestion fit the regime changes towards decentralised energy generation. The increasing linkages between the electricity and heat regimes were important, too, because they increased the economic feasibility of centralised biogas plants. However, a very important factor for the growth of the centralised niche was the changes in the agricultural regime. Stability in the agricultural regime was threatened by the environmental problems caused by a manure surplus. The government dealt with the instability by enacting several agro-environmental regulations. These regulations stimulated farmers to participate in centralised plants, stimulating growth of the manure digestion niche. Development of the centralised biogas niche also resulted in (limited) regime changes, predominantly changes in the formal rules of the agricultural regime – based upon developmental experiences – and farming practices relating to manure use and distribution.

In the third period, stability in the electricity regime decreased due to liberalisation. The instability blocked niche development, as returns on investments and energy policies were uncertain. In other words, instability in the electricity regime determined the development of the biogas niche, despite successful experimentation. Changes in the agricultural regime and waste regime created new opportunities for manure digestion, however, and manure digestion veered towards digestion on farms and codigestion of household waste, increasing the size of these niches.
### Appendix 5.1: tables

Table 5.7. Biogas plants in Denmark in the 1970s (Energigruppen, 1979)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year of construction</th>
<th>Input</th>
<th>Size (m³)</th>
<th>Type</th>
<th>Investment costs (DKK)</th>
<th>Builder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nors</td>
<td>??</td>
<td>30 sows</td>
<td>4x45</td>
<td>Batch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kibæk</td>
<td>??</td>
<td>300 sows, 1,000 piglets</td>
<td>1x90</td>
<td>Continuous</td>
<td></td>
<td>Engineering works</td>
</tr>
<tr>
<td>Nr. Aaby</td>
<td>1974</td>
<td>40 cows, 40 sows,</td>
<td>5x90</td>
<td>Batch</td>
<td>120,000 (1974)</td>
<td>Self-built and Craftsmen</td>
</tr>
<tr>
<td>Holsted</td>
<td>1976</td>
<td>160 beef cattle</td>
<td>1x45</td>
<td>Continuous</td>
<td>20,000 (1975)</td>
<td>Self-built</td>
</tr>
<tr>
<td>Bustrup</td>
<td>1977</td>
<td>90 cows</td>
<td>2x100</td>
<td>Batch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elsted</td>
<td>1978</td>
<td>80 cows, 260 piglets</td>
<td>2x200</td>
<td>Batch</td>
<td>300,000 (1978-79)</td>
<td>Self-built and craftsmen</td>
</tr>
<tr>
<td>Hygum</td>
<td>1978</td>
<td>150 sows</td>
<td>3x50</td>
<td>Batch</td>
<td>140,000 (1978)</td>
<td>Craftsmen</td>
</tr>
<tr>
<td>Gråsten</td>
<td>1979</td>
<td>100 cows, 120 sows,</td>
<td>2x180</td>
<td>Continuous</td>
<td>613,765 (1979)</td>
<td>Craftsmen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,500 piglets</td>
<td></td>
<td>and batch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sdr. Vilstrup</td>
<td>1979</td>
<td>150 cows, 345 other</td>
<td>2x150</td>
<td>Continuous</td>
<td>500,000 (1978)</td>
<td>Engineering works</td>
</tr>
</tbody>
</table>

Table 5.8. Biogas plants within the STUB project (Groen, 1981:6)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Gråsten</th>
<th>Gadebjerggård</th>
<th>Assendrup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of manure</td>
<td>Dairy and pigs</td>
<td>Pigs</td>
<td>Dairy</td>
</tr>
<tr>
<td>Number of animals</td>
<td>96 cows, 500 pigs, 100 sows</td>
<td>1,700 pigs</td>
<td>150 cows with breeding</td>
</tr>
<tr>
<td>Process type</td>
<td>Continuous two-step or batch</td>
<td>Continuous one-step</td>
<td>Continuous one-step</td>
</tr>
<tr>
<td>Process layout</td>
<td>Continuous</td>
<td>Continuous</td>
<td>Batch</td>
</tr>
<tr>
<td>Size of reactor (m³)</td>
<td>2x180</td>
<td>1x270</td>
<td>2x200</td>
</tr>
<tr>
<td>Reactor materials</td>
<td>Pre-cast concrete with flexible PVC gas-top</td>
<td>Glass-fibre reinforced polyester with floating GRP gas-top</td>
<td>Concrete block work with flexible gas-top</td>
</tr>
<tr>
<td>Gas utilisation</td>
<td>Gas-fired boilers</td>
<td>Electricity production and heat recovery</td>
<td>Electricity production and heat recovery</td>
</tr>
</tbody>
</table>
## Table 5.9. Farm-scale biogas plants in Denmark in February 1981 (Operations Analysis Centre, 1982)

<table>
<thead>
<tr>
<th>Location</th>
<th>Animals</th>
<th>Manure (t/day)</th>
<th>Process layout</th>
<th>Size (m³)</th>
<th>Material</th>
<th>Gas storage</th>
<th>Energy conversion</th>
<th>Production</th>
<th>In operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxviggård</td>
<td>Pigs</td>
<td>3.5</td>
<td>Continuous</td>
<td>100</td>
<td>Steel</td>
<td>None</td>
<td>CHP</td>
<td>Starting up</td>
<td>+</td>
</tr>
<tr>
<td>Give</td>
<td>Dairy cows</td>
<td>3</td>
<td>Batch</td>
<td>4x45</td>
<td>Concrete</td>
<td>Gasometer</td>
<td>CHP</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bukkerupgård</td>
<td>Pigs</td>
<td>8</td>
<td>Continuous</td>
<td>300</td>
<td>Steel</td>
<td>None</td>
<td>Gas-fired boiler</td>
<td>45 m³/day</td>
<td>-</td>
</tr>
<tr>
<td>Stenderup</td>
<td>Beef cattle</td>
<td>3</td>
<td>Continuous</td>
<td>45</td>
<td>Concrete</td>
<td>Flex. cover</td>
<td>Gas-fired boiler</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Skarild</td>
<td>Pigs</td>
<td>7</td>
<td>Continuous</td>
<td>100</td>
<td>Steel</td>
<td>None</td>
<td>Gas-fired boiler</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bustrup</td>
<td>Dairy cows</td>
<td>5</td>
<td>Batch</td>
<td>2x100</td>
<td>Concrete</td>
<td>Gasometer</td>
<td>CHP</td>
<td>Not yet in operation</td>
<td>-</td>
</tr>
<tr>
<td>Hoejboård</td>
<td>Dairy cows/pigs</td>
<td>3</td>
<td>Batch</td>
<td>4x40</td>
<td>Steel</td>
<td>Gasometer</td>
<td>Gas-fired boiler</td>
<td>0.2 m³/kg</td>
<td>+</td>
</tr>
<tr>
<td>Godrum</td>
<td>Pigs</td>
<td>2</td>
<td>Continuous</td>
<td>50</td>
<td>Concrete</td>
<td>Flex. Top</td>
<td>CHP</td>
<td>Not yet in operation</td>
<td>-</td>
</tr>
<tr>
<td>Hygum</td>
<td>Pigs</td>
<td>2</td>
<td>Batch</td>
<td>3x50</td>
<td>Concrete</td>
<td>None</td>
<td>Gas-fired boiler</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Elsted</td>
<td>Dairy cows/pigs</td>
<td>6-7</td>
<td>Batch</td>
<td>4x220</td>
<td>Concrete</td>
<td>Pressure tank</td>
<td>CHP</td>
<td>17 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Nors</td>
<td>Dairy cows</td>
<td>1.5</td>
<td>Batch</td>
<td>4x45</td>
<td>Concrete</td>
<td>None</td>
<td>Gas-fired boiler</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Sdr. Vilstrup</td>
<td>Dairy cows</td>
<td>11</td>
<td>Continuous</td>
<td>2x150</td>
<td>Steel</td>
<td>None</td>
<td>CHP</td>
<td>160 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Saxenhøj</td>
<td>Dairy cows</td>
<td>5</td>
<td>Continuous</td>
<td>175</td>
<td>Concrete</td>
<td>Flex. Top</td>
<td>CHP</td>
<td>Starting up</td>
<td>+</td>
</tr>
<tr>
<td>Sjoelundgård</td>
<td>Pigs</td>
<td>9</td>
<td>Batch</td>
<td>6x60</td>
<td>Concrete</td>
<td>Plastic bag</td>
<td>CHP</td>
<td>180 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Roeding</td>
<td>Dairy cows</td>
<td>1.5</td>
<td>Batch</td>
<td>4x30</td>
<td>Concrete</td>
<td>Gasometer</td>
<td>Gas-fired boiler</td>
<td>Not yet in operation</td>
<td>-</td>
</tr>
<tr>
<td>Hjelmerup</td>
<td>Pigs</td>
<td>3.5</td>
<td>Continuous</td>
<td>100</td>
<td>Steel</td>
<td>None</td>
<td>CHP</td>
<td>80 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Bredsted</td>
<td>Pigs</td>
<td>2.2</td>
<td>Continuous</td>
<td>100</td>
<td>Steel</td>
<td>None</td>
<td>CHP</td>
<td>85 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Assendrup</td>
<td>Dairy cows</td>
<td>16</td>
<td>Plug flow</td>
<td>2x200</td>
<td>Concrete</td>
<td>Flex. Top</td>
<td>CHP</td>
<td>150-200 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Grästen</td>
<td>Dairy cows/pigs</td>
<td>15</td>
<td>Continuous</td>
<td>2x180</td>
<td>Concrete</td>
<td>Flex. Top</td>
<td>Gas-fired boiler</td>
<td>350 m³/day</td>
<td>+</td>
</tr>
<tr>
<td>Gadebjergård</td>
<td>Pigs</td>
<td>7.5</td>
<td>Continuous</td>
<td>360</td>
<td>GRP</td>
<td>Floating cover</td>
<td>CHP</td>
<td>200 m³/day</td>
<td>-</td>
</tr>
<tr>
<td>Lejre</td>
<td>Pigs</td>
<td>0.8</td>
<td>Continuous</td>
<td>20</td>
<td>Steel</td>
<td>Plastic bag</td>
<td>Gas-fired boiler</td>
<td>6 m³/day</td>
<td>+</td>
</tr>
</tbody>
</table>
Table 5.10. Characteristics of the centralised biogas plants constructed in Denmark between 1988 and 1992 (Danish Energy Agency, 1992)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year of construction</th>
<th>Manure (t/day)</th>
<th>Industrial waste (t/day)</th>
<th>Total digester vol. (m³)</th>
<th>Construction costs (€ mill)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinding</td>
<td>1988</td>
<td>105</td>
<td>34</td>
<td>2,100</td>
<td>3.6</td>
<td>Bruun &amp; Sörensen</td>
</tr>
<tr>
<td>Fangel</td>
<td>1989</td>
<td>129</td>
<td>32</td>
<td>3,650</td>
<td>3.5</td>
<td>Krüger-Bigadan</td>
</tr>
<tr>
<td>Revninge</td>
<td>1990</td>
<td>31</td>
<td>11</td>
<td>540</td>
<td>1.3</td>
<td>CH4-Energi</td>
</tr>
<tr>
<td>Ribe</td>
<td>1990</td>
<td>301</td>
<td>42</td>
<td>4,600</td>
<td>6.2</td>
<td>Krüger-Bigadan</td>
</tr>
<tr>
<td>Lintrup</td>
<td>1990</td>
<td>236</td>
<td>76</td>
<td>6,900</td>
<td>6.0</td>
<td>Krüger-Bigadan</td>
</tr>
</tbody>
</table>

Table 5.11. Centralised biogas plants constructed during the Biogas Action Programme follow-up (Seadi, 2000:15-18)

<table>
<thead>
<tr>
<th>Location</th>
<th>Year of construction</th>
<th>Manure (t/day)</th>
<th>Industrial waste (t/day)</th>
<th>Total digester vol. (m³)</th>
<th>Construction costs (€ mill)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemvig</td>
<td>1992</td>
<td>362</td>
<td>75</td>
<td>7,600</td>
<td>7.6</td>
<td>BWSC</td>
</tr>
<tr>
<td>Hodsager</td>
<td>1993</td>
<td>42</td>
<td>6</td>
<td>880</td>
<td>2.6</td>
<td>NIRAS</td>
</tr>
<tr>
<td>Hasjøj</td>
<td>1994</td>
<td>100</td>
<td>38</td>
<td>3,000</td>
<td>3.0</td>
<td>Krüger</td>
</tr>
<tr>
<td>Thorsø</td>
<td>1994</td>
<td>230</td>
<td>31</td>
<td>4,650</td>
<td>4.0</td>
<td>BWSC</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Location</th>
<th>Year of construction</th>
<th>Manure (t/day)</th>
<th>Alternative biomass (t/day)</th>
<th>Total digester vol. (m³)</th>
<th>Construction costs (mill €)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Århus Nord</td>
<td>1995</td>
<td>346</td>
<td>46</td>
<td>8500</td>
<td>7.4</td>
<td>C.G. Jensen</td>
</tr>
<tr>
<td>Filskov</td>
<td>1995</td>
<td>61</td>
<td>18</td>
<td>880</td>
<td>3.2</td>
<td>NIRAS</td>
</tr>
<tr>
<td>Stodsgaard</td>
<td>1996</td>
<td>230</td>
<td>36</td>
<td>6000</td>
<td>7.6</td>
<td>Herning Municipal Utilities</td>
</tr>
<tr>
<td>Blåbjerg</td>
<td>1996</td>
<td>222</td>
<td>84</td>
<td>5000</td>
<td>6.0</td>
<td>BWSC</td>
</tr>
<tr>
<td>Sneringe</td>
<td>1996</td>
<td>66</td>
<td>42</td>
<td>3000</td>
<td>6.6</td>
<td>NIRAS</td>
</tr>
<tr>
<td>Blåhøj</td>
<td>1997</td>
<td>70</td>
<td>17</td>
<td>1320</td>
<td>4.6</td>
<td>NIRAS</td>
</tr>
<tr>
<td>Vaarts/Fjellerad</td>
<td>1997</td>
<td>110</td>
<td>26</td>
<td>?</td>
<td>4.5</td>
<td>NIRAS</td>
</tr>
<tr>
<td>Nysted</td>
<td>1998</td>
<td>180</td>
<td>31</td>
<td>5000</td>
<td>6.0</td>
<td>Krüger</td>
</tr>
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</table>
Table 5.13. Research institutes involved in the development of biogas plants in the 1970s and early 1980s in Denmark (Demuynck and Nyns, 1984:201; Operations Analysis Centre, 1982:175)

<table>
<thead>
<tr>
<th>Research Institute</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aalborg University Centre</td>
<td>Thermophilic and mesophilic anaerobic digestion of abattoir waste</td>
</tr>
<tr>
<td>The Technical University of Denmark</td>
<td>1. Various projects carried out by students</td>
</tr>
<tr>
<td></td>
<td>2. Utilization of biogas in internal combustion engines</td>
</tr>
<tr>
<td></td>
<td>3. Investigations into kinetics created by the microbial formation of methane</td>
</tr>
<tr>
<td>Royal Veterinary and Agricultural University</td>
<td>Biogas production from crop residues</td>
</tr>
<tr>
<td>Institute of Agricultural Engineering</td>
<td>1. Aerobic fermentation of solid and liquid manure</td>
</tr>
<tr>
<td></td>
<td>2. Extraction of heat energy from animal waste by a combined drying, combustion and water vapour condensation process</td>
</tr>
</tbody>
</table>

Table 5.14. The change in the consumption of artificial fertilizer at a farm connected to the Ribe biogas plant (Holm-Nielsen, Halberg and Huntingford, 1993:12)

<table>
<thead>
<tr>
<th>Year</th>
<th>Hectares</th>
<th>DKK used on mineral fertilizer</th>
<th>Purchase of kg N.</th>
<th>Purchase of kg N/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>39.0</td>
<td>64,134</td>
<td>10,696</td>
<td>274</td>
</tr>
<tr>
<td>1984</td>
<td>69.8</td>
<td>59,832</td>
<td>13,112</td>
<td>329</td>
</tr>
<tr>
<td>1985</td>
<td>39.8</td>
<td>54,191</td>
<td>8,650</td>
<td>217</td>
</tr>
<tr>
<td>1986</td>
<td>42.8</td>
<td>46,425</td>
<td>6,789</td>
<td>158</td>
</tr>
<tr>
<td>1987</td>
<td>37.7</td>
<td>25,111</td>
<td>4,645</td>
<td>123</td>
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<tr>
<td>1988</td>
<td>46.0</td>
<td>24,603</td>
<td>4,155</td>
<td>90</td>
</tr>
<tr>
<td>1989</td>
<td>46.0</td>
<td>44,433</td>
<td>7,438</td>
<td>161</td>
</tr>
<tr>
<td>1990</td>
<td>46.0</td>
<td>35,390</td>
<td>5,093</td>
<td>111</td>
</tr>
<tr>
<td>1991</td>
<td>46.0</td>
<td>18,699</td>
<td>2,240</td>
<td>49</td>
</tr>
<tr>
<td>1992</td>
<td>46.0</td>
<td>16,848</td>
<td>2,392</td>
<td>52</td>
</tr>
<tr>
<td>1993</td>
<td>43.0</td>
<td>13,470</td>
<td>2,153</td>
<td>50</td>
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</tbody>
</table>
Table 5.15. Sanitation requirements for waste products from the original Danish 1989 Statutory Order on application of waste in agriculture (Ministry of the Environment, 1990)

<table>
<thead>
<tr>
<th>Deactivation level</th>
<th>Waste type</th>
<th>Untreated</th>
<th>Stabilized</th>
<th>After controlled composting</th>
<th>After controlled deactivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Sludge, etc. from vegetable production</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>B) Sludge, etc. from animal production</td>
<td>Worked into soil immediately after application. Not for gardening</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>C) Waste separated at the source</td>
<td>Not for agricultural purposes</td>
<td>Not for edible crops or gardening</td>
<td>Not for edible crops (livestock) (x)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>D) Sewage sludge</td>
<td>Worked into soil immediately below soil surface. Not for gardening</td>
<td>Not for edible crops or gardening</td>
<td>Not for edible crops or gardening</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

Definitions

+ Can be used without sanitary requirements

Edible crops Crops which can be eaten raw by animals or humans, excluding, however, fruit tree crops

Untreated

Without deactivation, using one of the tree methods described below:

1. Stabilization
   a) Anaerobic stabilization through digestion in hot digestion tank or treatment in biogas reactor;
   b) Aerobic stabilization through sludge aeration, either in specially designed sludge aeration tank or in long-term aerated sludge plant. Furthermore, composting without temperature control;
   c) Chemical treatment through addition of burnt or slaked lime.

2. Controlled composting
   Composting with daily temperature measurement to ensure temperatures in all material not below 55 °C for not less than two weeks

3. Controlled deactivation
   Treatment in reactor ensuring temperatures not below 70 °C for not less than 1 hour, or similar deactivation
Table 5.16. Sanitation requirements from the 1996 Statutory Order on the Danish application of waste in agriculture (Ministry of the Environment and Energy, 1997)

Controlled deactivation

Before delivery, controlled, deactivated products must go through one of the treatments specified in a) – c) below.

At the time of delivery, deactivated products shall observe the following quality requirements:
- no occurrence of salmonella
- faecal streptococci below 100/g.

Sampling and analysis shall take place in accordance with methods specified by the Danish Environmental Protection Agency.

Forms of treatment:

a) Treatment in reactor ensuring temperatures not below 70 °C for not less than 1 hour, or similar deactivation. Treatment shall be documented by time and temperature recordings.

b) Treatment by addition of lime, to ensure pH 12 in all material for a minimum of three months. Treatment shall be documented by time and pH recordings of the whole batch.

c) Treatment in biogas reactor at thermophilic digestion temperature, and treatment in separate deactivation tank combined with digestion in thermophilic or mesophilic reactor and minimum dwell times of one of the following combinations.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dwell time thermophilic reactor tanks (hours)</th>
<th>Dwell time, separate deactivation tank (hours)</th>
<th>Before or after digestion in thermophilic reactor tank</th>
<th>Before or after digestion in mesophilic reactor tank</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.0</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53.5</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>55.0</td>
<td>6</td>
<td>5.5</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>2.5</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>65.0</td>
<td>1.0</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.17. Economic situation of the centralised biogas plants in 1998 in Denmark (Hjort-Gregersen, 1999). The economic situation of the plant is acceptable if it produces an income significantly above break-even level; it is balanced if it produces an income at the break-even level; it is under pressure if its income is less than break-even level; and it is unsatisfactory if its income is significantly less than break-even level. Århus Nord and Sinding/Studsgard also codigest organic household waste.

<table>
<thead>
<tr>
<th>Year of construction</th>
<th>Acceptable</th>
<th>Balance</th>
<th>Under Pressure</th>
<th>Unsatisfactory</th>
</tr>
</thead>
<tbody>
<tr>
<td>V. Hjermitslev</td>
<td>1984</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegger</td>
<td>1985</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Davinde</td>
<td>1988</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Fangel</td>
<td>1989</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Revninge</td>
<td>1989</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ribe</td>
<td>1990</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lintrup</td>
<td>1990</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Lemvig</td>
<td>1992</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hodsager</td>
<td>1993</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Hashøj</td>
<td>1994</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thorsø</td>
<td>1994</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Århus Nord</td>
<td>1995</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Filskov</td>
<td>1995</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinding/Studsgaard</td>
<td>1988/1996</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Blåbjerg</td>
<td>1996</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snertinge</td>
<td>1996</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Blåhøj</td>
<td>1997</td>
<td></td>
<td></td>
<td>x</td>
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</tbody>
</table>
Table 5.18. Economic situation of the Danish centralised biogas plants in 2000 (Hjort-Gregersen, 1999). The economic situation of the plant is acceptable if it produces an income significantly above break-even level; it is balanced if it produces an income at the break-even level; it is under pressure if its income is less than break-even level; and it is unsatisfactory if its income is significantly less than break-even level. Århus Nord, Sinding/Studsgard, Vjaarst/Fjellerad and Nysted also codigest organic household waste.

<table>
<thead>
<tr>
<th>Year of construction</th>
<th>Acceptable</th>
<th>Balance</th>
<th>Under Pressure</th>
<th>Unsatisfactory</th>
</tr>
</thead>
<tbody>
<tr>
<td>V. Hjermtitslev</td>
<td>1984</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegger</td>
<td>1985</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Davinde</td>
<td>1988</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fangel</td>
<td>1989</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Revninge</td>
<td>1989</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ribe</td>
<td>1990</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Lintrup</td>
<td>1990</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Lemvig</td>
<td>1992</td>
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<td>x</td>
</tr>
<tr>
<td>Hodsager</td>
<td>1993</td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td>Hashøj</td>
<td>1994</td>
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<tr>
<td>Thorsø</td>
<td>1994</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Århus Nord</td>
<td>1995</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Filskov</td>
<td>1995</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Sinding/Studsgaard</td>
<td>1988/1996</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Blåbjerg</td>
<td>1996</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Snertinge</td>
<td>1996</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Blåhøj</td>
<td>1997</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Vaarst-Fjellerad</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Nysted</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Table 5.19. Economic situation of three old, farm-scale plants in Denmark, in euros (Hjort-Gregersen, 1999a). The value of energy generation is the sum of energy savings plus energy sales. Operational costs include labour costs. The value of energy generation minus the operational costs is the net income of the plant in a year. This can be compared with the calculated break-even point for 1997, which is the minimal income in 1997 calculated to pay off the investment within twenty years, with a 6%-interest loan.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selvbyggeranlaegget (1980)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>2,040</td>
<td>1,927</td>
<td>1,586</td>
<td>1,810</td>
<td>1,627</td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>1,668</td>
<td>1,597</td>
<td>1,773</td>
<td>1,518</td>
<td>1,564</td>
<td></td>
</tr>
<tr>
<td>Net income</td>
<td>371</td>
<td>330</td>
<td>-187</td>
<td>292</td>
<td>63</td>
<td>700</td>
</tr>
<tr>
<td>Boltrupgard (1983)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>15,720</td>
<td>13,337</td>
<td>15,660</td>
<td>11,723</td>
<td>7,828</td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>9,139</td>
<td>11,400</td>
<td>12,797</td>
<td>10,001</td>
<td>7,545</td>
<td></td>
</tr>
<tr>
<td>Net income</td>
<td>6,581</td>
<td>1,937</td>
<td>2,863</td>
<td>1,722</td>
<td>283</td>
<td>10,780</td>
</tr>
<tr>
<td>Boltrupgard (1985)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>23,293</td>
<td>7,292</td>
<td>11,353</td>
<td>10,125</td>
<td>11,700</td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>12,200</td>
<td>18,352</td>
<td>12,748</td>
<td>4,308</td>
<td>14,206</td>
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</tr>
<tr>
<td>Net income</td>
<td>11,093</td>
<td>-11,061</td>
<td>-1,395</td>
<td>5,817</td>
<td>-2,506</td>
<td>19,740</td>
</tr>
</tbody>
</table>
Table 5.20. Economic situation of three commercial plants in Denmark in euros (Hjort-Gregersen, 1999a)

<table>
<thead>
<tr>
<th>Commercial plants</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>Break-even point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rade (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>25,384</td>
<td>30,103</td>
<td>20,352</td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>19,737</td>
<td>17,573</td>
<td>15,023</td>
<td></td>
</tr>
<tr>
<td>Net income</td>
<td>5,647</td>
<td>12,530</td>
<td>5,329</td>
<td>24,920</td>
</tr>
<tr>
<td>Tovsgard (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>23,618</td>
<td>51,581</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>6,193</td>
<td>12,318</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net income</td>
<td>17,425</td>
<td>39,263</td>
<td>22,400</td>
<td></td>
</tr>
<tr>
<td>Norgard (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>23,618</td>
<td>51,581</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>6,193</td>
<td>12,318</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net income</td>
<td>17,425</td>
<td>39,263</td>
<td>22,400</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.21. Economic situation of three experimental plants in Denmark in euros (Hjort-Gregersen, 1999a)

<table>
<thead>
<tr>
<th>Experimental plants</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>Break-even point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejstruplund (1994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of energy</td>
<td>2,777</td>
<td>2,782</td>
<td>3,094</td>
<td></td>
</tr>
<tr>
<td>Operational costs</td>
<td>1,890</td>
<td>2,050</td>
<td>3,871</td>
<td></td>
</tr>
<tr>
<td>Net income</td>
<td>887</td>
<td>732</td>
<td>-777</td>
<td>1,050</td>
</tr>
<tr>
<td>Risgard (1996)</td>
<td></td>
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</tr>
<tr>
<td>Value of energy</td>
<td>4,880</td>
<td>15,250</td>
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<tr>
<td>Operational costs</td>
<td>1,174</td>
<td>3,308</td>
<td></td>
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</tr>
<tr>
<td>Net income</td>
<td>3,706</td>
<td>11,941</td>
<td>8,120</td>
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<td>Houmarken (1996)</td>
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<tr>
<td>Value of energy</td>
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<td>Operational costs</td>
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<td>Net income</td>
<td>750</td>
<td>2,584</td>
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Table 5.22. Total CHP plants installed under the conversion programme for district heating systems (Ministry of Energy, 1993:16)

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<tr>
<th>Plants commissioned</th>
<th>Natural gas</th>
<th>Natural gas &amp; waste</th>
<th>Waste</th>
<th>Waste &amp; straw/wood</th>
<th>Straw</th>
<th>Biogas</th>
<th>Total</th>
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<td>1</td>
<td>3</td>
<td>4</td>
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<td>73</td>
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<tr>
<td>Power capacity (MW)</td>
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<td>28</td>
<td>44</td>
<td>25</td>
<td>7</td>
<td>337</td>
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<tr>
<td>Heat capacity (MW)</td>
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<td>43</td>
<td>87</td>
<td>114</td>
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<th>Plants approved but not commissioned</th>
<th>Natural gas</th>
<th>Natural gas &amp; waste</th>
<th>Waste</th>
<th>Waste &amp; straw/wood</th>
<th>Straw</th>
<th>Biogas</th>
<th>Total</th>
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<td>Number</td>
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<td>1</td>
<td>5</td>
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<td>Power capacity (MW)</td>
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<td>53</td>
<td>22</td>
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<td>3</td>
<td>428</td>
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<td>Heat capacity (MW)</td>
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<td>56</td>
<td>52</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>525</td>
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<table>
<thead>
<tr>
<th>All plants</th>
<th>Natural gas</th>
<th>Natural gas &amp; waste</th>
<th>Waste</th>
<th>Waste &amp; straw/wood</th>
<th>Straw</th>
<th>Biogas</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>87</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>16</td>
<td>120</td>
</tr>
<tr>
<td>Power capacity (MW)</td>
<td>548</td>
<td>88</td>
<td>50</td>
<td>44</td>
<td>25</td>
<td>10</td>
<td>765</td>
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<tr>
<td>Heat capacity (MW)</td>
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<td>99</td>
<td>149</td>
<td>114</td>
<td>52</td>
<td>15</td>
<td>1,107</td>
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</table>
Appendix 5.2: figures

Figure 5.15. Treatment of manure with additional organic waste in Danish centralised biogas plants in 1998 (Hjort-Gregersen, 1999:12-13)

Figure 5.16. Averages of biomass treated in Danish biogas plants in 1998 (Hjort-Gregersen, 1999:12-13)
Appendix 5.3: text boxes

Box 1. Guidelines for using digested manure to optimise the Danish use of minerals (Holm-Nielsen, Halberg and Huntingford, 1993:13)

- As a principle rule digested slurry should only be applied at the start of the growing season in March and April, and later on only in growing crops.
- By the establishment of spring-sown crops, the slurry must be incorporated into the soil immediately after it has been applied. The time from application to incorporation must be as short as possible to minimize ammonia volatilisation. The best thing to do is to incorporate the slurry simultaneously when spreading it.
- In overwintering crops, the crop must be started with 1/3 of the total N-requirement in mineral fertilizer. The best utilization of the digested slurry in overwintering crops is achieved in the period 15/4-1/6, when the crops are in vigorous vegetative growth. To make the slurry infiltrate quickly into the soil, dragging hose-equipment must be used.
- The risk of ammonia volatilisation can be reduced by using the right equipment (dragging hoses) and by taking the climate into consideration. The optimum weather conditions for application of slurry are when it is raining or there is very high humidity and no wind. Dry, sunny and windy weather reduces the N-efficiency considerably.
- When slurry is applied to grass crops the ammonium is very liable to volatilise if one of the following principal rules are not followed:
  - Direct injection of the slurry into the soil gives the highest N-efficiency
  - Application, if it can be done, in rain or weather with high humidity
Chapter 6.
Co-firing in Denmark

6.1 Historical overview

6.1.1 Decentralised CHP units (1990-1992)

In the early 1990s, the Danish power sector was divided into two parts. In eastern Denmark, power producers cooperated in the ELKRAFT association, while in western Denmark the power producers cooperated in the ELSAM association. The first two Danish co-firing units were established in the ELSAM area, the first by the Vejen Heat and Power Station company in Vejen (1991). The plant could be fired with waste, straw, wood chips and coal. Wood chips and waste were combusted on a traditional grate system, often used in waste incineration plants. Straw was combusted with a so-called ‘cigar-burner’. This type of burner was developed for the combustion of straw in district heating plants and in decentralised CHP plants fired with straw. In a cigar-burner, large bales of straw (‘Heston bales’) were continuously pushed into the boiler, while the straw burned at the end, inside the boiler. Ash and unburned particles fell on the grate, where the parts burned out and were removed from the boiler. Finally, the plant used a traditional pulverised coal burner for the combustion of coal. Plant capacity was small, i.e. 2 MWe and 9 MWth (Centre of Biomass Technology, 1993:33). Although the plant was capable of co-firing coal with biomass (and waste), it was mainly operated as a traditional waste incineration plant. Vejen Kraftvarmevaerk chose to co-fire waste, biomass and coal, as it was assumed that the energy content of waste (mainly hospital waste) was too low to maintain the combustion process. The results, however, showed that coal and biomass were not necessary to maintain the process. Moreover, the quantities of available waste appeared to be enough to cover maximum plant capacity. Because biomass and coal were more expensive to use than waste, Vejen Kraftvarmevaerk decided shortly after plant construction to combust waste exclusively (Centre of Biomass Technology, 1999:49; Gedbjerg, 2002).

In 1992, the Midtkraft power company began commercial operation of a second co-firing unit, a Combined Heat and Power plant (CHP) in Grenå (near Århus). The plant was of a type called Circulating Fluidised Bed plant (CFB). CFB plants were often used in decentralised

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1 In Danish: Vejen Kraftvarmevaerk A/S. The Danish company Vølund Energi supplied the boiler.
2 In a grate system the air supplied from below the grate has a low speed; combustion takes place on the grate.
3 The emission standards for waste incineration plants had also been applied.
4 In 1993, the Vestkraft power company installed another multi-fuel CHP plant in the ELSAM area, in Måbjerg. The plant primarily used municipal solid waste, although wood chips, straw and natural gas were also used (Energistyrelsen, 1999:9). In 1995, a small-scale CHP plant (16 MWe) was also commissioned in Rønne on a small island; it could co-fire coal, wood and oil (Centre of Biomass Technology, 1998:51). Only limited information about these plants is available.
coal combustion. The plants are characterised by the high speed of their air, blowing from below the fuel grate, which results in a circulation of fuel and air throughout the boiler. Midtkraft designed the plant to combust straw and coal (although sometimes other biomass like wood was used). The plant produced electricity for the grid (18.6 MWe), heat for the district heating network in Grenå, and heat for three nearby factories. The amount of straw could be varied from 100% coal to 60% coal and 40% straw; in general the plant operated on a 50-50 basis. Trucks transported the coal from an existing coal terminal in Århus to Grenå. In Grenå, automatic cranes carried the coal to a coal mill, from which it was further transported by a conveyor to two storage bins (Jacobsen, 1999:4). Straw was also transported to Grenå by truck. Midtkraft had drawn up a contract with a supplier association of farmers. The farmers produced and supplied Heston bales, transported to Grenå by trucks. A crane, capable of unloading twelve bales at a time, picked up the bales and put them in a storage building at the power plant location. A shredder first reduced the size of the straw, before a pneumatic system desposited the straw to the boiler. The plant combusted about 55,000 tons of straw per year (Jacobsen, 1999).

In general, the plant operated satisfactorily. However, there were several problems, in particular due to the specific characteristics of straw. First, straw availability depended on many circumstances (e.g. the weather conditions). The availability of straw within an acceptable distance could range between 0.5 Mton and 1.1 Mton per year. These amounts of straw were enough for the Grenå plant, but calculations showed that competition with other power plants could become a major problem in the near future. Second, there were economic problems. Straw was much more expensive than coal. Besides a higher cost price, straw required a larger and more complex storage and handling system. Third, the Grenå plant had technological problems. The presence of rocks in the straw bales, for example, caused machinery to fail. Ropes, used to tie the straw together, caused problems, too. The shredders needed regular maintenance because of the ropes, and they had to be stopped and cleaned every day. Finally, the straw contained high levels of chlorine, causing corrosion in a part of the CHP plant called the superheater (Morrison, 1996:41; Järvinen and Alakangas, 2000:19).

### 6.1.2 Centralised co-firing (1993-2000)

After 1993, the development of co-firing shifted towards co-firing in centralised power plants. ELSAM investigated several trajectories for co-firing. The first trajectory was to develop large scale CFB plants, similar to the Grenå plant for the combustion of coal and biomass. Though they investigated this route, ELSAM never implemented a second CFB plant. The second trajectory, the use of gasification technology, never moved from the research phase to the pilot plant phase, and power associations considered this option a long-term R&D trajectory. Two other trajectories, however, resulted in the implementation of a number of

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5 A superheater is a regular component in power plants and increases steam temperature to improve the efficiency of the steam turbine.

6 ELSAM and ELKRAFT did carry out a joint research programme with tests in Germany, Finland and the Danish Risø laboratory. The tests generally showed that gasification of straw alone was extremely difficult and
co-firing units. The first one was indirect co-firing of straw in pulverised coal boilers. ELSAM investigated this technology at the Studstrup power plant. The second unit was for parallel co-firing, i.e. the integration of a separate biomass boiler into the steam cycle of a fossil fuel power plant (see also section 1.4 in Chapter 1). ELSAM constructed a biomass boiler near the Ensted power plant, and ELKFRAFT also investigated this route. Together with the SK Power Company, they constructed a completely new gas-fired power plant using parallel and indirect biomass co-firing, i.e. the Avedøre 2 power plant near Copenhagen. I will discuss these plants below.

In 1993, ELSAM implemented a research and demonstration trajectory for indirect co-firing. Tech-Wise (an engineering company fully owned by ELSAM) was responsible for the programme. Tech-Wise first cooperated with the Vestkraft power company for tests with cofiring in a 150 MWe unit in Esbjerg. To enable straw combustion, the research institute replaced two coal burners with biomass burners, and constructed a straw processing unit. The straw processing unit consisted of two subunits, each with a feeding line for Heston bales and a straw cutter. An air blower transported the straw pieces from the straw cutter through a pipe and into the biomass burners (Figure 6.1). During the test period, from October 1993 to March 1994, 15,000 tons of straw were co-fired with 63,000 tons of coal (Petersen and Hansen, 1994).

Figure 6.1. Straw processing unit at the Studstrup power station (Petersen and Hansen, 1994)

The researchers argued that, in general, results from the experiment were promising: to co-fire straw in a pulverized coal boiler was possible. There were no serious consequences, even up to a straw share of 30%. However, they argued that several problems still needed further investigation. First, the straw processing system did not meet capacity and durability hardly feasible, while co-gasification of a certain amount of straw might be technically possible. In 1993 and 1994, two small wood gasifiers in Harboøre and Høgild were installed, but no gasifiers were installed for co-firing (Madsen and Christensen, 1996:1067; Davidson, 1997:6; Rasmussen, 1995; Madsen and Christensen, 1994; Energistyrelsen, 1999).
expectations, causing interruptions in the co-firing process. Second, the experiments showed that co-firing straw endangered the use of fly-ash (ashes produced in flue gas cleaning) for the production of cement, in particular when the amount of straw comprised more than 10% of the plant’s energy input. If the ashes could not be used for cement production, they had to be dumped on a landfill, thus involving high processing costs. Finally, the results indicated that the power plant suffered from rising corrosion rates due to large amounts of chlorine in the straw. High corrosion rates could seriously damage the plant, resulting in high maintenance costs (Petersen and Hansen, 1994).

ELSAM and Tech-Wise decided to perform more tests on the handling and preparation of straw for power production. They experimented with several manners of straw preparation at the Midtkraft power station in Århus in 1994 and at the Studstrup power station in 1995. The experiments showed again that processing and combusting straw in a power plant was very difficult and required more advanced processing equipment. Despite the poor results, ELSAM decided to convert Unit 1 of the Studstrup power station into a permanent co-firing unit, and started a two-year demonstration programme in 1996 (Davidson, 1999:8; Lauridsen et al., 1994).

Tech-Wise used technologies similar to those in the previous experiments. They adjusted three coal burners, so that they could fire coal and straw together (Figure 6.2). This was only a minor adjustment. The straw handling system required the construction of a new system, consisting of a storage facility and a processing building. Midtkraft agreed with the local authorities that straw transport would take place during working hours and that they would not transport straw in the weekends (to avoid inconveniencing neighbouring residents). It was therefore necessary to have a large storage capacity, capable of storing over a thousand Heston bales. Trucks transported the bales. A crane similar to the one in Grenå unloaded the bales. A new tool using microwave techniques measured the water content. These data were sent to a computer and were used for paying the farmers. Conveyors transported straw from the storage to the processing facility (Figure 6.3). In the processing facility, four parallel lines transported the straw through shredders and a stone trap (to remove purifications), and into a hammer mill. The straw left the mills in bits shorter than thirty or fifty mm (depending on the sieve). A pneumatic transport system fed the straw pieces into the boiler. Each straw line was capable of processing five tons of straw per hour. In total, these lines could process an amount of straw equivalent to 20% of the boiler’s total heat input (Wieck-Hansen, Overgaard and Larsen, 2000).

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7 This was based on the assumption that a higher humidity resulted in a lower straw energy content and thus in lower energy sales. If the humidity was too high, it could even damage the processing equipment and endanger the combustion process.
The objective of the demonstration program was to show the viability of co-firing coal and straw in a pulverised coal boiler on a long-term basis. Program results varied. The researchers had expected that in particular corrosion would be a major problem, based on previous experiments. The demonstration project, however, showed that corrosion did increase, but that it was still below the upper limits of commonly used coal. Another chemical reaction turned out to be a bigger problem. When some chemical elements (in particular alkali metals like potassium) are heated, these chemicals tend to deposit on the surface of the combustion unit. This process is called fouling. At higher temperatures, these deposits melt (called slagging), which can seriously damage the boiler and result in unforeseen plant shutdowns. Slagging and fouling turned out to be major problems, because of the high content of alkali metals in the straw. Also the straw handling system continued to have problems – despite
earlier optimisation tests in other plants – mainly due to the high moisture content in the straw and contaminants like stones and ropes. A decent quality check of the incoming straw was essential to prevent plant breakdowns. Finally, the researchers investigated several environmental parameters. Most of them were promising: NO\textsubscript{x} and dust emissions decreased; SO\textsubscript{2} increased somewhat. Again, a major problem turned out to be the deposition of fly-ashes. Ashes were used in the cement and concrete industry. A European standard for the concrete industry (the ‘EN450 standard’) dictated that the bottom ashes had to come from coal combustion (and not from other sources like co-firing). Therefore, the ashes from co-firing could not be used for concrete production. Furthermore, fly-ash for the production of cement was not feasible, because of agreements between the Danish power industry and the Danish cement industry (Wieck-Hansen, Overgaard and Larsen, 2000).

The test programme at Studstrup ended in 1998. Unit 1 was taken out of operation because of its age and due to a surplus of power generation capacity in Denmark. ELSAM decided not to continue indirect co-firing of straw and coal in another plant, but to focus on parallel co-firing. In 1994, the association decided to construct a parallel biomass boiler at the Ensted power plant, near Aabenraa, in the south of Jutland. The plant began operating in 1998. The main fuel of the biomass boiler was straw, but wood was used as a fuel for superheating the steam temperature (Figure 6.4). Wood contains less chlorine than straw and therefore caused less corrosion at higher temperatures. The straw boiler operated at 470°C. The second boiler combusted wood chips and superheated the steam to 542°C.\textsuperscript{8} The straw boiler could combust 120,000 tons of straw per year and the wood boiler another 30,000 tons of wood chips. Farmers produced the straw; trucks transported it to the power plant. At the power plant, a system similar to that in Studstrup unloaded, processed and stored the straw. A quality control system similar to that at the Grenå CHP plant controlled the straw quality. Specialised producers, located within a 200 km radius of the plant, supplied the wood chips. The total capacity of both boilers was 88 MWth (equivalent to 40 MWe power capacity). The heat produced in the boiler was fed into the existing infrastructure of the coal-fired boiler, a 660 MWe unit. A steam turbine produced power and supplied it to grid. Heat was supplied to the local district heating system (Ramsgaard-Nielsen, 2001:64; Cadet, 2000b; Sørensen and Jespersen, 1996; Fernando, 2002:17).

\textsuperscript{8} Both boilers were grate boilers, similar to the one in Grenå and often used in biomass fired boilers and waste incinerators. A major difference with the combustion of biomass in a pulverised coal plant is the required size of the biomass. Combustion in a pulverised coal requires a much smaller straw size than combustion in a grate boiler.
The power company operated the plant as a commercial unit, but it did not operate satisfactorily. The main problems were similar to the problems in other plants that combusted straw, including poor operation of the straw handling system and slagging and fouling in the boiler. In addition, corrosion occurred at high temperatures – despite the use of wood – and a major superheater repair was necessary in 2000. The plant only operated at 58% of planned capacity in 1998, at 73% in 1999 and at 54% in 2000 (Ramsgaard-Nielsen, 2001; Fernando, 2002).

The power associations in eastern Denmark, cooperating in ELKRAFT, also experimented with co-firing straw in the 1990s. In mid-1994, SK Power Company (one of two large power producers cooperating in ELKRAFT) conducted a one-week experiment at the Amager power plant, Unit 3, near Copenhagen. Unit 3, with a capacity of 263 MWe, had been commissioned in 1988 and was fuelled entirely by coal. The plant produced power for the grid, and heat for the district heating system in Copenhagen. SK Power Company did not make any adjustments to the power plant. They bought (experimental) straw pallets, which could be handled and fired in the same way as coal. During the experiment, straw pallets and coal were co-fired for four days with a straw share of 11% and for one day with a straw share of 22%. SK Power Company conducted a second experiment for four weeks in 1995 at the Kyndby power station in northern Sealand. The aim of the experiment was to test whether the coal processing equipment was able to handle the straw pallets. In this experiment, only straw was fired, without coal. The results from both experiments were very uncertain, in particular because of the experiments’ brief duration; long-term effect on the equipment and power plant could hardly be measured. In particular, it remained unclear whether corrosion would occur in the long term. SK power company, however, was explicit about one thing: the economic
Co-firing in Denmark

profitability of co-firing straw pellets was highly doubtful, due to the manufacturing costs of the pallets (Christensen and Jespersen, 1996).

ELKRAFT and the associated power producers mainly focussed on the construction of separated biomass boilers connected to fossil fuel plants. They designed two plants. The first one was a 41 MWe straw-fired boiler. This boiler’s steam cycle was to be integrated into the cycle of an existing coal-fired power unit at the Asnaes Power station in north-western Sealand. Despite much research on the matter, ELKRAFT never constructed the plant, the main reason being the ongoing development of a completely new power plant, which also applied co-firing technology. This plant was the Avedøre Unit 2, a power station near Copenhagen. SK Power began developing the plant in 1989, and finished the first design in 1992. The original plant design consisted of a coal-fired boiler in combination with a gas turbine. At that stage, the biomass boiler was not yet integrated into the plant plan (Noppenau, 2002:5). In 1994, SK Power changed the design and added a straw boiler and wood chip-fired superheater to it (Christensen and Jespersen, 1996). SK Power applied for authorisation, but the Danish Energy Agency (DEA) rejected the application in 1996. One year later, SK Power company submitted a second application. This one differed from the first in three ways. First, they changed the main fuel from coal to natural gas. Second, the application included a strategy to phase out several older production units, immediately after production was to begin at the Avedøre Unit 2, including the unit at the Asneas power station. Closing older power plants increased the environmental performance of the overall energy system, because most of the older plants had lower efficiencies and were not equipped with NOx and SO2 filters. Finally, the SK Power company emphasised the need for Avedøre 2, with new estimations of the heat demand in Copenhagen (Nielsen and Sørensen, 1998:23).

Now the DEA did approve the plant, and SK Power company could start the construction of Avedøre 2. The plant’s main boiler was an Ultra Super Critical plant (USC), the state-of-the-art in combustion technology and capable of operating at a high temperature and pressure. The plant comprised three generating units (Figure 6.5). The main unit (a 430 MWe boiler) combusted natural gas, although it could also combust coal and oil. All the equipment was installed for coal combustion, except the coal mills. The second unit (also a boiler) combusted biomass and was one of the largest biomass boilers in the world at the time of construction (about 40 MWe). The boiler was designed to fire 150,000 tons of straw per year. Finally, a pair of gas turbines provided peak load capacity, and produced heat for preheating the feed water for the main boiler. Heat from the three units was supplied to a steam turbine plant for the generation of electricity. Remaining heat was supplied to the district heating network of Copenhagen (Noppenau, 2002; Mosbech, 2002; Fernando, 2002, Anonymous, 2000).

SK Power's application for the plant included a large number of arguments, from arguments referring to the reduction of carbon dioxide emissions and the 1993 Biomass Agreement (see section 6.2), to the growing demand for heat in the Copenhagen area, and to the advantages for the Danish power industry. Furthermore, the plan for the Avedøre 2 was closely related to an agreement between SK Power and Vattenfall, a Swedish company, about future jointly owned plants. Vattenfall would buy a share of 40% in the Avedøre 2 unit, while SK Power would buy 800 GWh per year of Swedish hydropower by buying stocks in one of Vattenfall’s hydro power plants (Nielsen and Sørensen, 1998:22).
Figure 6.5. Layout of the Avedøre Unit 2. The unit exists of a biomass boiler using straw, an Ultra Super Critical boiler designed for coal, gas and oil combustion, and a gas turbine with heat recovery unit. The steam cycles from all units are integrated into one steam turbine plant, producing electricity and heat.

The plant began operations only in 2002, and data on experiences with the plant are limited. Early results did show that the biomass boiler had problems with fouling, but ELKRAFT expected that it would be able to deal with the problems (Noppenau, 2002). Besides the Avedøre 2, ELKRAFT did not implement any other co-firing unit in eastern Denmark.


In 2000, only two co-firing units were in operation, i.e. the small indirect co-firing unit at the Grenå plant and the Ensted power plant with a parallel biomass unit. ELSAM had not continued the co-firing experiment in Studstrup and the Avedøre 2 plant was not yet in operation. The associations, however, tried to increase the amounts of biomass and to implement new co-firing plants. ELKRAFT (now called Energi E2 due to a merger of several power producers in eastern Denmark) began operating the Avedøre 2 plant, but made an important adjustment to the plant. Even before the plant went into operation, Energi E2 decided that the main boiler was to be converted so that it would also be able to fire wood chips (together with natural gas). The company made a new proposal to the government. A nearby factory that produced wood floors had plans for the construction of a wood-fired CHP plant. Energi E2 proposed to the government and the factory that Energi E2 would build a factory for making wood pallets from the factory waste and combust the pallets in the main (gas-fired) boiler of the Avedøre Unit 2. In return, E2 asked that a minimum price be guaranteed for the power produced from the wood pallets, and that it be released from the duty of using specific amounts of natural gas per year. E2 also needed permission to construct...
mills for grinding the wood pallets. The government and the wood factory agreed to the conditions, and E2 began reconstructing the Avedøre Unit 2 (Noppenau, 2002:6).

ELSAM also continued co-firing after 2000. Despite their earlier decision to focus on parallel co-firing, ELSAM decided to convert Unit 4 of the Studstrup power station into an indirect co-firing unit. The straw handling system (still in place from the demonstration programme at Unit 2) could be used for this purpose. The plant came into operation in 2002, increasing the amount of biomass used by ELSAM by 86% as compared to 2001. Furthermore, ELSAM converted a coal-fired CHP plant in Herning (89 MWe) to a natural gas-fired plant in 2000, followed by a second conversion of the plant to a co-firing unit for natural gas and wood chips in 2002. The plant could co-fire 200,000 tons of wood chips on a yearly basis, equivalent to 55% of the plant’s total heat input. The wood chips were fired on a grate inside the boiler, while the natural gas was combusted in special natural gas burners (Ramsgaard-Nielsen, 2001:165; Overgaard, Kierkegaard and Junker, 2002; ELSAM, 2003:17; Sander, 2000:775).

Conclusion
The Danish utilities had implemented the following co-firing units in 2002 (Table 6.1). In western Denmark, there was one decentralised CHP co-firing plant (Grenå), a large pulverised coal plant converted into an indirect co-firing unit (Studstrup), and a small coal-fired CHP plant, converted into a natural gas plant that also co-fired wood chips indirectly. Finally, ELSAM had constructed a parallel biomass boiler and integrated it in the Ensted power plant. In eastern Denmark, Energi E2 had constructed one co-firing unit, i.e. the Avedøre 2, using parallel co-firing for straw and indirect co-firing for wood pallets.
Table 6.1. Biomass and coal co-firing initiatives in Denmark

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<th>Year</th>
<th>Plant</th>
<th>Co-firing concept</th>
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<th>Biomass capacity (MWe)</th>
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<td>Grenå (ELSAM)</td>
<td>Indirect co-firing</td>
<td>18.6</td>
<td>9.3</td>
<td>Coal/straw: 70,000 tons straw</td>
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<tr>
<td>1998</td>
<td>Enstedvaerket</td>
<td>Parallel co-firing</td>
<td>660</td>
<td>40</td>
<td>Coal/straw/wood chips: 120,000 tons straw 30,000 tons wood</td>
</tr>
<tr>
<td>(ELSAM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>Studstrup 4</td>
<td>Indirect co-firing</td>
<td>350</td>
<td>35</td>
<td>Coal/straw: 250,000 tons straw</td>
</tr>
<tr>
<td>(ELSAM)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2002</td>
<td>Herning</td>
<td>Indirect co-firing</td>
<td>89</td>
<td>49</td>
<td>Natural gas/wood chips: 200,000 tons wood chips</td>
</tr>
<tr>
<td>(ELSAM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>Avedøre 2</td>
<td>Parallel and indirect co-firing</td>
<td>615</td>
<td>40</td>
<td>Natural gas/straw/wood: 150,000 tons straw 300,000 tons wood pallets</td>
</tr>
<tr>
<td>(Energi E2)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total</strong> 173.3</td>
</tr>
</tbody>
</table>

The historical overview shows that Denmark developed a substantial number of co-firing units since the early 1990s, representing a total biomass capacity of 177.3 MWe in 2002, a figure equivalent to 1.3% of the total power capacity installed in 2002 and 2.2% of total centralised power capacity. Several questions and puzzles emerge from the overview. The first puzzle is why the Danish utilities began to develop co-firing units in the first place; what were the incentives to adapt to new fuels and technologies? I will investigate this in the analysis below. The second puzzle is: why did the associations focus so much on straw combustion, and continue to do so, despite the technical difficulties of straw co-firing? The third question is: why did ELKRAFT focus on constructing separate biomass boilers, while ELSAM focused on indirect co-firing, a less expensive option? The fourth question is: why did ELSAM return to co-firing after 2000, despite earlier decisions to focus on parallel co-firing? Previous experiments had shown the difficulties of this indirect co-firing, yet the association still decided to construct a permanent indirect co-firing unit in 2002. The fifth question is: why did the Danish government reject ELKRAFT’s application for the construction of the Avedøre 2 in 1994, despite their plant design, which included a large

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10 Circulating Fluidised Bed
11 Pulverised Coal
12 10% of total energy input
13 Data from ELSAM Website, based on 55% heat input of the boiler.
14 Total capacity including natural gas fired boiler, biomass boiler and gas turbines.
15 This is the biomass boiler capacity. If wood chips replace natural gas in the main boiler, the total biomass capacity increases. Conversion of the unit has already started and E2 expects to use 300,000 tons of wood chips in the main boiler (Energi E2, 2002:20)
16 The biomass boiler can fire a maximum of 150,000 tons of straw annually, but straw can be replaced by wood chips. In addition, wood chips are being co-fired with natural gas in the main boiler.
17 Total power capacity in 2002 in Denmark was 13,210 MWe. Total central power capacity (large-scale units owned by the utilities) was 8,220 MWe in 2002 (Energistyrelsen, 2003).
Co-firing in Denmark

biodiesel boiler? I will try to answer these questions in the analysis of niche processes below. The questions I cannot answer will be investigated in the regime analysis of section 6.4.

6.2 Analysis of niche dynamics

6.2.1 Visions and expectations

In the early 1990s, the Danish utilities did not have a strong vision or high expectations about co-firing. In 1986, the main political parties agreed that further growth in the electricity sector was to be achieved through the construction of decentralised units instead of large-scale production units (see also sections 5.4 and 6.4). In that year, the government and opposition reached an agreement that instructed the electricity associations (cooperating in ELSAM and ELKRAFT) to establish decentralised CHP plants based on natural gas, biomass and waste, equivalent to 450 MW before 1995. In 1990, another agreement instructed district heating associations to switch over to CHP plants, either based on natural gas or biomass. ELSAM mainly left the construction of decentralised CHP to a newly emerging group of actors (decentralised producers), while ELKRAFT more or less incorporated the decentralised development into their strategies; they participated in the construction of decentralised CHP, including some plants based on biomass. However, these plants were constructed as part of a strategy towards decentralised production rather than towards replacing coal with biomass.

In 1993, the political parties made another agreement about the replacement of coal within centralised energy generation, with the aim of reducing carbon dioxide emissions. This agreement (The Biomass Agreement) dictated that ELSAM and ELKRAFT use 1.4 million tons of biomass by the year 2000, equivalent to 19.5 PJ primary energy. The biomass was divided into 1.2 million tons of straw and 0.2 million tons of wood, and the obligation was divided between the two associations. This agreement created visions about co-firing; niche actors (such as researchers from Tech-Wise) used the agreements to legitimise their research and development activities in the field of co-firing, and to acquire financial resources. Rasmussen and Overgaard of the Midtkraft company argued as follows (1996:158):

The Danish utilities have been committed to specific targets both for biomass application (year 2000) and also for CO$_2$ (year 2005). As part of the efforts to develop viable technologies, the Danish power pool ELSAM has recently committed the equivalent of ECU 215 million in medium-sized demo plants, based on co-combustion technologies.

In another research publication, Sørensen and Jespersen of the SK-Power Company and the Ensted power plant company argued as follows:

In order to fulfil the objective of the Danish CO$_2$-reduction policy and the Danish biomass policy, both the ELSAM group and SK-Power Company have been investigating various concepts of replacing coal with biomass at the central power stations. [...] A solution requiring low capital investments is co-firing of coal and straw in existing pulverised-coal plants.
Researchers in the ELSAM association decided to focus on demonstrating the co-firing concept in three ways.\textsuperscript{18} They expected that in the short term, indirect co-firing in pulverised coal plants was the most promising option, because it was inexpensive and could be implemented with no major technological risks. On the basis of experiments in Grenå, the association also thought that co-firing in CFB plants was a promising option. Finally, ELSAM expected that stand-alone power plants and parallel co-firing were a promising third route for biomass combustion, in particular when indirect co-firing turned out to be difficult. Tech-Wise, the engineering company fully owned by ELSAM, later interpreted the three development routes as follows:

Our company was at that time looking at technologies for the conversion of biomass. We had a three leg solution. The first, co-firing in pulverised coal plants, was a dirty, short term and cheap solution. Dirty because it was connected to coal, short term because it has a short term perspective, because at that time at least there was a policy plan to take coal out of the energy production sector in Denmark. The second option was the fluidised bed combustion of biomass. We have a fluidised bed unit, a small one, originally designed to fire 50% coal and 50% biomass and the aim was of course lowering the amount of coal. The third one was the stand-alone biomass combustion, which is a fixed bed. Already in 1993 or maybe earlier, ELSAM decided that they should investigate these three technologies (Overgaard and Friborg, 2002).

ELSAM tested their expectations for the three routes in several trajectories (see previous section). The experiments with co-firing straw showed that straw was a difficult fuel, in particular due to pre-processing problems and corrosion, slagging and fouling. This motivated ELSAM to put more emphasis on developing parallel combustion. They expected that parallel co-firing could solve some of the problems – despite higher costs. In a joint contribution of ELSAM and ELKRAFT researchers, some of the early optimism on the direct co-firing of coal and straw was moderated:

The perspectives of these separate biomass-fired boilers depend on the test results from the co-firing boilers. If the co-firing concept manages to eliminate the mentioned problems, the central power stations will prefer the co-firing concept either as pulverised coal/straw plant or as CFB-boiler plants because of the lower investment required. On the contrary if co-firing does not succeed the separate biomass-fired boilers will be the only alternative in replacing coal with biomass at the central power stations as long as the biomass gasification process is not commercialised (Sørensen and Jespersen, 1996:191).

The experiences at the Studstrup power station affected the choice of co-firing technology. The recycling of fly-ashes in cement production and the corrosion in super heaters turned out to be a large problem (see also section 6.2.3). I conclude that the experiments at the Studstrup power station changed the expectations of ELSAM and Tech-Wise and explains the decision to move towards parallel co-firing in the late 1990s.

From the outset, the ELKRAFT association had a different vision on biomass and co-firing. The Biomass Agreement also forced this association to buy large amounts of biomass

\textsuperscript{18} Gasification of biomass was considered a long-term R&D activity. See footnote 6.
by the year 2000, but ELKRAFT focussed on developing stand-alone biomass applications (not connected to existing power plants). One of the reasons for doing so was a strong emphasis on the ability to recycle by-products of the combustion processes. The general manager of the ELKRAFT R&D department considered the landfill of fly-ashes an unacceptable solution:

Ash residues from central power plants are today recycled and used for cement production. Likewise, gypsum today is used for plasterboard production. Ash residues from straw-fired CHP and district heating plants are also taken back by the farmers supplying the plants and spread as fertilizer. Mixing coal and straw may render the mixed ash and residue quality impossible to use for industrial purposes, which again would mean the unacceptable solution of landfill (Mosbech, 1994:12).

In 2002, he emphasised the difference with ELSAM regarding by-products:

One of the main reasons [for focussing on mono-fuel plants] is that we did not want any residues that had to be deposited. That has been a sort of principle. That is why the mixed residues of co-firing are a problem. ELSAM has not been so strict on that. You can also see that for example in the desulphurisation technologies for coal-fired power stations. We chose the more expensive one, which produces gypsum while ELSAM, at least in the beginning, also used semi-drying, a technology which also produces a mixture. I believe that they by now have found some way of using it, but it shows that ELSAM has been less principled on using residues. So the re-using of the end products was a very important reason why we chose the one-fuel concept (Mosbech, 2002).

ELKRAFT constructed one co-firing unit at the Avedøre plant. The construction of a new high-tech coal plant was, in ELKRAFT’s view, environmentally superior to co-fire biomass in old low-efficiency coal boilers (Mosbech, 1994:13).

After 2000, the associations changed strategies again. Both associations began to focus on indirect co-firing, resulting in the construction of several co-firing units. The construction of these units was strongly linked to ongoing developments towards liberalisation at the regime level (see section 6.4).

Finally, the associations also began to develop ideas about co-firing waste in power plants, primarily for economic reasons. The experiments with co-firing biomass spawned these new ideas. Hakon Mosbech (2002) of Energi E2 argued as follows:

A disadvantage throughout all technological routes (stand-alone biomass, separated biomass boilers, direct co-firing and gasification) is that straw is a very expensive fuel. The farmers know that we have to buy it because of the biomass agreement. From their point of view straw is not really a waste product and they are used to being paid to get rid of it. So we also tried to use a little bit of waste with a negative prices in the plants. Our biomass activities actually increased our interests in the waste sector. The classification of what biomass is and what waste is has more or less blurred. The line is not clear anymore.

The association began to develop a new view on the combustion of biomass and waste, resulting in new ideas about the difference between biomass and waste. Although the Danish associations have not yet experimented with co-firing waste in fossil fuel plants, this new
vision may trigger such experiments in the near future, but this was not (yet) tested in experiments.

**Conclusion**

The expectations about co-firing were directly linked to political agreements made in the late 1980s and early 1990s. In the early 1990s, the associations did not have a strong vision on co-firing. The 1993 Biomass Agreement changed their visions, and the associations began to experiment with co-firing. ELSAM had strong expectations about indirect co-firing, but experiments did not support the expectations. ELSAM began to focus on parallel units in the late 1990s, while ELKRAFT focussed on stand-alone units from the beginning, in particular because of a stronger emphasis on recycling residues. I conclude that visions and expectations about co-firing were created by political agreements, but that results from experiments did result in changing expectations, explaining a process of niche branching from indirect co-firing to parallel co-firing in the late 1990s. In the early 2000s, the associations also developed new ideas about co-firing waste.

### 6.2.2 Network formation

In this section I discuss the social network that was involved in co-firing. The associations ELSAM and ELKRAFT and the cooperating power producers (e.g. Midtkraft and SK Power) were the main actors in co-firing. However, the Danish Energy Agency also played an important role, especially in implementing and discussing the political agreements on biomass with the associations. Other relevant actors I discuss are biomass suppliers, research institutes and technology suppliers.

**Production companies and power associations**

The most important actors in the co-firing niche in Denmark were the associations ELSAM and ELKRAFT and the power producers that cooperated in these associations. The 1993 Biomass Agreement dictated that the two associations fulfil the agreement, but production companies were closely involved in the actual implementation. These companies operated the coal-fired power plants. Co-firing mainly developed within this stable social network. The research, development and experiments of co-firing technologies have mainly been carried out by (the R&D institutes of) ELSAM and ELKRAFT, in cooperation with the production associations.

For developing co-firing plants, the associations relied on existing R&D knowledge inside the associations or on established relations with other research institutes. In the ELSAM area, the research institute Tech-Wise developed and tested the indirect co-firing concept in the Studstrup plant. In the case of separate biomass boilers, the associations could rely on earlier experience with (small) biomass-fired boilers (see Table 6.2).
The energy associations also used knowledge and experience from waste-fired plants and biomass-fired, district heating plants. In these cases, the associations cooperated with the technology suppliers. The general manager of the Energi E2 R&D department stated the following:

We started with the technology of burning straw in small steam boilers. The first one was in operation in 1989, the second in 1990, and the third in 1992/1993. Waste incineration plants heavily inspired the technology for these plants, the grate fired plants. Also some new ideas came up. One of these was the feeding-in system. [...]. The second inspiration for the technology of these plants came from a few district heating boilers, which the owners of the plants (municipalities or cooperatives) had already converted to straw-fired for economic reasons (previously they were fired by oil). Together with the manufacturers they developed straw-fired district heating boilers. We could use some of this knowledge (Mosbech, 2002).

The Biomass Agreement was external pressure on a social network that had existed for a long time (ELSAM, ELKRAFT, production associations, research institutes, technology suppliers). In earlier niches (stand-alone biomass combustion), this network had built up experiences with straw combustion, which they could now use to implement the Biomass Agreement.

**Danish government and Danish Energy Agency**

The national government pushed the development of co-firing technologies by means of political agreements. The Danish Energy Agency carried out most of the negotiations with the energy sector. Two agreements forced the central energy associations to develop technologies with improved environmental characteristics. The first agreement (1986), between the government and the Social Democratic Party, dealt with the future expansion of the Danish electricity supply. They decided that the power associations should construct 450 MWe CHP power before 1995. The agreement only allowed for domestic fuels, i.e. natural gas, straw, wood chips and biogas. The first 80-100 MWe were to serve as a demonstration project. The plants’ economic and technological feasibility would be monitored. If the results were promising, then expansion could be continued (Energiministeriet, 1986). This agreement contained no specific incentive for developing co-firing units. The government aimed to increase CHP capacity and the use of domestic fuels. The production associations mainly developed mono-fuel plants, in particular based on natural gas (see section 6.4). The 1993

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19 300 MWe in the ELSAM area and 150 MWe in the ELKRAFT area.
biomass agreement was different. The government aimed to reduce the use of coal in the central power sector by dictating the power associations to buy 1.2 million tons of straw and 0.2 million tons of wood annually by 2000 (Energiminstieriet, 1993). This agreement was a strong incentive for developing biomass conversion technology in general, but especially co-firing technology.

ELSAM and ELKRAFT challenged the interpretation of the biomass agreement. One of the main issues in the negotiations between the energy sector and the DEA was the choice to define the biomass as 1.2 million tons of straw and 0.2 million tons of wood. Straw was the dominant source of biomass in Denmark, but the government could have left the choice to the power associations. The associations feared high straw prices; the agreement created a monopoly for the fuel suppliers (farmers). The definition of biomass in the agreement continued to be discussed in the 1990s. In 1997, the government decided to revise the biomass agreement and give more freedom to power associations with regard to fuel choice. ELSAM and ELKRAFT were still obliged to use biomass corresponding to 19.5 PJ, but now had to buy a minimal amount of 1.0 million tons of straw (instead of 1.2 million). The remaining part could either be wood chips, straw or willow chips. The revision gave the power associations more flexibility in fuel type. Nevertheless, the biomass definition remained narrow, as compared to emerging biomass definitions within Europe (see Chapter 4) (Energiminstieriet, 1997).

The narrow definition of biomass in the agreements was a disadvantage for the power associations. The definition forced them to develop technologies for combusting straw, a particularly difficult fuel due to its high alkali and chlorine content. The advantage, however, was that there was no discussion on emission standards, as was the case in the Netherlands (see Chapter 4). The definition of biomass did not cause any troubles in implementing co-firing plants or biomass-fired plants in Denmark. At Tech-Wise, the head of the biomass division argued the following:

> When we talk about biomass in Denmark we have a clear definition of what biomass is and what waste is. This definition is not only straw and wood, but also other types. The idea is that the biomass is not polluted. Of course you can call the straw on the fields waste, but it is clean biomass and therefore not considered as waste (Overgaard and Friborg, 2002).

The discussions between the power associations and the Danish Energy Agency resulted in the delayed implementation of the Biomass Agreement. In 2000, the utilities combusted 400,000 tons of biomass in about 10 plants, two of which were co-firing units. In 2000, the government decided to implement a second revision of the 1993 biomass agreement. Although the objectives remained the same, the time of compliance was now 2005. An important reason for postponing the deadline was that the Danish Energy Agency

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20 Denmark had implemented the European guideline on large combustion plants in 1990 (Ministry of the Environment, 1991). This regulation was a general standard for solid fuels used for energy production in plants larger than 50 MWe, it also applied to wood chips and straw combustion. In 1997, the Ministry implemented a statutory order on biomass waste, which employed a broader, yet strictly defined, definition of biomass (Ministry of the Environment and Energy, 2000). This definition was used to determine the emission standards for biomass combustion plants of a size smaller than 50 MWe (Ministry of the Environment, 2002).
acknowledged the technical difficulties of straw firing (Pedersen, 2002). The government implemented new regulations to improve the plants’ economic feasibility. These regulations were profitable for the power associations. Overgaard and Friborg of Tech-Wise argued as much:

A new energy plan was made in which the government said that if the utilities fulfilled the biomass agreement, they would get a premium price of fifty øre per kWh plus ten øre from the CO₂ emission fund. What then happened was that it became feasible to establish these plants and another unit later on; there were three units established burning 225,000 tons of straw annually (Overgaard and Friborg, 2002).

I conclude that decisions on the parts of the national government and the Danish Energy Agency strongly affected the development and implementation of co-firing plants in Denmark. The Danish Energy Agency has taken a strong position in the network, remaining close to the initial 1993 agreements, but still allowing the power associations to negotiate the interpretation of the agreement, based on experimental results. This interaction culminated in the early 2000s with most of the co-firing plants being fuelled with straw, despite the technical difficulties of straw firing in general.

Fuel suppliers
There are two types of fuel suppliers in Denmark, suppliers of straw and suppliers of wood. Danish farmers are the main suppliers of straw. They produce straw as a by-product of commercial crop farming (primarily grain). The annual production of straw can vary up to 30%, depending on for example climate conditions and the type of crops produced. In 1996, farmers produced six million tons of straw on 1.55 million hectares of farming land (representing about 46 million PJ of energy). The farmers use the straw for several purposes. The major part is used in agricultural applications like feeding, bedding in livestock housing systems and drying of grains. A large part is ploughed back into the soil, which can (potentially) be used for energy generation.21 Figure 6.6 shows that between 1991 and 1996 the straw surplus decreased, while the use of straw for energy generation (small-scale and central power production) increased (Centre of Biomass Technology, 1998:9; Anonymous, 1999a:4).

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21 Although the straw – which is ploughed back into the soil – is characterised as surplus straw from the viewpoint of energy generation, it has a useful application from an agricultural point of view: the straw increases the organic matter content of the soil, which increases the fertility.
The farmers in Denmark are familiar with supplying straw for power production. They developed standardised manners of straw trading in the 1980s, when straw was increasingly being used for district heating purposes. Generally, farmers and energy associations traded straw through so-called crop delivery contracts for several years. These contracts included conditions like the duration of the contract, the amount of straw delivered, provision when the contracted amount was not met, and quality as well as price of the straw. Farmers either supply straw individually to (small scale) power plants, or cooperate in supplier organisations. The latter are also used for straw supply to centralised power plants.

Farmers also recycle the bottom ash from straw combustion as a fertilizer for their fields. Straw ash contains nutrients – e.g. potassium, which is useful for crop growth. To enable the use of straw ash in agriculture, the Ministry of the Environment and Energy implemented an executive order in 1996 on residual products for agricultural applications. This order dictated the maximum values for heavy metals in the ash. The re-use of straw ash for agricultural purposes on farming land was an important reason for ELKRAFT to focus on the development of separate biomass boilers; the straw ash remained separated from the coal ash (which cannot be recycled into agriculture).

Another fuel used for co-firing is wood. The dominant wood resources in Denmark are forest residues (about 11 PJ annually). In 1999, about 75% of the wood was used for energy generation. Other wood resources in Denmark are industrial by-products (e.g. from wood industries) and wood products like domestic firewood and refined wood pallets. Wood plays only a minor role in co-firing technologies in Denmark, due to definitions in the Biomass Agreement. The wood used in central power production (e.g. for superheating) is mainly wood chips from forest residues. The majority of wood chips (75%) come from Danish resources, while the remainder is imported, primarily Canada and the Baltic countries.

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22 Small amounts of straw are also traded on specific spot markets.
Overall, the suppliers of wood chips have not played an important role in developing the co-firing niche – they have mainly sold on other biomass markets, in particular the domestic market and the district heating market (Anonymous, 1999a; Nikolaisen, 2001). However, both wood and straw markets emerged and stabilised already in the 1980s, mainly for supply to decentralised heating systems. Fuel supply to co-firing plants was therefore less of a problem.

After 2000, energy associations increasingly began to focus on waste combustion in power plants. In the future, the waste market and waste producers may become increasingly important in the Danish co-firing niche.

Research institutes
Another social group in the co-firing niche is research institutes. Several research institutes investigated biomass combustion in Denmark, and while co-firing was sometimes explored as part of biomass combustion, research institutes did not focus in particular on co-firing. The power associations carried out much of the research themselves. Research institutes like the Technical University of Denmark, dK-Teknik (this institute also participated in the IEA bioenergy Tasks 19 and 32, see Chapter 4), the Danish Technological Institute and Risø mainly dealt with more fundamental problems, e.g. in the case of high-temperature corrosion (Andersen, 1998).

Mosbech of Energi E2 described the cooperation with research institutes as follows:

We cooperated with research institutes, especially the technical university of Denmark. We have also had quite a lot cooperation with ELSAM, of course now we are more or less competitors. For instance, we have cooperated with the institute of material science from the university, where we have one person who is specialist in corrosion, which is employed by ELSAM and us together but working at the university. We have a cooperation between Energi E2, ELSAM and the university. [...] She gets samples from our power stations and she does analysis on them. DTU thus functions as an indirect cooperation platform for ELSAM and Energi E2. [...] It gives us a good contact to the university and of course we influence the research topics at the university so they do research that might be interesting to us. [...]. It is important to share on the basic knowledge and the competitive advantage will be in the field of how to use the knowledge. It is not the development of basic knowledge that energy associations should do (Mosbech, 2002).

In this case, the Technical University of Denmark operated as an institutional research link between ELSAM and ELKRAFT. In the late 1990s, these linkages continued to exist, enabling continuous cooperation between ELSAM and ELKRAFT despite increasing competition (see section 6.4).

Technology suppliers
Technology suppliers were only involved in the parallel co-firing projects, i.e. in Avedøre Unit 2 and the Enstedvaerket near Aabenraa. In the first case, a consortium of Ansaldo Vølund and Babcock Borsig Power supplied the boiler. The Danish company Ansaldo

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23 Even in the case of fundamental research on the gasification of coal and straw, the research project was carried out by ELSAM and ELKRAFT. They did however cooperate with Risø on straw and wood gasification tests in their laboratory (Madsen and Christensen, 1994; Madsen and Christensen, 1996).
Vølund, part of the American Babcock and Wilcox company, had a history of supplying biomass boilers in Denmark. This company supplied the first straw-fired boiler in 1987 and the first wood-fired boiler in 1980. However, integration into an ultra-supercritical steam system was new. The Babcock Borsig Power company contributed to this process, as they had experience with advanced technology and these kinds of steam parameters. Ansaldo Vølund and Babcock Borsig Power together designed the biomass boiler at Avedøre Unit 2.

In Aabenraa, the boiler was supplied by the Danish company Burmeister & Wain Energi A/S. These associations are all large, traditional boiler suppliers already involved in developing boiler technology for a very long time (Centre of Biomass Technology, 1999:50). In the case of the direct co-firing plant in Studstrup, implemented by ELSAM, the technology was mainly developed by ELSAM, in particular Tech-Wise. The main technology involved in this plant is the straw processing equipment. The equipment was originally developed for agricultural processes, but Tech-Wise adjusted and improved it to make it suitable for large-scale use at a central power station. I conclude that technology suppliers did not directly interfere with the direction and outcome of the development of co-firing in Denmark. However, their early experience with biomass boilers in the district heating and decentralised CHP sectors enabled the power utilities to purchase boilers, and to use their knowledge and practices to implement the boilers in existing coal plants, with limited problems.

**Conclusion**

I conclude that the social network supporting co-firing technology was small, mainly existing of traditional regime actors (ELSAM, ELKRAFT, power producers). However, new social groups were also involved, particularly farmers who supplied the fuel. Suppliers of biomass boilers were mainly traditional suppliers of fossil fuel combustion technologies. Nevertheless, these groups had already had extensive experience with biomass, due to previous supply to the district heating market and decentralised CHP markets. Network alignment was therefore relatively high when the co-firing niche emerged. The role of the Danish government was important, because they put pressure on the social network to develop technologies with improved environmental performance. The specific obligation to buy large amounts of straw (with difficult combustion characteristics) forced the associations to develop (or purchase) advanced technologies like parallel co-firing units, or at least indirect co-firing units. Power associations resisted the obligation to buy straw, but the Danish Energy Agency remained close to the agreement – despite adjustments in 1997 and 2000.

### 6.2.3 Learning processes

In the first period, ELSAM mainly learned from co-firing straw and coal in the Grenå CFB plant. The focus was on technical and economic learning, how to make straw processing feasible for power production, and how to combust straw in a CFB plant. ELSAM later used

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24 Since 2002, Burmeister and Wain is part of the Italian company group STF. A second Danish company, FLS Miljø group, supplied the desulphurisation equipment.
technical lessons from this co-firing unit to construct and improve the straw processing
equipment in the Studstrup power plant. More important in the late 1980s and early 1990s
was that the power associations, farmers and technology suppliers experimented with stand-
alone biomass boilers for district heating and decentralised CHP plants. The actors developed
market rules and practices for (domestic) biomass trade, quality standards, improved
combustion parameters, etc. (see below). Lessons learned during the development of the
stand-alone biomass combustion niches in the 1980s were a stepping-stone for the
development of co-firing niches after 1993.

After 1993, ELSAM developed an explicit strategy to learn about co-firing, particularly
through the experiments at the Studstrup power station. ELSAM and Tech-Wise focussed on
technical and economic parameters of co-firing. Almost no data are available on the economic
parameters, but the general lesson from the experiments seems to be that the economic
feasibility of indirect co-firing units depends to a large extent on the price of the biomass.
However, the investment costs for an indirect co-firing plant are 20-25% lower than the costs
of a stand-alone biomass system; costs of co-firing plant electricity can be half of the costs of
the electricity generated in stand-alone systems (Overgaard, Kirkegaard and Junker, 2002).
These conclusions confirmed initial expectations about lower cost prices for direct co-firing
systems.

The participants in the project have primarily documented the technological experiences
with the Studstrup power plant and the lessons they learned. They learned about all parts of
the conversion system. The researchers learned about the fuel composition, how it differed
from the composition of coal and how it affected analysis methods. They developed
techniques to measure the straw’s moisture content. In the case of coal, the general practice
was to measure the moisture content after grinding the coal. In the case of straw, they learned
that in order to pay the farmers, it was necessary to measure the moisture content before
grinding the straw (Wieck-Hansen, Overgaard and Larsen, 2000:399). The researchers were
also able to improve the straw processing facility considerably. At the Grenå plant, Tech-
Wise had used agricultural equipment for straw processing. The large amounts of straw
processed at the Studstrup station set higher requirements on the technology regarding
capacity and availability. In Studstrup, they learned how to operate the plant (at partial load)
to deal with most of the problems (Wieck-Hansen, Overgaard and Larsen, 2000:400).

Furthermore, participants in the demonstration programme learned to control the
combustion process parameters in order to reduce the risk of corrosion, slagging and fouling.
Nevertheless, these chemical processes continued to be a problem in co-firing plants in the
1990s. Participation on the part of the Technical University of Denmark resulted in a tool to
estimate the risks, based on specific fuel compositions (Wieck-Hansen, Overgaard and
Larsen, 2000:404). The demonstration project also focussed on studying emissions and how
they fit in the existing standards for combustion, i.e. for NOx, HCL, SO2 and dust. The
demonstration project showed that the emissions remained within reasonable limits. In
addition, learning about the re-use of ashes was important. A European industry standard

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25 The power company used the straw humidity to determine the price of the straw. If the sample was taken after
the grinding, the price would be higher.
(EN-450) for the concrete industry prohibited the use of ashes (Wieck-Hansen, Overgaard and Larsen, 2000:407). In the case of cement production, agreements with the Danish industry complicated the use of fly-ash from co-firing. Initially, ELSAM concluded that ‘environmental questions turned out to be an economic question’. The standards and agreements forced the utilities to landfill the ashes – which was subject to taxation. After 2000, ELSAM and Tech-Wise took a more active approach and lobbied to change the industry standard and the agreements with the cement industry. They were able to change the agreements with the cement industry in 2002, and they continued lobbying to change the European standard on concrete production (Overgaard and Friborg, 2002; Overgaard et al., 2004). Finally, ELSAM learned from the Studstrup demonstration project how to handle and secure the supply of straw:

We learned how to handle the straw from processing in the field through storage and transport to the delivery at the power station with the necessary measurements and accounts to the farmers. We have built up a good cooperation with suppliers whom we can trust to supply an acceptable biomass quality for our system (Wieck-Hansen, Overgaard and Larsen, 2000:407).

With respect to the construction of separate biomass boilers, the focus was on solving technical issues and improving the boilers’ performance. Performance improvement was strongly linked to improvement of stand-alone biomass boilers in Denmark. Supplying companies had previously installed (smaller) biomass boilers for decentralised CHP plants and district heating systems. Learning about the design and operation of these boilers contributed to the implementation of biomass boilers in parallel co-firing plants, as illustrated in Figure 6.7. The figure shows the steam temperatures of the straw-fired CHP boilers installed in Denmark, including the separate biomass boilers at the Ensted power plant and the Avedøre 2 power plant. The steam temperature is an important design parameter in power production; the higher the temperature, the higher the efficiency in power generation. The figure shows that the steam temperature continuously increased in the 1990s.
After 2000, the associations used their knowledge from previous experiments to further expand the co-firing niche. ELSAM continued to focus on indirect co-firing, and used the processing equipment from the Studstrup experiment to construct a new co-firing unit at the same location. Furthermore, E2 increased the use of biomass in centralised power plants.

Conclusion
I conclude that learning about indirect and parallel co-firing was strongly related to the niche for stand-alone biomass boilers (without coal). Straw combustion had previously been applied in decentralised CHP and district heating plants. Power associations, technology suppliers and fuel suppliers built upon these experiences, e.g. in terms of improving boiler efficiency, straw handling equipment and biomass markets. Nevertheless, the chemical composition of straw continued to cause problems in the co-firing experiments of the 1990s, in particular due to corrosion, slagging and fouling. This stimulated the associations to discuss the amounts and definitions of biomass in political agreements with the Danish Energy Agency.

6.3 Interaction between niche processes

Table 6.3 depicts a summary of the internal niche process in the case of co-firing in Denmark. I conclude that the quality of niche processes was high, in particular because there were strong visions and expectations due to political agreement, and because niche actors could build upon previous biomass combustion niches in decentralised heat and power production. This stimulated the actors to continue supporting the co-firing niches, despite several technological problems.
I am also able to explain some of the puzzles I addressed in section 6.2.3. The first puzzle was why the Danish associations began to develop co-firing units in the first place. The analysis has shown that the Biomass Agreement of 1993 was the primary reason. The power associations had no other reason to develop this technology. The agreement resulted in expectations about the use of biomass, and forced the associations to investigate co-firing in existing power units. The second puzzle was why the associations continued to use straw, despite the difficulties of combusting straw. Again, the Biomass Agreement is an important explanation, due to the specific definitions in the agreement. However, the persistent position of the Danish Energy Agency is also important; they only allowed limited change of the definitions, despite lobbying on the part of the power associations. However, the reason for defining biomass mainly as straw comes from another development, as I will show in the regime analysis below. The third question was why ELKRAFT focussed on a more expensive route – parallel co-firing – while ELKRAFT focussed on indirect co-firing. From the niche analysis I conclude that this was caused by a different vision on re-using ashes from the combustion processes. ELKRAFT emphasised recycling ashes more than ELSAM. The fourth question was why ELSAM returned to indirect co-firing after 2000. The niche analysis showed that they were able to lobby for new agreements with the Danish cement industry, and that they lobbied for an adjustment of the European standard. This removed a substantial barrier to indirect co-firing after 2000. However, the liberalisation process was also important. I will investigate this in the regime analysis below. The fifth question was why the government rejected the application of the Avedøre Unit 2 in 1994. The niche analysis did not provide an answer and I will investigate this in the regime analysis.
Table 6.3. Main characteristics of niche processes

<table>
<thead>
<tr>
<th>Period</th>
<th>Main characteristics of niche processes</th>
<th>Results in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990-1992</td>
<td>In this period, the Danish associations do not have a strong vision about co-firing or expectations about future co-firing units. They do participate in the construction of decentralised (mono-fuel) CHP plants, due to a political agreement. From participation in this niche, farmers, energy associations and technology suppliers learn about small-scale straw combustion.</td>
<td>Limited construction of co-firing units</td>
</tr>
<tr>
<td>1993-2000</td>
<td>The Biomass Agreement of 1993 creates visions and expectations about co-firing in centralised power plants. The power associations focus on straw, because of the specific definitions in the agreement. ELSAM favours indirect co-firing because of expectations about lowest cost prices; ELKRAFT focuses on parallel co-firing because of expectations about recycling fly-ashes. The associations, farmers and technology suppliers build upon previous experiences with the niches for decentralised biomass combustion. The main lessons from the co-firing experiments are that (1) indirect straw co-firing is difficult due to the composition of the straw, (2) recycling of fly-ash is complicated, and (3) economic feasibility is limited due to the high straw prices. The associations discuss the lessons with the Danish Energy Agency. The agency decides to allow more wood and implement extra financial benefits. At the same time, the power associations develop parallel co-firing units, which solve some of the problems, but increases investment costs.</td>
<td>Demonstration projects on indirect co-firing and parallel co-firing</td>
</tr>
<tr>
<td>2001-2003</td>
<td>The associations’ lobby for changes in the Biomass Agreement resulted in extra financial benefits from the government. This is an important incentive to implement new co-firing plants. Learning from experiments and lobbying for new industry standards takes away some of the barriers to re-using fly-ashes from indirect co-firing. Finally, a new vision about co-firing waste emerges in the co-firing niche due to previous experiences with co-firing.</td>
<td>Rapid expansion in (indirect) co-firing units</td>
</tr>
</tbody>
</table>

6.4 Danish regime dynamics

6.4.1 Natural gas and decentralised CHP (1990-1992)

Electricity and heat regimes

Prior to 1985, Danish energy policy had been concerned primarily with safeguarding the Danish energy supply. The government and power associations supported the introduction of nuclear power, but it was eventually rejected in 1985. Most efforts were put into replacing oil
with coal and reducing energy demand. A strong social movement rejected nuclear power (see also Chapter 5). After 1985, the Danish government turned to stimulating domestic fuels and increasing the environmental performance of the electricity and heat regimes. A major contribution was expected from natural gas. The gas infrastructure was commissioned in 1985, and gas production increased rapidly (Figure 6.8). To create a market for the gas and to improve the environmental performance of energy generation, the government decided to stimulate decentralised CHP plants. This resulted in the first agreement between the government and the power associations (1986), enacting the construction of a 450 MWe decentralised CHP plant before 1995. Moreover, the government increased taxes on fossil fuels and exempted domestic fuels (natural gas and biomass) from taxation.

The agreement was only partially implemented, but the small-scale CHP programme paved the way for a second agreement in 1990. This agreement was aimed at the district heating companies, and determined that all small and medium-sized district heating plants should convert to small-scale CHP or biomass district heating before 1998.26 This CHP programme was divided into three phases. In the first phase (1990-1994), the programme focussed on the largest coal-fired and gas-fired district heating plants (about thirty plants). The second phase (1994-1996) included the remaining coal-fired district heating units, the medium-sized, gas-fired plants and a part of the oil-fuelled district heating plants. The third phase (1997-1998) was to focus on converting the remaining small district heating plants (Danish Energy Agency, 1998:13). The environmental motivation came in particular from a new plan of action for sustainable development, called Energy 2000 (Ministry of Energy, 1990). The plan’s overall aim was a 20% reduction in the carbon dioxide emissions of the Danish energy sector in 2005 as compared to the level of 1988. To stimulate the use of CHP, the government implemented investment grants for CHP plants combusting natural gas, waste and renewables in 1992 (Danish Energy Agency, 1998:22).

The conversion of district heating plants into CHP plants was subject to three criteria. First, municipalities and district heating associations had to choose natural gas-fired CHP if the plant was situated in a natural gas supply area. These areas were previously defined in the 1979 Heat Supply act; natural gas covered the majority of Denmark. Second, they were forced to purchase heat from an existing CHP plant when situated in the vicinity of areas already supplied with heat from a CHP plant. Third, they had to choose biomass when located outside areas supplied with natural gas or heat from a CHP plant (Danish Energy Agency, 1998:13). This order of priorities strongly favoured natural gas, while biomass was only applied in a limited number of plants.

26 In 1990, 40% of the heating consumption was supplied by district heating systems; 55% of all district heating systems were CHP plants. In the Energy 2000 document, the Ministry expected that in the near future 90% of all district heating systems and more than half of total net heat consumption would be supplied by CHP plants (Ministry of Energy, 1990:57).
The political agreements undermined stability in the electricity regime, but did not result in opening the regime to co-firing technologies. The traditional power producers in the ELSAM and ELKRAFT area did not own the district heating plants; municipalities or cooperatives of energy consumers owned the plants. With the conversion of the district heating plants into CHP plants, these companies began to produce electricity, undermining the large utilities’ monopoly. In the ELSAM area, the number of decentralised producers increased especially rapidly. ELSAM preferred not to participate in the plants. ELKRAFT tried to integrate the decentralised development into their strategy as much as possible, but was only moderately successful (Danielsen and Halkier, 1995:99). In 2001, over 1500 MWe decentralised CHP had been installed in Denmark; ELSAM and ELKRAFT owned about 480 MWe of this capacity. There was no specific incentive for co-firing technology in the regime during this period. Coal replacement was not (yet) an issue, the introduction of natural gas and CHP was the dominant strategy. Biomass stand-alone was stimulated, but only in (a small part of) Denmark outside the natural gas area. The late 1980s and early 1990s to a large extent paved the way for post-1992 developments, in particular the breakdown of the power supply monopoly, the focus on domestic and renewable energy technologies and fuels in governmental policies, and the agreements for increasing decentralised CHP.

**Conclusion**

In the 1990-1992 period, stability in the electricity regime decreases. The main reasons are the impact of emerging notions on carbon dioxide and climate change, and two political agreements. The agreements aimed to increase the use of domestic fuels, but strongly favoured natural gas. As a result, actors from the heat regime increasingly attacked the market position of actors from the electricity regime. These dynamics did not create a specific incentive to investigate co-firing. Electricity regime actors were trying to deal with the emerging decentralised power producers, rather than implementing biomass-coal co-firing
units. I conclude that in this period there was no incentive from regime dynamics to develop co-firing plants, and regime dynamics created only a few local opportunities.

6.4.2 Banning coal and introducing competition (1993-2000)

Electricity regime
In 1993, the political parties made a third agreement (the Biomass Agreement). This agreement differed from those previously because it explicitly aimed at introducing biomass in the electricity regime. Moreover, ongoing discussions on climate change in the early 1990s stimulated efforts to reduce carbon dioxide emissions. In ‘Energy 2000’, the Ministry of Energy had focussed on developing small-scale solutions for the climate change problem. These efforts turned out to be insufficient. In 1993, the Ministry of Energy published a follow-up report of the Energy 2000 White Paper in which he argued:

The objective concerning a 20% reduction in total CO$_2$ emission in Denmark before the year 2005 confirmed on many occasions is still valid. Unfortunately, however, development is not on the right track! [...] The effect of measures both initiated and planned, is not sufficient (Ministry of Energy, 1993a:1).

A major opportunity for reducing carbon dioxide emissions appeared to be the reduced share of coal in power generation (86.7% in 1993). Coal combustion produced large CO$_2$ emissions. If absolute amounts of coal used in electricity generation were to increase in the future, the reduction aims would be in great danger (Ministry of Energy, 1993a:8). Coal was increasingly perceived as a dirty fuel in the policy arena. In discussion with the energy sector, the government began to look for solutions, including the substitution of coal with natural gas and biomass.

Although the use of coal in power generation was reduced, it was still the dominant fuel in electricity production in 1995 (75%). At the same time, the SK Power company applied for the construction of the large coal- and biomass-fired plant, the Avedøre Unit 2. The application stimulated an ongoing political discussion on allowing the construction of new coal plants, and forced the Ministry of Energy and Environment (established in 1994) to make a decision. The Minister was working on a new White Paper on energy, in which he tried to combine the reduction of carbon dioxide and the further expansion of renewable energy with liberalisation of the electricity regime. In 1996, the Ministry published the White Paper, Energy 21. Energy 21 included two scenarios for the future development of the Danish electricity regime. The first scenario illustrated what would happen if Denmark were to continue without adjusting policies. CO$_2$ emission goals were not reached in this scenario. The second scenario was more positive, but included the idea of phasing coal out of the Danish electricity regime prior to 2030. In this scenario, the CO$_2$ emissions were reduced to half the 1990 level. The discussion following Energy 21 divided the political parties, with the opposition – Liberals and Conservatives – rejecting the decision. Energy associations also rejected the decision, as they depended to a large extent on coal. Nevertheless, the government was able to enact the decision in 1997. The opposition argued that they would
withdraw the decision if they gained a majority in the parliament (Nielsen and Sørensen, 1998:12). The direct result for the Avedøre plant was that the government rejected the application for the new unit. After the SK Power company redesigned the plant into a natural gas-fired plant, the government allowed construction because the plant no longer used coal.

ELSAM was also affected by the decision to phase out coal. In several publications ELSAM had announced the construction of two new CFB power plants, combusting coal and biomass, similar to the Grenå power plant, but on a larger scale (Rasmussen, 1995; Henriksen, Larsen and Hansen, 1994). ELSAM expected to have a second CFB unit fuelled by coal and biomass operational in 1997 near Århus (90 MWe) and a third unit with a capacity of 250 MWe in 2005 (Rasmussen, 1995). The ongoing discussions about phasing out coal, however, prevented further development of these plants. Peter Overgaard argued as follows in 2002:

We had a plan for establishing a fluidised bed unit in the city of Århus for some 200,000 ton straw and also some amount of wood chips. We used about 25 million DKK in just designing the plant (the total investment was 1,200 million DKK). It was decided by ELSAM to establish that plant, but the ministry did not give the permission. That caused a very deep hole in the Biomass Agreement, because the utility associations leant back and said, ok, we are stuck. Than there was a period of some two years when actually nothing happened (Overgaard and Friborg, 2002).

The second part of Energy 21 dealt with liberalising the Danish electricity regime. The Danish electricity regime had never been organised as a competitive sector; there was no competition in power generation or supply, there was no consumer choice, and prices were regulated. Ownership in electricity generation had been organised hierarchically. At the bottom were a large number of distribution associations (105 in 1998), owned by consumer cooperatives and municipalities. These associations owned eight central power stations, which produced about 75% of all electricity in Denmark. The power associations cooperated in the ELSAM and ELKRAFT associations. These associations operated two grids, separated by the Great Belt, without a power line to connect the two systems. Prices had been regulated through a non-profit system; any surplus from electricity sales was to be reimbursed to the system, either via lower prices in the following year or via investments in new power plants. Distribution associations supplied solely to the regions in which they were located (Hvelplund, 1997:141; IEA, 1998:63). Energy 21 formulated the strategy to change this non-profit regime into a liberalised, competitive regime. The transition towards competition began with a 1996 amendment of the former Electricity Supply Act, followed by a new Electricity Supply Act in 1999 (the energy reform). The first steps towards opening the power market were taken in 2000 (IEA, 2002a:24).

Agricultural regime

Dynamics in the agricultural regime played an important role in determining the final version of the Biomass Agreement. Traditionally, Denmark has been a farming country. In the 1930s, over three-quarters of Danish land was used for agricultural purposes. In 1990, the total agricultural area had declined to 64% of the total Danish area, the remainder consisting of mainly urban areas and forests. Compared to other European countries, a relatively large share
of agricultural land (57%) was used for growing cereals (Danish Farmers Unions, 2000). As straw is an important by-product of cereal growing, farmers used to combust the straw on the farming land. During the late 1980s straw combustion on the fields was increasingly criticised, because it caused much air pollution. In particular the contribution to carbon dioxide emissions was perceived as a problem and was an issue in the discussions on the greenhouse gas emission reductions in the early 1990s. In 1991, the Ministry of the Environment implemented a ban on the combustion of straw on agricultural land (Ministry of the Environment, 1992). Farmers who continued straw combustion on fields after 1992 faced penalties. Limiting air pollution and carbon dioxide emissions were primary reasons for implementing the ban, but it had an important side effect: farmers were now facing a large straw surplus. One of the solutions was to plough the straw into the farmland to improve the soil for crop growing. The other solution was to sell the straw to power plants for energy generation. Farmers began to lobby the Danish government for the latter solution (Overgaard and Friborg, 2002). The farmers’ lobby came at a time when the government was discussing the Biomass Agreement, and the government decided to use the straw for combustion in power plants. A senior advisor of the Energy Agency later formulated it as follows:

The only explanation of saying that they [the power associations] had to use a specific amount of straw would be that they [the government] also wanted to give a specific amount of support to the farmers. There is an element of agricultural support in it. Otherwise there is no clear logic to it. If you want CO₂ savings you could also just say, you have to reduce a certain amount of CO₂ emissions. So the biomass agreement had actually two agendas: CO₂ savings and agricultural support (Pedersen, 2002).

The Biomass Agreement thus not only resulted from a political process for dealing with environmental problems in the electricity regime, but also from the straw surplus in the agricultural regime.

Conclusion
Political discussions about the reduction of carbon dioxide created instability in the electricity regime; it forced the utilities to combust biomass instead of coal. The decision to phase out coal interfered with the development of the co-firing niche in two ways. First, it resulted in a rapidly growing co-firing niche, because it forced regime actors to use substitutes for coal. Second, it prevented the construction of new co-firing plants based on coal and biomass combustion, because new coal-fired capacity was no longer allowed. After 1995, liberalisation in the electricity sector becomes a source of instability, but this only began affecting the co-firing niche after 2000. Changes in the agricultural regime (regulations) affected the choice for fuels in the Biomass Agreement.

6.4.3 Implementing competition (2001-2003)

Electricity regime
After 2000, the Danish electricity regime continued to develop towards liberalisation. The production associations merged into one company in western Denmark (ELSAM A/S) and
one company in eastern Denmark (Energi E2 A/S). The merger simplified the construction of co-firing units in Denmark, particularly in western Denmark. The head of the Tech-Wise biomass division formulated the changing relationship as follows:

Some years back the general opinion was that co-firing was a pollution for their nice coal fired plants and now we suddenly brought in the risk of chlorine and corrosion and fouling and so on. Because of that, the operators of the plants were against it. Up until the year 2000 there were six independent utility associations in the Jutland and Funen area and all the managers of these plants were more or less against it. They were not very progressive in their thinking: ‘we want to do it the same way as we have always done it, we don’t want to pollute our fine coal fired plant, we don’t want to bring in risk of corrosion and fouling’. At that time ELSAM was only an umbrella organisation, but in 2000 the six utilities merged into ELSAM. [...] That helped partly to get over the problem (Overgaard and Friborg, 2002).

The liberalisation process thus improved conditions for the implementation of co-firing units. However, problems occurred, too. Transition towards liberalisation and competition was a major topic on the political agenda. As in many other European countries, the Danish government struggled with the question of how to shape the regulatory framework. One of the topics was the formulation of new rules and supporting schemes for renewable energy generation. In the 1990s, the scheme had been based on a feed-in model (see also Chapter 5). The expectation was that the existing feed-in model would not survive in the long term due to European trends towards other, more market-orientated models. In the 1999 reform, the government introduced new promotional schemes, based on a certificate trading system for CO₂ (see also Chapter 5). The exact formulation of these schemes continued to be discussed after the energy reform was implemented. In 2001, the Danish people elected a new government, formed by right-wing political parties. The two developments decreased stability in the electricity regime. One consequence was that energy associations put more emphasis on the economic feasibility of co-firing projects, namely, feasible under competitive market circumstances. ELSAM decided that initial plans for constructing separate, straw-fired boilers at central power plants were no longer feasible; the large investments and expensive biomass fuels would result in a higher ‘green electricity’ production price than the Danish Energy Agency could accept. Despite the previous disappointing results, ELSAM decided to turn to direct co-firing again (Ramsgaard-Nielsen, 2001:165). Another decisive factor was that the political parties now in the government – Liberals and Conservatives – were the same parties that had argued that they would reject the decision to phase out coal if they gained a majority in the parliament (Nielsen and Sørensen, 1998:12). Although rejection of the coal ban was not (yet) a part of their policies, they implemented comprehensive reductions of the support for renewable energy sources.

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27 In 2000, the Danish government implemented a follow-up document to Energy 21, i.e. ‘Climate 2012’. This document was based on international commitments to reduce emissions of climate gasses (Kyoto Protocol) and newly forecasted calculations for energy consumption and carbon dioxide emissions. The document announced the CO₂ trading system for the electricity sector.
Conclusion
After 2000, the electricity regime mainly develops in the same direction as in the previous period. The liberalisation process, however, changes the organisation of the sector, improving the conditions for co-firing. New energy policies, on the other hand, emphasise the need for less expensive and more competitive solutions for the climate change problem. This results in a stronger focus on less radical solutions.

6.5 Conclusions
In the final section of this chapter I begin by discussing how the questions from section 6.3 can be answered with the regime analysis. As in the previous chapters, I will then construct the niche pattern that emerges from the niche analysis. Finally, I will examine niche-regime interaction.

Regime dynamics
In section 6.3 I addressed the question of why ELSAM returned to indirect co-firing, despite plans for more radical ways to combust straw, i.e. the construction of separate biomass boilers. From the niche analysis I concluded that niche actors were able to change the agreements with the cement industry, removing a major barrier to the implementation of indirect co-firing units. The regime analysis adds a second explanation. The Danish production associations in western Denmark merged into ELSAM, a reaction to the ongoing liberalisation of the electricity sector. This removed another barrier in the co-firing niche, i.e. convincing owners of power plants to participate in the co-firing experiments and to use co-firing equipment. Another question that remained unanswered after the analysis of the co-firing niche was why the government rejected the application of the new Avedøre Unit 2 despite the fact that it was designed with a very large biomass boiler. From the regime analysis I conclude that this was due to ongoing debates in the electricity regime about banning coal from the electricity regime (in particular discussions in the political arena). External developments, especially the emergence of the climate change problems, triggered this debate. The application of the Avedøre Unit 2 in 1994 reinforced this discussion, resulting in a formal rejection of the construction of new coal-fired capacity in Denmark, including the Avedøre Unit 2. Finally, the niche analysis did not answer the question of why the government put so much emphasis on straw in the Biomass Agreement if the aim was to reduce carbon dioxide emissions from coal combustion. I conclude from the regime analysis that this was due to a ban on burning straw on fields in the agricultural regime. The government tried to find solutions for the straw surplus, and used straw as the major source of biomass in the Biomass Agreement.

Construction of niche patterns
Figure 6.9 shows the niche development trajectory of co-firing in Denmark. In 1993, the associations started three types of experiments to meet the aims in the biomass agreement. ELKRAFT focused on parallel co-firing, because they had a strong vision on recycling by-
products from the combustion process. Moreover, the association was already in the process of constructing a new power plant, including a parallel biomass unit. ELSAM also investigated this technology. In general, the actors involved could build upon previous experiments with stand-alone biomass combustion, both in decentralised CHP plants and in district heating systems. There was already stabilisation in design heuristics, in guiding principles on how to optimise process conditions, in ways of trading straw and wood, and in biomass quality standards. The associations, in particular ELSAM, also investigated two other trajectories, i.e. indirect co-firing of biomass and coal in CFB plants, and indirect co-firing in large pulverised coal (PC) plants. The associations learned from the experiments that straw combustion in PC plants is very difficult, in particular due to straw’s chemical composition. Problems also emerge with the re-use of ashes from co-firing straw and coal. The other trajectory (CFB plants) never took off, mainly due to regime dynamics (banning coal from the electricity regime). The two niches began to lose support in the late 1990s. ELSAM decided to put more emphasis on parallel co-firing. However, ELSAM was able to overcome some of the problems (re-using fly-ash) in the co-firing niche, while the liberalisation process in the electricity regime put more emphasis on inexpensive production and inexpensive solutions to the climate change problem. ELSAM regained interest in indirect co-firing. Parallel co-firing, a more expensive option, began to lose support from the associations. Stability in all niches remained limited, although parallel co-firing reached a significant level of stabilisation in terms of design heuristics, fuel supply contracts, industry development, etc., because of linkages with the niche for stand-alone biomass combustion.

![Diagram showing niche development pattern for co-firing in Denmark](image)

**Figure 6.9. Niche development pattern for co-firing in Denmark**
Table 6.4. Indication of size of niches for co-firing in Denmark

<table>
<thead>
<tr>
<th>Total biomass co-firing capacity (MWe)</th>
<th>1992</th>
<th>1998</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capacity in all niches</td>
<td>9.3</td>
<td>49.3</td>
<td>208.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed capacity in Denmark (MWe)</td>
</tr>
<tr>
<td>Share of coal capacity (MWe)</td>
</tr>
</tbody>
</table>

Niche-regime interaction

Table 6.5 summarises the interaction that occurred between niche development and regime dynamics. I conclude that the co-firing niche developed mainly against the backdrop of the electricity regime; dynamics in the agricultural regime – the regulation regarding straw combustion – and the heat regime - heating actors becoming active in the electricity regime - were of minor importance. This is an interesting conclusion; in all my other cases more regimes were involved in and important for understanding niche development. The main reason is that the dominant vision on co-firing was that it is a way to replace coal, to reduce the use of coal in centralised power generation. Compared to co-firing in the Netherlands, co-firing in Denmark was less an option to process waste. Only in the early 2000s did the ELSAM and Energi E2 associations begin to develop new visions based on waste processing in their power plants.

Table 6.5. Niche-regime interaction in the co-firing case in Denmark

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Regime dynamics</td>
<td>• The electricity regime is in flux, due to political agreements about increasing decentralised CHP on natural gas and biomass and an emerging group of decentralised producers.</td>
<td>• Stability decreases in electricity regime due to political agreement and decisions (banning coal) and implementation of electricity reform.</td>
</tr>
<tr>
<td></td>
<td>• Electricity regime actors (ELSAM, ELKRAFT) lose market share to actors from heat regime (decentralised producers).</td>
<td>• Implementation of a ban on straw combustion on agricultural fields</td>
</tr>
<tr>
<td>Effect of regime dynamics on niche development</td>
<td>• Creation of local opportunities in decentralised power and heat production</td>
<td>• Rapid increase in number of co-firing units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Focus on straw in co-firing experiments due to biomass definition in Biomass Agreement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rejection of the construction of new co-firing units using coal</td>
</tr>
<tr>
<td>Effect of niche development on regime dynamics</td>
<td>• None</td>
<td>• Reinforcement of the discussion on banning coal</td>
</tr>
</tbody>
</table>

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28 Data from various sources in this chapter. Data from 2003 includes the parallel co-firing unit at Avedøre 2 (40 MWe), which is co-fired with natural gas. Data on total capacity from Energistyrelsen (2003) and my own calculations.
In the first period, stability in the electricity regime decreased, because of the introduction of CHP, natural gas and biomass, and the emergence of a new actor (decentralised producers). This created overlap with the heat regime and some local opportunities for co-firing in decentralised plants. However, the instability in the electricity regime did not lead to a large co-firing niche in the early 1990s, and there was no direct incentive for the companies to investigate co-firing.

After 1993, this situation changed, because new policies and regulations specifically aimed to replace coal with biomass in centralised production. The implementation of political agreements and the stimulation of biomass in the electricity sector created the co-firing niche and stimulated growth until 2003. The specific contents of the new policies in terms of biomass definition affected design choice at the niche level: actors were forced to experiment with technologies that were able to process straw, necessitating more radical interventions in traditional coal plants (indirect co-firing, parallel co-firing). Although energy companies tried to contest this rule, the Danish government was able to enforce it, with a minor adjustment in the late 1990s. The same policy also restricted the expansion of the co-firing niche, because it forbade the construction of new plants based on coal.

After 2000, the liberalisation of the electricity sector interacted with the design choices at the niche level in the early 2000s, resulting in a preference for low-cost co-firing solutions, i.e. indirect co-firing. Nevertheless, successful negotiations between niche actors and policy makers culminated in the implementation of new financial incentives for co-firing, resulting in a rapidly growing co-firing niche. Successful lobbying on the part of niche actors also affected agreements at the regime level, i.e. agreements between the electricity sector and the cement industry on the composition and sources of the fly-ashes.
Chapter 7.
Analysis and conclusions

7.1 Introduction

In this chapter I will draw conclusions and answer the research questions addressed in Chapter 1. The main research question was: how and why does the Danish development of bioenergy from manure digestion and co-firing differ from the Dutch development? To investigate this question, I have used the Strategic Niche Management approach. This resulted in two additional research questions: what are the crucial factors for the emergence of market niches? And how does niche development interact with regimes? In this chapter I will subsequently deal with these questions. In section 7.2 I first combine the four cases, discussing and explaining differences between the case studies, as a first step to answering the main research question. These comparisons are a summary of my case study findings (readers who read the previous four chapters should feel free to skip this section, referring back to it only when necessary). The storylines are the basis for the next sections, in which I discuss the additional research questions in more detail. In section 7.3 I present the four patterns to illustrate how niche development occurred in terms of protection and stabilisation, discuss characteristics of emerging market niches, and discuss how internal niche processes explain these characteristics. In section 7.4 I focus on the niche-regime interactions found in my cases. On the one hand, these sections are an elaboration of the main research question: they identify crucial factors and processes for successful versus unsuccessful niche development. On the other hand, they contribute to enhancing the Strategic Niche Management approach by confirming findings from previous research and by adding new insights on the basis of the case studies. In addition, I will discuss the role of public authorities in section 7.5. This was not a systematic research theme in the thesis, but I discussed the aspects available in SNM literature (section 2.5). In this chapter I speculate about the relation between policy strategies and the kinds of outcomes they are likely to produce, on the basis of my case studies. The chapter closes with section 7.6, a discussion of issues that deserve more investigation.

7.2 Comparing the cases

The main research question of my thesis was: how and why does the development of bioenergy from manure digestion and co-firing in Denmark differ from the Dutch development? In answering this question, the first step is to make two comparisons. The first
comparison is between manure digestion in the Netherlands and manure digestion in Denmark. The second comparison is between co-firing in the Netherlands and co-firing in Denmark. These contrasts not only allow me to summarize the four cases, but also provide me a stepping-stone towards explaining the differences, focussing on the processes in the niche and niche-regime interactions.

7.2.1 Manure digestion (NL) versus manure digestion (DK)

Both the Netherlands and Denmark began to experiment with manure digestion on individual farms in the 1970s. In the early 2000s the outcomes of the two development trajectories diverged widely: in the Netherlands, two centralised digesters were installed (of which one was already out of operation) as well as four small, farm-scale plants. In Denmark, twenty centralised plants were installed as well as over thirty-five farm-scale digesters. How should we understand this difference?

The Netherlands

The first farm-scale plants in the Netherlands were mostly established in the 1979-1982 period, supported by national funds and the expectation of large markets and high energy yields. The high energy price was a crucial reason for technological niche creation in this period. The national government made financial resources available for experimenting and testing. The results, however, were very poor; they did not meet the expectations. Farmers had no experience with manure digestion; researchers and technology suppliers were uncertain about the optimal design. The results were so disappointing that only a very few farm-scale plants were constructed after 1982. Nevertheless, monitoring, research and improvement continued at the plants already installed. The experiences from these plants were combined and codified in several publications and at meetings of the biogas community. This process resulted in detailed technical knowledge about manure composition, component design, biogas usage and biogas yield optimisation, but not in a dominant, standardised design.

In 1986, the Dutch developments were disrupted by external circumstances. Global oil prices collapsed, resulting in a much lower energy price for households in the Netherlands and making energy generation in biogas plants unfeasible; expectations about future markets and energy savings decreased. The national government dropped financial support for these plants. At the same time, the environmental consequences of the intensive agricultural sector were recognised, resulting in overwhelming political pressure on the agricultural sector to deal with over-fertilized farmland, stench and other types of environmental degradation. The process was accompanied by the introduction of several new regulations, which provoked much resistance among the agricultural sector. Agricultural organisations tried to regain control by investigating large-scale solutions. Digestion comprised part of the solutions they sought, combined with processing equipment. A new plant in Helmond (Promest) represented
a radical break with previous plants in terms of size, complexity and markets. The plant received major financial support from the national government (investment grants and supply levies), but no support from the farming community (they were forced to pay the levies). Although the national government, agricultural organisations and technology consortia anticipated a rapid increase in the number of these plants, only one was constructed. The process turned out to be very expensive and technologically very difficult. The experiment also lacked a clear market for the fertilizer products. Nevertheless, the plant was upgraded in 1993. When financial support ended in 1995 - because of European regulations – the plant was shut down. This had a tremendous effect on the development of biogas plants: governments and agricultural organisations no longer perceived manure digestion and processing as a desirable solution to the problems they were dealing with.

In one location (Deersum), the disruption with previous farm-scale plants was limited, but this experiment received limited protection. Farmers cooperated in a small centralised plant and combined energy generation with agricultural benefits: there was a dedicated market niche for reasons like stench reduction and centralised storage. The project ended in 1995, when attempts to implement a new (larger) plant that combined the digestion of manure with household waste failed – because of resistance from the province and a new waste infrastructure. The experiment in Deersum remained a local practice.

In the late 1990s and early 2000s, Dutch energy companies and agricultural organisations began to experiment again with manure digestion. External circumstances had changed. A green electricity market had emerged, and renewable energy became a more prominent element in the strategies of energy companies. Renewable energy was stimulated through taxation and grant schemes, and renewable electricity prices were now similar to the price for electricity from fossil fuels. Moreover, the government provided funds for research and experimentation, aimed at reducing agricultural methane emissions. Energy companies, anticipating large green energy markets, made resources available for pilot projects. Agricultural actors (ministry, large agricultural organisations) hesitated, however. Memories still lingered of the negative results from previous experiments. Moreover, a new mineral distribution system and a reduction of animals in the agricultural sector had contributed to a reduction of the manure surplus. Other actors (technology suppliers, research institutes) emphasised the need for manure digestion on the basis of insights from other countries. Through international linkages like foreign technology suppliers, publications and participation in conferences, they emphasised many functions of manure digestion plants, including renewable energy generation, agricultural benefits, and environmental benefits like waste recycling and greenhouse gas reductions. However, there was much uncertainty, too, in particular uncertainty about regulations and the type of waste allowed for codigestion. Also, liberalisation in the energy sector created uncertainty in subsidy schemes, preventing investments in biogas plants.
Denmark

The Danish developments in the late 1970s were similar to the Dutch developments. Actors from the grassroots movement like farmers, Folke High Schools and researchers established several farm-scale plants, supported by a national research programme. Lessons learned from combined experiences were shared through monthly visits and the publication of results in a magazine. Nevertheless, despite the invention of codigestion in some cases, most of the plants were not able to meet the expected biogas yields; they suffered from poor design and operation.

In Denmark, the shift towards centralised plants was triggered not only by external circumstances, but also by results from previous experiences with farm-scale plants. The first centralised plants had already been constructed before external circumstances – global oil prices, environmental awareness, new policies – changed. These plants were characterised by an incremental change in size, complexity and markets with respect to previous farm-scale plants. These first centralised plants suffered from severe technical problems, and Danish biogas plant development might have stopped, if not without the financial aid from the Committee for Renewable Energy. The committee was an alignment actor, bringing together the necessary means (financial, political) to maintain the development of biogas plants, despite their initial poor performance. In 1986, the Biogas Action Programme built upon experiences with these plants. The three participating ministries aimed at alternative energy generation, and reduction of environmental problems in agriculture and waste recycling, but applied a bottom-up approach. The programme brought together experiences from different locations through monitoring, exchange of information in regular meetings, active participation of actors such as governmental employees, farmers, plant operators, researchers and technology suppliers. Increase in plant number was moderate, one or two plants annually, and was supported with investment grants (lowered during the decade). The programme continued until 2002. In the 1986-2002 period, the centralised biogas plant emerged as a technology bridging many different functions. Codigestion of manure with industrial waste, supported by all participating actors, played a crucial role in bringing the functions together. Moreover, specific regime conditions like the existence of district heating systems, the early establishment of taxes on fossil fuels, the emergence of CHP as a central element in national energy policy, agro-environmental policies such as an obligation for storage capacity, and a general preference for cooperation among farmers enabled the successful introduction of centralised biogas plants in Denmark.

The Folke Center for Renewable Energy continued to investigate the development of farm-scale plants despite limited support from the government. The only support came from the Committee for Renewable Energy, which financed most of the biogas plant experiments at the Folkecenter. Through linking up with international experiences and local testing, this institute was able to improve the farm-scale concept in the early 1990s. With increasing attention for the reduction of methane emissions in agriculture, the establishment of
(temporary) financial support from climate funds, and structural change in agriculture (larger farms), the number of farm-scale plants increased rapidly in the late 1990s. Another trajectory also emerged as a spin-off of the Biogas Action Programme, when municipalities tried to anticipate future waste policies (separate collection of organic waste) and combined manure digestion plants with codigestion of organic household waste. Waste policies (taxation of landfill and incineration) stimulated waste producers to search for alternative processing routes.

The establishment of centralised biogas plants came to a halt in the late 1990s, because of two regime changes. First, liberalisation in the energy sector created uncertainty in financing schemes for the generation of renewable energy. Although grants were still available for the construction of new plants until 2002, no new plants were constructed. Second, in 2002 the Danish people elected a new government, resulting in the abolition of many grants, research programmes and subsidy schemes. The Biogas Action Programme ended in 2002.

7.2.2 Co-firing (NL) versus co-firing (DK)

Co-firing has rapidly developed into the second-largest renewable energy niche in the Netherlands. Most coal-fired plants were co-firing organic material after 2000. Danish utilities have also implemented a significant number of co-firing plants: total capacity is equivalent to the capacity in the Netherlands. The main difference is that Danish utilities investigated solutions that are integrated further down the processing line in coal plants, i.e. the construction of parallel co-firing units. How should we understand the similarities and differences?

The Netherlands

The Dutch utilities began experiments with co-firing in the early 1990s. These experiments were economically attractive for the companies, because they used waste resources with a negative economic value like sewage sludge and demolition wood. Most of these experiments required no or only incremental change in the existing power plants. Waste was processed and combusted in the same processing lines as the coal (direct co-firing), or separate milling and grinding equipment was constructed (indirect co-firing). Learning at this point mainly focussed on technical issues, i.e. investigating if the coal plant was able to process the waste without major complications for process conditions and emissions. There were additional reasons for this testing and experimentation: the government provided financial support for waste-to-energy projects; public authorities supported the processing of waste outside the waste regime. The experiments stayed close to the existing practice for coal combustion. The energy companies faced only limited uncertainty about technical issues. The Amer gasification plant is an interesting exception, because it was a more radical innovation. The reasons are complicated, being a combination of high expectations about gasification (high
efficiencies, lower gas cleaning costs), an anticipation strategy to create a separate, green market for renewable energy, and previous experience with a large coal gasifier. The feasibility of a gasifier, combined with gas cleaning on the scale that the energy companies were investigating was very uncertain: only small-scale biomass gasifiers had been constructed abroad, and there were no similar designs at that time. In general, the co-firing experiments were not strongly linked, production companies were able to conduct most research and construction in-house, and most practices remained local. However, some companies participated in an international research project in which European experiences were compared. Furthermore, the KEMA – participant in several projects – acted as an institutional link between projects. Governmental involvement was limited, and only for general financial support. Government did not (yet) strongly advocate the technology, nor did they oppose it. The government solved a problem with emission standards for waste combustion in power plants, by implementing temporary emission standards based on existing standards from the waste and electricity regimes.

These initial, loosely coupled experiments were the stepping-stone towards a second phase (1996-2000) in co-firing in the Netherlands. Several issues are important. First, the niche experiments with direct and indirect co-firing were (technically and economically) successful and most energy companies decide to continue co-firing on a permanent basis. Second, the national government (in particular the Ministry of Economic Affairs) increasingly recognised co-firing (and biomass in general) as a technology with a large potential for renewable energy generation, and increased the financial resources. Third, regime dynamics (company strategies to create a green market, the establishment of a tax exemption for renewable energy and the accelerated liberalisation of the market for green electricity) resulted in a rapid increase in green electricity customers and created high expectations about future renewable energy markets.

These three factors stimulated energy companies to increase the share of biomass in coal plants; the size of the co-firing niche increased. Moreover, the international dimension of the co-firing niche expanded. Research institutes and energy companies participated in international programmes, which enabled them to contribute to and use information, guiding principles and rules of thumb from other locations. These research networks eventually developed standardised solutions for most of the technical problems with co-firing.

The main problem occurred in the societal embedding of the co-firing niche. Energy companies often used organic material classified as waste, provoking resistance from several societal groups. These groups were successful in contesting the experiments, because the emission standards for combusting waste in power plants were not clear. Divergent emission standards for waste incineration and energy generation became increasingly problematic, with neighbours and environmental organisations legally fighting the co-firing experiments, and with utilities starting to emphasise the need for standardisation of the regulatory framework. Utilities and public authorities compared experiences from different locations,
reconsidering some of the initial views, perceptions and regulations regarding the combustion of organic waste streams (e.g. about sustainability, emission standards). On an international level, they lobbied to modulate the ongoing development of new waste, and renewable energy definitions and emission standards into directions similar to the Dutch views. Eventually (after 2000), the definitions and standards stabilised on a European level, resulting in broad definitions, including contaminated organic sources like demolition wood and sewage sludge. Nevertheless, the co-firing niche continued to face resistance, because environmental groups did not support the definitions.

In the early 2000s, the development of the co-firing niche accelerated due to increasing concern on the part of the Minister of Environment about the necessity of reducing greenhouse gasses. Measures taken at coal-fired power plants were designated the most important strategy to reduce greenhouse gas emissions in the Netherlands. Although there was strong resistance from the utilities, they agreed to a large reduction aim for carbon dioxide emissions. The companies investigated and experimented with co-firing, including increasing the share of organic material in coal plants, investigating a broad range of new fuels (including import), and investigating more radical adjustments to the power plant (thermal pre-treatment like gasification and pyrolysis). Nevertheless, indirect co-firing emerged as the dominant trajectory for two reasons. First, there were niche-internal causes. The gasifier constructed by Essent and EPZ (and gasifiers worldwide) revealed major technological problems, which lowered expectations about the short term application of these technologies. Moreover, direct co-firing turned out to be unsuitable for co-firing at large biomass/coal ratios, leaving only indirect co-firing as a suitable solution. Also, around 2003 many of the technological problems for indirect co-firing were solved and there were now detailed rules of thumb on how to overcome specific problems (developed primarily in international research programmes). Second, regime changes favoured indirect co-firing over more advanced technologies. The liberalisation processes emphasised economic performance, which made utilities hesitate to invest in long term, risky projects. The ongoing reorganisation in the energy sector also affected established planning and R&D structures, resulting in uncertainty in roles and mutual relations (who is the innovator). This frustrated the development of more radical solutions like gasification and pyrolysis.

**Denmark**

The Danish development of the co-firing niche differs from the Dutch in several ways. The Danish niche developed primarily because of political agreements (versus local, economic motivations in the Netherlands). In the late 1980s, the first agreements focussed on the establishment of decentralised CHP and district heating systems on biomass. This did not contribute to a significant development of co-firing experiments, or the emergence of a co-firing niche. However, for strategic reasons (in reaction to an emerging decentralised power sector), in particular the ELKRAFT association participated in the development of
decentralised CHP. A niche for decentralised stand-alone biomass combustion for power generation emerged. This niche already built upon the niche for biomass combustion in district heating systems, an important factor in understanding the development of the Danish co-firing niche that emerged in the 1990s. After the 1993 biomass agreement, the Danish actors could build upon experiences with stand-alone applications for biomass combustion.

The 1993 biomass agreement was an attempt to increase the use of biomass in large utility boilers. It was also an attempt to create a large market for the farmers’ straw surpluses. The political agreement instructed ELSAM and ELKRAFT to buy over 1 million tons of biomass annually by the year 2000. This triggered three different trajectories of testing and experimentation. The first trajectory built upon the previous development of stand-alone applications (parallel co-firing). ELRAFT focussed particularly strongly on parallel co-firing for three reasons. First, the association had previous experience with stand-alone biomass units for power production, there were established relations with suppliers of fuels and technologies, and it had R&D experience in this field. Second, it was already in the process of constructing a large new power plant based on a multi-fuel concept including coal, biomass and natural gas. The biomass unit in this plant was a parallel co-firing unit. Third, ELKRAFT had a strong vision on re-using by-products from power production; a parallel co-firing unit enabled the association to keep the bottom ashes from coal combustion and biomass combustion separated.

ELSAM also investigated the trajectory of parallel co-firing, and implemented one plant. Moreover, this association investigated two more routes, i.e. indirect co-firing in CFB plants and indirect co-firing in pulverised coal plants. The CFB trajectory was cut off by regime changes, i.e. policies to phase out coal from the electricity regime (see section below). ELSAM put most effort into indirect co-firing straw, implementing a long-term demonstration project, which improved the understanding of indirect co-firing straw in a coal plant. Although they were able to improve processing equipment and develop tools for reducing the risks of slagging, fouling and corrosion, the experiment results showed that co-firing straw indirectly was very difficult. Eventually, ELSAM also decided to focus on parallel co-firing.

The biomass agreement explicitly defined the types of fuels that could be used by the utilities for combustion, i.e. wood and, primarily, straw. As a result, most local activities in the experiments were directed towards learning about the production, processing and combustion of these fuels. The companies could link up with other experiments and use experiences from previous biomass combustion, for example in terms of supply contracts, quality standards and transportation. The Technical University of Denmark acted as an institutional research link between projects. Moreover, there was very limited societal resistance to the combustion of biomass, because there was no uncertainty about the type of fuels, the emissions or other environmental problems when combusting biomass: biomass referred to either wood or straw rather than all kinds of different organic materials that could be contaminated with inorganic or toxic fractions (such as in the Netherlands). Because the
fuels were strictly defined, there was more stability and alignment in technological designs, fuel markets, fuel supply contracts, processing equipment etc.

The specific definition of biomass also had a downside. It provided the utilities with a powerful argument to slow down the introduction of biomass in large utility boilers in the late 1990s. The experiments with straw co-firing were complicated, and associations seized the opportunity to argue that they were not able to meet the aims, because they had only limited freedom in the choice of fuels. Although the Danish government adjusted the agreement in 1997, it remained close to the definitions in the original agreement. This forced the power companies to develop more advanced equipment for co-firing, in particular parallel co-firing units. Furthermore, the difficulties of recycling fly-ash from co-firing contributed to a focus on parallel co-firing plants. Another consequence was that Danish views on and perception of biomass and biomass definition were not (yet) broadened, despite institutionalisation of the broad biomass definition at the European level. This began to change after 2000, when energy companies began to develop new ideas about co-firing waste in power plants.

Regime dynamics are also important in understanding the outcome of niche development in Denmark. Acknowledgement of the greenhouse effect in the late 1980s and early 1990s provoked a discussion on the use of coal in the Danish energy sector. ELKRAFT’s plan for the construction of a new power plant using coal (Avedøre 2) accelerated the discussions. In anticipation of a possible political rejection of the plant, ELKRAFT decided to design the new power plant with a parallel biomass unit. In the mid-1990s, the Danish government officially decided to phase out coal completely, making the construction of new, coal-based power plants impossible. This also prevented the construction of a new large CFB plant for combusting biomass and coal in the ELSAM area. In reaction, ELSAM decided that the biomass agreement was no longer achievable. Eventually, parallel co-firing emerged as the dominant trajectory in co-firing, in particular because of technological difficulties associated with the indirect co-firing of straw, and previous experiences with stand-alone biomass units. However, after 2000 parallel co-firing began to lose support due to the ongoing process of liberalisation, and more emphasis on low-cost production. The companies were now reorienting to indirect co-firing of straw in coal and natural gas-fired plants.

This section has drawn up the main storylines in the case studies. They show the important role of niches and regimes in understanding the innovation journey. In the following sections I continue with discussing two issues in more detail, namely crucial factors in the emergence of market niches and niche-regime interactions.

7.3 Crucial factors for the emergence of market niches

In Chapter 2 (2.4.1) I argued that there was still an important puzzle in SNM, i.e. what the crucial factors are for the emergence of market niches. I proposed a matrix that combined the
sociological dimension of stabilisation with the evolutionary dimension of protection. The horizontal axis represents the level of stability in heuristics, regulations, preferences; it represents the stability in rules on niche level. The vertical axis represents the level of protection from dominant socio-technical regimes. Protection refers to the shielding of the niche against harsh design and selection rules, e.g. through subsidies, regulatory exemptions, expectations and strategic decisions. In my case studies, I used this matrix to construct niche development patterns. In this section, I present the patterns again (7.3.1), discuss characteristics of emerging market niches (7.3.2), discuss how internal niche processes explain the characteristics and explain on the basis of these conclusions the differences between the case studies (7.3.3)

7.3.1 Niche development patterns in the four cases

In Figure 7.1 I have mapped the development of the niches in four matrixes. The first figure represents the development of manure digestion in the Netherlands, the second figure the development of manure digestion in Denmark, the third figure the development of co-firing in the Netherlands and the fourth figure the development of co-firing in Denmark.

Figure 7.1. Niche development patterns for manure digestion in the Netherlands (a), manure digestion in Denmark (b), co-firing in the Netherlands (c) and co-firing in Denmark (d)
The first conclusion I can draw from the patterns is that all niche development trajectories are characterised by non-linearity. There are large jumps in stability and protection levels – innovations jump from technological niches to protected market niches and dedicated market niches, and sometimes backwards. There is no linear pattern from technological niche to regular market niche. Moreover, although in most cases niche development started in technological niches, in the case of Dutch co-firing there was a dedicated market niche for direct and indirect co-firing in the early 1990s. This supports my initial hypothesis that the ideas about niche development patterns were too simplistic in Strategic Niche Management. The emergence of market niches is a much more non-linear trajectory than previously assumed. In the following section I will discuss in more detail three important characteristics of these patterns.

### 7.3.2 Characteristics of emerging market niches

The patterns above represent one case in which experiments did not result in the emergence of a market niche – namely, manure digestion in the Netherlands – and three cases in which experiments resulted in the emergence of (protected and regular) market niches – manure digestion in Denmark, and co-firing in the Netherlands and Denmark. I conclude that the pattern of the case where no market niche emerged (unsuccessful), and the patterns of the cases where market niches did emerge (successful), differ in three crucial ways. The first difference is that the unsuccessful case shows a *sequential development pattern*, while the successful cases show a *parallel development pattern*. In a sequential development pattern, only one trajectory is explored at a time, while in a parallel development pattern, multiple trajectories are explored. Parallel trajectories are important for emerging market niches for three reasons. First, they result in increased market share, because a technology is applied in an increasing number of geographical locations and application domains. Second, parallel development enables broader and faster learning (but does not guarantee it), because technological variations are applied under different circumstances and by different actors. There may also be spill-overs of lessons from one trajectory to another, e.g. in terms of technological solutions or emerging functionalities. Third, parallel development benefits the development of market niches, because it enables a back-up strategy: when one trajectory appears to be unfeasible (e.g. because of new regulations or technological problems), firms or policy makers can turn towards another trajectory. This is particularly well illustrated by the co-firing cases. Energy companies were able to fall back on previous developments when regime changes (liberalisation) began to frustrate the development of more advanced technologies. I conclude that parallel development is an important characteristic of emerging market niches.

The second difference is that in cases where market niches emerged, a *continuous development pattern* is visible, while in the case where no market niches emerged, a
discontinuous development pattern is clearly visible. In a continuous development pattern, experimentation continuous without disruption, while in a discontinuous development pattern, the trajectory is disrupted by periods without experiments. Continuity is important for the emergence of market niches to prevent the loss of experiences for future use. In the Dutch manure digestion case, no experiments took place in the late 1990s, which frustrated the reintroduction of biogas plants in the early 2000s. Although experiences from the past had been codified in reports, most actors had no prior experience with manure digestion. There was no biogas industry left, for example. In the Danish case, there was continuity in the development of manure digestion, enabling the reintroduction of farm-scale plants in the late 1990s. The co-firing cases both show a continuous development, although it should be mentioned that the time period is shorter in the co-firing cases. I conclude that continuity is an important characteristic of emerging market niches.

The third difference is that market niches are (by definition) characterised by a pattern of increasing stability, while in the case where no market niche emerged, there is a pattern of decreasing stability. In the successful cases the development pattern moves from left to right, not necessarily from top to bottom (decreasing protection), while in the Dutch manure case (least successful), there are also backward jumps. Stabilisation is important, because it reduces uncertainty and the risk of participation: stabilisation enables actors to anticipate the future. Protection can also reduce uncertainty, but can be a source of uncertainty as well (e.g. in the Dutch cases). Also, protection can become a more or less permanent feature of the selection environment (e.g. in the form of taxes). Protection is thus not a sufficient condition for the emergence of market niches. Stabilisation, on the other hand, creates a more durable and internalised form of certainty for niche actors, one that is less sensitive to external dynamics at the regime level or in the socio-technical landscape. Increasing stabilisation is thus the third important characteristic of emerging market niches.

In the following section, I will discuss what the role of internal niche processes is in bringing about these characteristics of emerging market niches. I will also discuss for each internal niche process how my cases confirm or refute findings from previous SNM research.

7.3.3 The role of internal niche processes in emerging market niches

Dynamics in visions and expectations
Previous research on SNM has shown that expectations play a crucial role in niche development (Hoogma, 2000). I had a specific hypothesis about the way expectations change, i.e. changes in expectations are in particular caused by external circumstances and not by experimental results (see section 2.4.2). I will first discuss whether my cases do or do not support this hypothesis, moving on to discuss how visions and expectations can bring about the three characteristics of emerging market niches.
My cases support the hypothesis that changes in expectations and visions are often caused by external circumstances (regime and landscape changes). Examples from my cases are fluctuations in energy prices, the emergence of dominant environmental problems, liberalisation, and changing policies and regulations. These external dynamics created the expectation of large opportunities or, on the contrary, lowered expectations about future feasibility. The link between results from experiments and changing visions and expectations is less clear. In the case of negative results (i.e. when results do not meet the expectations), experimental results can have a major impact on expectations, but only when the results are dramatically lower than initial expectations (e.g. in the case of centralised manure digestion in the Netherlands). If experiments produce positive results (i.e. when results do meet the initial expectations), my cases suggest that it is much more difficult to contribute to the development of visions and expectations. In cases when results from experiments did contribute to changing visions and expectations (e.g. manure digestion in Denmark), this was the result of a strong social network and much interaction between different types of actors; it required a lot of work and effort. My conclusion is that changing expectations are in particular caused by external circumstances. Experimental results may only have an effect on niche expectations when results are very poor, or when much effort is put into learning from the results.

With respect to the relationship between expectations and emerging market niches, I conclude that for a market niche to emerge, a broad set of expectations is crucial. First, broad expectations can result in a parallel development, because they enable actors to experiment with different alternatives simultaneously to realise expectations. If the majority of actors support a change in expectations, a specific niche trajectory may be abandoned while another trajectory becomes dominant, resulting in a sequential development pattern. In particular in cases of large (infrastructure) technologies, sequential development in experiments may be the only feasible route. This was the case in the Netherlands in niche branching from farm-scale plants to centralised plants. The advantage of this development is that more resources can become available for a specific niche trajectory. In the case of parallel trajectories, resources may become scattered, resulting in a limited number of experiments and a limited gain of experience within a specific trajectory. However, the disadvantage of a sequential development is that combining experiences becomes much more complex: experiences should not only be transported in space, but also in time. Sequential development patterns require more effort to maintain a broad set of expectations and to be able to confirm or refute them in experiments.

Second, broad expectations also contribute to continuity. In particular actors with a vision that deviates from the mainstream can be important factors in maintaining continuity in niche development. The Folkecenter in Denmark maintained the development of farm-scale plants on the basis of visions about autarky and decentralised energy systems, despite the absence of broad financial support from the Danish government. This enabled the reintroduction of farm-scale plants in the late 1990s.
On the basis of these results, I conclude that a broad set of expectations is important in the beginning of a niche trajectory (to allow a parallel and continuous pattern), but that expectations should be made concrete and tested in experiments along the innovation journey (expectations should be linked to experimental results).

**Network dynamics**

On the basis of my case studies, I can confirm most of the previous SNM research findings. Following Hoogma, I argued in section 2.3 that in particular the composition of the network (for understanding the direction of niche development) and the alignment in the network (for understanding the scope of niche development) are important. My cases support these findings. The co-firing cases were dominated by traditional electricity regime actors, resulting in less radical change with respect to the electricity regime, while in the cases of manure digestion (in particular in the Netherlands), the actors from the electricity regime were less dominant (until the late 1990s), resulting in more radical deviation from the electricity regime (decentralised generation). The participation of regime actors in the Dutch co-firing case also contributed to a stronger position for creating alignment, in particular in the regulatory framework, while in the Dutch manure digestion case, creating alignment in the regulatory framework was the most important barrier to the introduction of manure digestion.

However, I suggest a refinement here. Hoogma’s work was based on the development of niches against the backdrop of one regime. In my cases, multiple regimes have been important to understanding niche development. This complicates the original statement of Hoogma that the participation of actors who do not have strong ties to the dominant technological regime results in more radical niche development. Actors may have no strong ties with the electricity regime, but they may have them with the agricultural regime. As a result, what may appear as a radical innovation in one regime may only be an incremental innovation in another regime. The aspect of multiple regimes in niche development certainly needs more attention in future research on SNM (see section 7.6).

In addition to previous SNM research, I add that a broad social network with high alignment is important because it can bring about a continuous development pattern. Broad social networks with high alignment are important for continuity, because actors carry the niche, actors design and set up experiments, put efforts into learning and maintaining lessons, have visions and expectations. If a network no longer carries a niche, a niche trajectory can become extinct and experiences and lessons are forgotten, even when lessons are codified (e.g. in the case of manure digestion in the Netherlands). Actors disperse again, and their activities become misaligned. The Danish development of centralised biogas plants is very illustrative for the importance of a broad, active social network. The Committee for Renewable Energy played a decisive role in creating alignment in the early 1980s, while later on the alignment was created by the participants of the Biogas Action Programme. This network was characterised by a bottom-up development, and lively participation on the part of
different social groups including farmers, researchers, technology suppliers and governments. Through effective experimentation, exchange of experiences and information and a cycle of designing experiments and learning, there was continuous development and increasing alignment. The Danish farm-scale case shows how a dedicated actor network can play a role in maintaining continuity in the absence of formal support and protection.

Learning processes

In SNM it is argued that learning can occur concerning many different aspects, including technological development, the development of a user context, societal and environmental impact, industrial development and government policy. Learning should be orientated to creating alignment between these aspects. Moreover, learning can be orientated towards learning about the effectiveness of a certain technology to achieve a specific goal (first-order learning), and it can be orientated towards learning about underlying assumptions and norms, towards changing the rules of the games (second-order learning). The hypothesis was that broad learning processes that included both first- and second-order learning were important for successful niche development, in particular to improve societal embedding and bring about more radical innovation. There was special attention for the role of users in SNM, in particular for generating second-order learning processes.

To a large extent my cases support previous SNM findings. In the case of co-firing in the Netherlands and manure digestion in Denmark, there were broad learning processes. Interestingly, the causes for the broad learning processes were different in each case. In the manure digestion case in Denmark, broad and second-order learning was triggered by a network including users (farmers), as predicted by SNM literature; but in the Dutch co-firing case, the broad and second-order learning processes were mainly triggered by substantial problems in the societal embedding of co-firing plants, combined with external pressure to realise new, or increase existing, co-firing activities. My cases thus suggest that broad learning can be triggered by other means than by user involvement. In particular, in industrial technologies like co-firing, involvement of (non-industrial) users is a relatively less important precondition. Other social groups can be more relevant in such cases, e.g. societal groups like environmental organisations or a social group representing the neighbours of an experiment. Including these groups at an early phase of experimentation can result in the inclusion of their concerns in the innovation process and prevent societal resistance in later phases, through early adjustment of the design. The manure digestion case in Denmark illustrates how users or relevant social groups can participate in the experiments, i.e. by taking part in the organisation of the plant (cooperative).

Learning processes are important for the emergence of market niches, because they enable stabilisation in niche development. In this respect, learning is the most crucial process in the emergence of market niches; by definition, regular market niches cannot emerge without stabilisation. Most important for stabilisation is learning between different locations
and between different social groups. The interaction between social groups and the dissemination of knowledge and experiences in regular meetings and workshops was crucial for the emergence of a stabilised level of rules in the Danish manure digestion case. In the Dutch case of co-firing, comparison of local experience took place in an international context, mainly through international conferences, publications, European research groups, etc. Learning from different local practices stimulated stabilisation.

To a lesser extent, learning is also important for a parallel development. When learning influences expectations and visions, it can result in a shift in application domain or technological variation. When experiments do not produce expected results, actors can learn (negative learning) and search in different directions, investigating different niches. However, as I mentioned above, transforming lessons from experiments into new visions and expectations requires much effort.

To conclude, my case studies have resulted in two contributions to SNM research. First, they confirm most of the findings from previous SNM research, but within a new empirical domain. This strengthens the use of SNM as a research tool. Second, the case studies show why dynamics in expectations, network formation and learning are important for the emergence of market niches. My main argument was that a broad set of expectations is important because it enables a parallel development and (to a lesser extent) can bring about a continuous pattern; that a broad social network with high alignment is important, because it enables a continuous development; and that learning is the most crucial process, because it enables stabilisation. A summary is provided in Table 7.1.

Table 7.1. Relation between the characteristics of emerging market niches and internal niche processes

<table>
<thead>
<tr>
<th>Characteristics of emerging market niches</th>
<th>Parallel development</th>
<th>Continuous development</th>
<th>Increasing stabilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad set of expectations, but tested in experiments</td>
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<td></td>
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<tr>
<td>Broad social network with high alignment</td>
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<td></td>
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</tr>
<tr>
<td>Learning on many dimensions and second-order learning</td>
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</table>

Now that I have a more precise idea of how market niches emerge, I am also better able to understand the differences between the case studies. In the unsuccessful case (manure digestion in the Netherlands), expectations were generally limited to a single aspect of the
technology (e.g. either energy generation or manure processing). Although varying throughout the three decades, also the quality of social network formation was incomplete, with a lack of attention of integrating users or societal actors in the design process (in particular in the second and third period). The quality of learning processes also remained narrow, focussing mainly on techno-economic optimisation with minimal attention for second-order learning. The overall quality of niche processes was thus limited, thereby not enabling the emergence of a market niche through the intermediary variables of parallel development, continuous development and increasing stabilisation.

In the successful cases, however, the niche processes were of a higher quality. In the Danish manure digestion case, the quality of niche processes was highest, enabling a parallel development, a continuous development and an increase of stability. In the two co-firing cases, niche process quality was also high, but lacking on some dimensions. In the particular the lack of the development of a broad social network (including societal actors) and attention for second-order learning on many dimensions has led to only a limited level of stability.

I conclude that internal niche processes are important for the emergence of market niches: the quality of niche processes was higher in the successful cases, compared to the quality of niche processes in the unsuccessful cases. Nevertheless, even in the three successful cases, the level of success was only partial: the further development and diffusion of the technology was threatened in all three cases, in particular by regime dynamics. Internal momentum of the niche was still not sufficient to survive possible threats. The causes for these threats from regime level, however, differ across the cases. In the next section, I will analyse the role of regime dynamics in depth, answer my research question on niche-regime interaction, and discuss how niche-regime interactions can explain the differences between my case studies.

7.4 Niche-regime interaction

The final research question in Chapter 2 was: how does niche development interact with regimes? I expected that decreasing stability at the regime level would result in increased niche size. In addition, I discussed three extra issues that I found interesting to investigate. The first issue was related to the effect of experimenting in niches on regimes. Did any regime change occur due to experimenting in niches? The second issue was related to multiple regimes. Was the electricity regime the only important regime in my cases, or were other regimes relevant? The third issue was about the sources of instability. If niche development had not yet reached the point of reversal, then what were the sources for instability in the electricity regime in my cases? I will discuss these issues successively in the following sections.
7.4.1 Relation between regime stability and niche size

The general conclusion from my case studies is that stability in the Dutch and Danish electricity regimes began decreasing in the 1970s. In both countries, the electricity regime changed from being a stable centralised regime, based on large-scale power plants, fuelled by oil and coal, dominated by a few large companies and without any consumer choice, to being a regime that is much more in flux. Centralised production was increasingly complemented with decentralised production units – in both countries fuelled mainly by natural gas; import of electricity increased; the market share of decentralised producers increased; and consumer choice was introduced, as was competition in energy generation and supply. These changes were accompanied by new visions on the electricity regime in terms of liberalisation and sustainable energy generation, by increasing interference on the part of the government, and by internationalisation in the electricity sector.

My cases support the hypothesis that instability at the regime level increases opportunities for niche development or creation, and can result in increased niche size. I conclude that there are three ways in which regime instability can result in increased niche size. First, regime instability can create local opportunities for experiments, because niche actors develop expectations and visions linked to regime instability. This happened in all my cases. In the 1970s, actors in the Danish and Dutch biogas niches developed expectations about alternative energy generation, because centralised energy generation was in trouble, due to the high oil prices. Too, in the co-firing cases (particularly in the Netherlands), limited instability in the electricity regime created local opportunities, because niche actors expected to reduce fuel costs and to be able to develop a more competitive way of production.

Second, when stability in the regime decreases, regime actors may become interested in the niche. The reason they become interested is that they expect the niche to be a promising option for the future. This was in particular the case in the Dutch co-firing case. The emerging green market, the increasing emphasis on a sustainable energy system, and the emergence of regime actors with a broad interest in energy generation and waste processing resulted in an increased size of the co-firing niche. Co-firing was increasingly recognised within the regime as a promising option for producing renewable energy. Furthermore, in the Dutch manure digestion case in the late 1990s, regime actors participated in the projects, because they perceived that manure digestion was a promising option.

Third, in cases of very high instability, regime actors may adopt the niche as a problem solver. This is clearly the case for both co-firing cases in the Netherlands and Denmark. Political agreements created a sense of urgency in both countries, resulting in rapidly increased niche size in both countries – as was the case for manure processing in the early 1990s in the Netherlands, when huge environmental problems and political pressure created a sense of urgency among agricultural regime actors. These actors adopted manure processing
as the main solution to the problems. When a niche is seen as a problem solver, size can increase much more rapidly than when it is seen as promising technology.

I conclude that instability at the regime level does increase the opportunities for niche development, and can result in increased market size. However, instability in regimes does not determine niche development. As argued in SNM literature and in the section above, the quality of niche processes is also important for the potential of a niche. In Figure 7.2 I have combined both factors in a matrix. This matrix displays the assessment of niche potential based on regime stability and the quality of niche processes. First, niches located in the upper left-hand corner have very limited potential to grow and break through. The quality of the niche processes is limited, e.g. due to is discontinuity or very limited niche branching. Moreover, stability in the dominant regime is high, resulting in very limited opportunities for increasing the size of the niche. I call these niches a dead-end street. An example of such a niche is the farm-scale biogas niche in the Netherlands in the early 1980s. Second, niches in the lower left-hand corner can be characterised as missed opportunities. Despite stability in the dominant regime being low, which creates opportunities for increasing niche size, the quality of niche processes is also low. Niches in this corner do have a chance of a successful breakthrough, but require more effort to increase the quality of the niche processes. Depending on the niche, these efforts could for example be improving learning between experiments, or creating a broader network with more intensive relations between actors. Centralised manure digestion in the Netherlands in the early 1990s is an example of a missed opportunity. Third, niches in the upper right-hand corner are promising technologies. Experiments at the niche level are successful, the social network involved is broad, and actors are able to learn effectively from experiments. The high quality of niche processes does result in niche growth, but high stability in the regime prevents a rapid growth. Centralised biogas plants in Denmark in the early 1990s and co-firing in the mid-1990s in the Netherlands are examples of this type of niche. Finally, niches in the lower right-hand corner are problem solvers. Regime stability is low and regime actors are searching for solutions to recreate stability or control. They begin to participate in niches, because they expect that the niche offers a solution to the problems with which they are dealing. This high quality of niche processes and the participation of regime actors enable a rapid increase of niche size. An example is co-firing in the Netherlands after 2000.
The matrix in Figure 7.2 is useful, because it can be used to assess niche potential, for example by policy makers or firms. I can also use this matrix for explaining the different outcomes in my case studies. In general, the electricity regime has become less stable in the 1970-2000 period. According to the matrix, the technologies in my case studies would either end-up as a missed opportunity or as a problem solver, depending on the quality of niche processes. Indeed, the least successful case can be characterised as a missed opportunity: although decreasing stability in the Dutch electricity regime did create opportunities for new experiments (broadening of expectations, broadening of the social network, new financial incentives for learning in experiments), the limited quality of niche processes prevented a breakthrough. In the successful cases regime instability (in particular the instability caused by governmental agreements) made the technologies (in particular co-firing) a problem solver: the social network broadened to include regime actors or their level of participation increased.

There are, however, still some problems with explaining the level of success using this matrix, in particular related to the robustness of success (or the level of internal niche momentum). All three successful cases were facing difficulties in the late 1990s or early 2000s, caused by different issues. The Dutch co-firing niche was facing problems originating from mis-alignments between the electricity regime and the waste regime, and the inability of the actors involved to deal with the problems. The Dutch co-firing case was also threatened by high instability on regime level, in particular due to uncertainties about innovation and uncertainty about the incentive structure for renewable energy. Also the Danish manure digestion case and the Danish co-firing case were facing problems due to a decreasing willingness to invest, caused by a very high level of instability in the electricity regime. The electricity reform, new energy policies and changes in incentive structures for renewable
energy stopped the investments in centralised biogas plant, and resulted in less willingness to invest in more radical co-firing solutions. Thus, two issues need further investigation. The first issue is that the matrix does not take into account the possibility of multiple regimes. I come back to the issue of multiple regimes in sections 7.4.3 and 7.6. Second, my cases suggest that regime instability can result in larger niches, but only to a certain degree. If regime stability decreases too much, it may result in a high level of uncertainty in niches. I will come back to this issue in section 7.6, in relation to future SNM research.

7.4.2 Effect of experimentation in niches on regime dynamics

In section 2.4.3 I argued that in none of my cases did reversal occur, but that niche development can still have an effect on regimes. In these cases, I have investigated what kinds of changes occurred, and how they occurred. Most of the changes that did occur were adjustments in formal regulations, after niche actors lobbied for changes. In the Dutch co-firing case, emission standards and biomass definitions were changed, because of large problems with the societal embedding of co-firing technologies. Energy companies advocated a broad definition and a clear emission framework, because it would enable them to continue co-firing. The climate change negotiations between the Dutch government and the energy companies enabled the companies to pursue the required changes. Another example of changes in formal regulations is the Danish co-firing case. In this case, niche actors lobbied for changes in the regulations for re-using by-products, which would allow them to recycle the by-products instead of dumping them on a landfill. The Danish manure digestion case also contains examples where regulations were changed on the basis of niche experiments. These regulations benefited expansion of the niche.

Niche development and experimentation affected regimes in two other important examples, and both are related to the participation of regime actors in niche development. The first is the Dutch manure digestion case. In this case, centralised digestion and processing of manure failed. Because of the failure, regime actors and agricultural policy makers rejected manure digestion as a desirable technology in the agricultural regime, and they searched for other solutions (distribution without processing, reducing the number of animals and farms). In the second example the opposite happened, such as in the Dutch co-firing case: co-firing experiments were successful and were taken up as a problem solver in the electricity regime, to deal with climate change problems.

My general conclusion, however, is that experimentation in niches has had limited effect on the electricity regime. One reason is that the relative niche size in my cases remained limited. Therefore a recommendation for future research is to investigate cases in which much larger niches emerged and replaced (parts of) the regime.
7.4.3 Multiple regimes

In all my case studies, dynamics in multiple regimes were important for understanding niche development. In particular changes in the agricultural regime, the waste regime and the heat regime were important. I did not take multiple regimes as a starting point in my analysis, but argued that it could be an interesting issue in my cases. Therefore, I cannot draw any solid conclusions on the relation between multiple regimes and niche development. However, the cases do shed light on an interesting issue. The development of a niche against the backdrop of multiple regimes can be both an advantage and a disadvantage. When a niche offers a solution to a range of problems in different regimes, this can increase the available resources for niche development. In the Dutch co-firing case, resources from waste processing and renewable energy generation were available, while later also resources for climate change prevention became available. In Denmark, the centralised biogas plant concept was protected by expectations about manure distribution, waste processing and energy generation.

The development of niches against the background of multiple regimes can also be a disadvantage, because complexity increases. Rules from different regimes may conflict and prevent niche expansion. This is very well illustrated by the Dutch co-firing case. The expansion of co-firing slowed down due to conflicting emission standards from the waste regime and the electricity regime. Too, in the Dutch manure digestion case, conflicting rules for codigestion slowed down niche expansion.

Niche development against the backdrop of multiple regimes is an interesting field for further research (see section 7.6).

7.4.4 Sources of regime instability

The final issue I addressed in section 2.4.3 was related to the sources for regime instability. I addressed the question of where regime instability came from, if not from successful niche development. My conclusion is that external circumstances are a major source of instability, i.e. developments in the socio-technical landscape. Trends that were important were global energy prices, liberalisation of European energy markets and emerging environmental problems. These trends often stimulated public authorities to intervene in the regime and to enact new policies and regulations. Policies and regulations were thus a mechanism between landscape trends and regime instability. Furthermore, regime actors’ visions acted as a mechanism between landscape trends and regime instability. Regime actors developed new strategies on the basis of these emerging trends. These strategies were also often the reason why regime actors participated in niche development. Finally, the emergence of decentralised electricity systems and decentralised producers was also a source of regime instability. These actors began to threaten the stability in the regime already in the late 1980s, both in the Netherlands and Denmark.
7.5 The role of public authorities in niche development

SNM authors have claimed that SNM can be used as a policy tool. In this section I will speculate about the kinds of strategies that policy makers can use and what kinds of outcomes these strategies are likely to produce. I do so on the basis of SNM literature and my own case studies. In section 2.5 I made a distinction between three types of policy strategies: top-down, centralised planning strategies, market-based, bottom-up strategies, and process and network management models like SNM. I expected that in the case of co-firing, top-down, centralised planning strategies have been used most, while in the case of manure digestion, process and network management strategies have been used most. In this section, I map the different strategies used by public authorities and discuss the results of these strategies.

In the case of manure digestion in the Netherlands (Table 7.2), the main policy strategy in the 1973-1985 period was a combination of a process and network management strategy (stimulating research, experiments and learning) and a market-based, bottom-up strategy (general subsidies). A similar strategy was followed in Denmark (Table 7.3). In the second period, there is a clear difference between the two countries. The Dutch government mainly followed a top-down, centralised planning approach, trying to realise a large infrastructure for manure processing, and combined this strategy with market-based instruments like generic levies on manure distribution. In Denmark, the main strategy was to create a network for learning and experimentation, to stimulate interaction. Public authorities actively participated in this network. This strategy was accompanied by specific investment grants and favourable loans, which stimulated a bottom-up decision to participate in the network and in the experiments. Top-down planning is not absent, but applied only limitedly, e.g. when choosing experiments and locations. In the late 1990s and early 2000s, the top-down planning strategy was abandoned in the Netherlands and the focus turned more to market-based instruments (generic investment grants, tax exemptions for renewable energy). These are instruments for renewable energy in general, not manure digestion specific. Within the policies for climate change prevention, some attention was indeed paid to experimentation, learning and dissemination of knowledge, but none was paid to an active strategy to combine results from different locations (learning between projects). The 1995-2003 period in Denmark was characterised by a shift towards a market-based strategy, in particular after the election of a new Danish government. There was less attention for process and network management, illustrated by the cessation of the biogas action programme.
Table 7.2. Policy strategies in the case of manure digestion in the Netherlands

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<tr>
<td>Top-down, centralised planning strategy</td>
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<td>Market based, bottom-up strategy</td>
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<td>Process and network management strategy</td>
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Table 7.3. Policy strategies in the case of manure digestion in Denmark

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<td>Top-down, centralised planning strategy</td>
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<td>Market based, bottom-up strategy</td>
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<td>Process and network management strategy</td>
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Tables 7.3 and 7.5 show the policy strategies that apply to co-firing in the Netherlands and Denmark. In the 1993-1995 period, the Dutch public authorities did not have a specific strategy for co-firing, but general, market-based instruments (investment grants, research grants for waste-to-energy) supported the co-firing experiments financially. In the 1996-2000 period, the market-based strategy remained dominant, but public authorities also began participating in the (international) network on co-firing, discussing emission standards within the Netherlands and within Europe. In this period, the market-based instrument of tax exemption was very important for stimulating investments in renewable energy. In the 2001-2003 period, the top-down, centralised planning approach became dominant. The Ministry of the Environment applies technology forcing by defining high end-goals for carbon dioxide emission reductions. Market-based instruments remained a part of the strategy to stimulate local initiatives through investment grants; tax exemptions were replaced with a new system for production subsidies based on fixed feed-in tariffs for electricity.

The Danish co-firing case is dominated by a top-down, centralised planning approach in all periods, in particular because of the biomass agreements made for increasing biomass in decentralised (1985-1992) and centralised (1993-2000) energy production. This strategy was backed up with favourable fixed tariffs for the power produced, but these were generic instruments for renewable energy in general. The Danish government also used elements of network management approaches through negotiating the Biomass Agreement with the electricity sector. In the 2001-2003 period, the strategy became more market-based, a result of the ongoing liberalisation. The top-down, centralised planning approach was still maintained, but this was mainly the result of previous planning strategies.
Table 7.4. Policy strategies in the case of co-firing in the Netherlands

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<td>Top-down, centralised planning strategy</td>
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<td>Market based, bottom-up strategy</td>
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<td>Process and network management strategy</td>
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Table 7.5. Policy strategies in the case of co-firing in Denmark

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<td>Top-down, centralised planning strategy</td>
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<td>Market based, bottom-up strategy</td>
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<td>Process and network management strategy</td>
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The tables show that in the case of manure digestion in Denmark, the process and network management strategy has been dominant (in particular for centralised biogas plants), while in the case of co-firing in the Netherlands and Denmark, the top-down, centralised strategy has been dominant. Market-based strategies have played a role in all cases. This confirms my hypothesis.

The tables highlight several other interesting aspects in relation to the mix of policy strategies. First, for successful niche development (co-firing NL, manure digestion DK, co-firing DK) it seems necessary to have at least some elements of the process and network management approach in the mix of policy strategies. Without stimulating experiments, enabling broad and deep learning processes, creating new social networks and active participation of public authorities in these networks, the chances of successful niche development are very limited. On the other hand, some centralised planning and coordination should also be part of the strategy, in order to efficiently combine experience and align different actors’ activities. The optimal mix of strategies combines bottom-up experiments, learning processes, and network formation (stimulated by market-based instruments) with a clear and decisive top-down policy that is strongly based on experimental results. A purely top-down, centralised policy is likely to fail, because it is insensitive to the actual practices, problems and preferences in local networks built around the innovative technology. A purely bottom-up approach, on the other hand, focussing only on generic instruments through investment grants, tax exemptions and favourable tariffs reflects a naive perception and strong belief in the self-organisation of local actors. The pitfall of this strategy is that local decisions may not add up to an optimal solution for a society on the whole. The policy strategy that is likely to be the most effective aims to bring together and compare experiences from different locations, create broad social networks and stimulate broad and deep learning, while applying these lessons in making or adjusting policies.

Second, market-based strategies and instruments have a very important role to play in realising successful niche development; they should be part of every strategy that aims to stimulate sustainable technologies. The case of manure digestion in Denmark is very
illustrative. High investment grants for centralised biogas plant were a prime mover in the early stimulation of this technology in Denmark; a very favourable tax exemption for renewable energy created a strong stimulus for developing co-firing technologies in the Netherlands. These kinds of instruments are necessary to make projects economically feasible, a necessary pre-condition for survival in a market economy. However, market instruments should not be too generic, but niche-specific, and be accompanied by a process and network management strategy to create a social network that is eventually able to continue niche development without external financial resources.

Finally, in sections 2.5 and 2.6 I have distinguished between strategies aimed at regime optimisation and strategies aimed at regime shift. I argued that top-down strategies like technology forcing are the most appropriate strategies for realising regime optimisation, because they put pressure on the existing regime to come up with technologies with specific characteristics. The existing regime does change, but the basic structure in terms of rules, dominant actors and socio-technical system remains largely the same. In the case of a regime shift, the incumbent technology is replaced by a new, radically different technology that has been developed through policy strategies focused on process and network management in niches. The new regime in terms of rules, actors and socio-technical system is radically different from the old regime.

On the basis of my cases I now expect that another trajectory and outcome may be possible. I call this *regime reconfiguration*. In this trajectory, a sufficient number of incremental changes in socio-technical parts of the regime occur in such a way that they build up to (or modulate into) a regime that is overall structurally different. This outcome is the result of a top-down strategy and a process and network management strategy, and will most likely occur when regimes are already unstable. Increasing pressure on the regime increases the awareness that specific problems cannot be solved by optimising the existing technological base. Regime actors themselves may be evolving into actors with different roles and perceptions. At the same time, successful process and network management strategies contribute to the replacement of several connected parts of the regime. These include technological innovation, but also the emergence of niche markets for fuels or products (electricity). In itself, replacement of small parts of the system only produces incremental changes, but over time, replacements add up and eventually result in a structural regime shift. The relationships between the three strategies and the three outcomes are shown in Table 7.6.
Table 7.6. Optimum mix of policy strategies versus different outcome scenarios

<table>
<thead>
<tr>
<th>Regime optimisation</th>
<th>Top-down planning strategy</th>
<th>Market-based, bottom-up strategy</th>
<th>Process and network management strategy</th>
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<td>Regime shift</td>
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<td>Regime reconfiguration</td>
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Table 7.6 is a hypothesis about possible outcomes of niche development. My cases cannot confirm this table. However, the Dutch co-firing case may become an example of a regime reconfiguration. Replacing part of the coal with biomass does not radically change the electricity regime. Nevertheless, this process is linked to a large number of other replacements in different parts of the regime, including an emerging market for green electricity, horizontal and vertical integration, a new fuel supply system including different fuel suppliers located in different countries, emerging markets for emission trading, different perceptions on the role and function of waste. Although not intended to be interconnected, and not (only) the result of the co-firing niche development, these linkages may finally result in a regime that is structurally different from the previous, fossil fuel-dominated electricity regime.

7.6 Future research agenda

On the basis of my research, I herewith list the following issues that deserve more attention in future research on SNM.

First, the issue of multiple regime analysis deserves more attention. I have mentioned this several times in my conclusions. In all cases, multiple regimes were involved, in particular the electricity, heat, agricultural and waste regimes. Niches can develop against the backdrop of several regimes (i.e. when regulations, perceptions, problem definitions, visions, actors, technological knowledge and artefacts from different regimes shape the niche). Multiple regimes can result in opportunities, in particular when a niche is able to provide solutions to problems experienced in different regimes. There may also be barriers, when regime rules are contradictory. These dynamics result in a much more complex background for niche development than previously assumed. This needs to be investigated further.

One way of investigating the interaction between multiple regimes is illustrated in Figure 7.3.\footnote{I thank Geert Verbong for suggesting these figures.} In the simplest case (a) only one niche develops against the backdrop of one regime. These kinds of relations have been investigated in previous SNM research. A more complicated case is when a niche develops against the backdrop of more than one regime (b). Now, not only interactions between the niche and the regime are important, but also...
interactions between regimes. An example is the development of centralised biogas plants in Denmark. A third possible situation (c) is the development of multiple niches against the backdrop of one regime. Now there can be competition between niches, niches are fighting for resources, or there can be spill-overs between niches. An example is the competition of several renewable energy technologies against the backdrop of the electricity regime. Finally, the most complicated case is when multiple niches are developing against the backdrop of multiple regimes (d). Now there are multiple interactions between niches and between regimes, increasing the complexity even more. The question of how these complex relations affect niche development deserves more attention in future research.

Figure 7.3. Four different types of niche-regime relations

A second issue that deserves more investigation is the issue of high instability. In section 7.4.1, I argued that if regime instability decreases too much, this can result in high uncertainty at the niche level, suggesting that there is a turning point after which instability in regimes decreases the opportunities (or creates barriers to) for niche breakthrough. I have the following hypothesis on this issue (see Figure 7.4). In the graph, I make a distinction between three situations. In situation I, there is high stability in the regime. There is a clear and dominant social network, the role relations between actors are stable, firms produce for stable markets and their ideas correspond to user preferences. There is also a dominant design, supported by an effective regulatory framework; firms, authorities, societal groups and other actors have a clear and shared vision about the regime, and about the direction of development. There may be urgent problems, but the general perception is that they can be
solved while maintaining most of the existing regime through optimising the dominant design. In this situation, the chances for niche breakthrough are very limited.

In situation III, the regime is highly unstable. There is no longer a dominant design, e.g. because it has been abandoned due to substantial environmental problems. Firms that previously dominated the regime may be looking in different directions; they no longer have shared search heuristics nor do they share a vision on the regime’s future. Moreover, new firms have emerged, trying to gain market shares by using new strategies or by supporting different technologies. Because of diversification in the technological base, there is no longer a clear and effective regulatory framework, there are no longer obvious user preferences or clear markets. In this situation, the opportunities for niche breakthrough are also very limited, due to a high level of uncertainty about future requirements for innovative technologies, and scattered use of resources.

Finally, in situation II the regime is also unstable, but still offers enough certainty and structure. In this situation, dominant regime actors are facing large problems (e.g. environmental problems, external (political) pressure or competitors gaining market share). They are increasingly aware that they cannot solve these problems while maintaining the existing regime. They orientate towards more radical solutions. The established regime in terms of social network relations, regulatory frameworks, market rules, R&D-infrastructures, etc. is to a large degree still intact; regime actors can build upon established relations in the past and maybe continue the cooperation. Nevertheless, they are also looking for solutions and partners outside established networks. This situation creates the most opportunities for niche breakthrough, because it makes resources at the regime level available for niche development.

Figure 7.4. Relation between stability at the regime level and opportunities for niche development
Finally, a third issue that deserves more attention is the use of SNM as an instrument. In this thesis I have investigated the use of SNM as a research framework and as a policy strategy tool. However, it can also be used as an instrument, namely as a practical tool for governments or other actors concerned with the introduction of sustainable technologies (Weber et al., 1999). SNM can be used for improving the design of experiments, for evaluating policies in the past, or for using SNM as part of scenario development, or for designing future policies on niche management. However, SNM has not been used as such in practice, but mainly as a research tool. The policy claims that are often made by SNM researchers still remain a promise; SNM needs real-life experimentation in society.
Epilogue

Strategic Niche Management as a tool in regional transitions and policy

The transformation of a national energy sector towards sustainability is a complex process, one that is hard to manage. Not only are many social groups shaping the innovation process or taking part in the adoption and diffusion process, the international context, too, has become increasingly important over the last thirty years. National energy regimes like that of the Dutch are affected by international take-overs, liberalisation of European markets and international commitments regarding sustainability, climate change and renewable energy sources. Nevertheless, one of the most urgent transformations, reaching sustainability, is still mostly a utopia. Unsustainable energy generation and use continue to be the most important sources for environmental degradation, climate change and social and political tensions. Western nations depend heavily on the foreign supply of fossil fuels, making them vulnerable to huge disruptions in the economic environment. Although new fossil fuel resources are still being discovered, sustainable fuels will become a necessity for improving or at least maintaining the current economic, social and environmental standards in Western societies.

Not only energy regimes change; policy paradigms change as well. The unbridled belief in a ‘makeable society’, in top-down policy instruments and large technological projects to create a better society is long gone, beaten by emerging flaws in sectors like energy, agriculture, waste and water management. The 1970s and 1980s witnessed the feast of free markets and liberalisation of formerly public sectors. New policy approaches emerged again in the 1990s, taking on the network society and focussing on network management approaches (Rotmans, 2004). In addition, the Dutch government adopted a new approach in its fourth National Environmental Policy plan in 2001. The approach, called ‘Transition Management’, is characterised by the creation of long term visions, a systems approach, cooperation between the government and societal stakeholders, and societal experiments to initiate new trajectories (Ministry of Economic Affairs, 2004). Biomass and bioenergy was the spearhead in one of the envisioned trajectories (Ministry of Economic Affairs, 2003a).

Strategic Niche Management (SNM) can be used as a tool in transition management. SNM provides insights into the role of experiments in transformation processes – the creation and exploitation of technological niches and strategies to build up market niches, through a continuous process of niche branching, and stabilising of rules and practices. SNM can thus be used by policy makers or other technology promoters or stakeholders to design new trajectories, or ‘transition paths’. SNM can act as a focussing lens for recognising flaws in learning, can be used for deciding on the inclusion or exclusion of actors in the social
network, and can be used for assessing the potential of niches, based on the stability of the dominant socio-technical regime and the quality of niche processes (see Chapter 7).

In particular, regional policies for sustainable innovation can be enriched with SNM. Regional policy structures like the Dutch ‘provinces’ form a natural bridge between local activities and interests, and national structures like national policies and regulations. Regional policy actors and stakeholders can use SNM as a tool for designing (a set of) experiments such that they build up to local market niches for a specific sustainable technology. Regional actors are in a (potentially) optimal position to judge local interests and benefits, choose between locations and divide resources across locations, while also maintaining a broader scope and considering benefits for society as a whole. They can participate in projects and discussions and maintain the overview between the different experimental results. I do not argue that current policies are completely lacking elements of such an approach. In many regions policy makers and stakeholders cooperate in projects or set up intermediary organisations to stimulate the exchange of experiences and dissemination of knowledge. Nevertheless, I believe that SNM can be a fruitful addition to regional sustainability policies for two reasons.

The first reason is that SNM puts learning at centre stage. Societal experiments like pilot and demonstration projects are often established for the local, individual interests of a company, user or other stakeholder. Projects are termed a demonstration or pilot project, because they incorporate an innovative feature – a new technological variation - and receive public funding for it. Yet these projects are often not fine-tuned for knowledge dissemination. Learning remains local; companies and stakeholders involved learn about the problems and advantages of using or producing the specific innovation, but the experiences are not shared widely or compared explicitly with similar experiments in other locations. Using SNM in regional policies can enhance this process, because SNM focuses on designing experiments in such a way that they contribute to a process of cosmopolitanism: experiences are compared at an inter-local level and used for input in the design of new experiments. Here I see a promising opportunity for regional policy actors. They can play a crucial role in cosmopolitising experiences, by formulating a regional vision (supported by the stakeholders), through network management (bringing actors together), by enabling learning (monitoring results from different experiments) and by exchanging lessons (organising seminars and meetings and publishing results).

The second reason SNM can be a fruitful addition to regional sustainability policies is that SNM explicitly situates the local nature of experimentation against the backdrop of dominant rules, technologies and social networks. Innovations are not born in a vacuum but are shaped by existing regimes and social groups. A well designed experiment, in terms of socio-technical configuration, exploits (temporary) instabilities in the dominant regime, e.g. a specific (local) problem that cannot be solved through normal practice. Protection through funding or temporary exemptions from laws can add up to the feasibility of a project.
Carefully selecting experiments on the basis of instabilities in socio-technical regimes is a second opportunity for regional policy actors. A long-term analysis of the dominant regime(s) can give insight into crucial regime problems and in particular how these problems come about in the relevant region. The selection of experiments should thus be based on (a) how they add up to the emergence of a cosmopolitan niche level, and (b) if and how they exploit instabilities in dominant socio-technical regimes.

SNM can improve current policies, but one should always be aware of possible pitfalls. For one thing, the role of regional policies must not be overestimated. Policies and policy actors are embedded in a hierarchal network of rules, interests, and labour and power division in policy making. Local policies are embedded in regional policies; regional policies are embedded in national and international policies. The possibility of diverging from decisions made on a higher level in the hierarchy is often limited, or decisions at the higher level are opposed by actors at the lower level of the hierarchy. Although this can bring about serious problems, it also emphasises the need for cautious and precise selection of experiments and niches. Unfortunate choices in the past can seriously limit the possibilities of an innovation in the future, because actors in other parts of the hierarchy are no longer willing to support its development. Moreover, the hierarchal structure of policy networks emphasises the need for alignment between choices and strategies at different levels. Early involvement or consultation with local and national actors is crucial in regional projects.

Another pitfall, when using SNM for regional policies, can be that continuity is not always secured in (regional) policies. Sustainable innovations often take decades to take off, surpassing the duration of general policy cycles, a possibly serious disadvantage in realising a successful niche development trajectory, because surpassing policy cycles complicates the transfer of experiences from the past into the designing of new projects and policy measures. Active stakeholder involvement in policy making and execution and in supporting and maintaining a vision on the future can secure progress in niche development. In other words, a niche trajectory and niche policies need ‘distributed support’ in order to be maintained, in case actors drop out of the network.

A third pitfall is of a more practical nature. The emphasis within SNM on learning between experiments might face problems in practice, because of the individual interests of actors involved in an experiment. Companies participate to benefit in a certain way, e.g. to explore new markets. Individual companies or other actors might be uninterested or even frustrate the exchange of knowledge and experiences. Companies might patent parts of the technology in early phases of innovation, complicating the dissemination and use of these parts in other experiments. One solution is that regional public authorities adhere to certain preconditions for receiving financial funds, e.g. conditions for taking part in monitoring programmes, in regular meetings, or for publishing results. However, future profitability is often the main incentive for companies to participate in experiments, and should not be underestimated in SNM policies. Stimulating the exchange of experiences while maintaining...
individual actors’ profitability requires a balanced approach, a pragmatic approach in which both aims can be accomplished simultaneously.

To conclude, Strategic Niche Management offers several opportunities to regional policy actors, and can seriously enhance the policy process for sustainable innovations. Most importantly, policy efforts should be directed towards creating a learning environment that stimulates actors to be reflexive, and one that allows discussions on the desirability of the innovation. I hope that SNM itself will be part of this learning process, and that learning will result in continuous improvements of the tool, both for policy makers and for researchers. Above all, I hope that SNM can live up to its promise and contribute to making current energy regimes more sustainable.
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Samenvatting

Strategisch Niche Management voor Biomassa
Een vergelijkende studie naar de experimentele introductie van bioenergie technologieën in Nederland en Denemarken

Hoofdstuk 1. Inleiding

Bioenergie is energie opgewekt uit organische materialen zoals hout en mest. Het speelt een belangrijke rol in de Nederlandse doelstellingen voor duurzame energie, maar de introductie van technologieën voor de productie van bioenergie verloopt niet zonder problemen. In vergelijking met andere Europese landen is de bijdrage van bioenergie in de totale primaire energie toevoer laag. Met name Finland, Zweden, Oostenrijk en Denemarken scoren hoog. De eerste drie landen zijn gekenmerkt door een groot aanbod van hout door relatief veel bebossing en de aanwezigheid van houtindustrie. Denemarken vormt hierop een uitzondering. Dit land heeft geen grote hoeveelheden bos en geen grote houtindustrie. Toch is het aandeel van bioenergie relatief groot in dit land. Het centrale thema van dit boek is het verschil tussen Nederland en Denemarken te begrijpen. Twee cases worden bestudeerd: mestvergisting en meestoken van biomassa in elektriciteitscentrales. Dit resulteert in de volgende onderzoeksvraag: hoe en waarom verschilt de ontwikkeling van bioenergie van mestvergisting en meestoken in Nederland en Denemarken?

Om deze vraag te onderzoeken wordt gebruik gemaakt van de aanpak van Strategisch Niche Management (SNM). SNM is ontstaan vanuit de observatie dat veel duurzame technologieën (met name in de transportsector) veelal niet slagen door te breken. Centraal in SNM staat de gedachte dat nieuwe technologieën zich ontwikkelen tegen de achtergrond van een dominant regime, d.w.z. de set van (formele en informele) regels die het gedrag van actoren stuurt (maar niet dicteert). Om nieuwe technologieën tot ontwikkeling te laten komen, is het noodzakelijk beschermd ruimtes te creëren (technologische niches), waarin actoren kunnen experimenteren met technieken en regels die afwijken van het dominante regime. Bescherming kan bijvoorbeeld plaats vinden door subsidies of uitzonderingen op regelgeving. Technologische niches kunnen worden gecreëerd door middel van maatschappelijke experimenten, zoals demonstratie- en pilot projecten. Naarmate actoren leren de technologie en maatschappelijke inbedding te verbeteren, kan de bescherming worden verminderd, en kan uiteindelijk een markt niche ontstaan. SNM claimt dat het creëren van technologische niches geen garantie is, maar wel een noodzakelijke stap in het totale innovatieproces.

Het gebruik van SNM als analyse kader levert twee additionele vraagstukken op. De eerste vraag is: wat zijn de cruciale factoren voor het ontstaan van markt niches? In voorgaande SNM studies zijn alleen technologische niches onderzocht die nog niet zijn doorgebroken tot markt niches. Dit onderzoek biedt daarom de mogelijkheid inzicht te krijgen
in factoren die belangrijk zijn voor het ontstaan van markt niches. De tweede vraag is: hoe werken niche en regime ontwikkelingen op elkaar in? Ook deze vraag is in voorgaand onderzoek onderbelicht, met name omdat duurzame transport technologieën zijn onderzocht, die zich ontwikkelen tegen de achtergrond van een zeer stabiel transport regime. Dit onderzoek biedt de mogelijkheid inzicht te krijgen in niche ontwikkeling tegen de achtergrond van een instabiel regime, d.w.z. het elektriciteitsregime. Ter aanvulling wordt in dit onderzoek ook aandacht besteed aan de vraag welke strategieën overheden kunnen gebruiken voor het stimuleren van duurzame technologieën, en tot welke mogelijke uitkomsten deze strategieën kunnen leiden. Dit is geen volledig onderzoeksthema, maar ik speculeer over deze vraag op basis van SNM literatuur en de case-studies in dit onderzoek.

De vragen worden beantwoord door het volgen van een casestudie strategie. In een casestudie strategie worden verschillende casussen zo gekozen dat ze een contrast of een replicatie vormen. In dit onderzoek is mestvergisting in Nederland en Denemarken als contrasterende casus gekozen. In de Nederlandse casus zijn er in de periode 1973-2003 veel experimenten geweest met mestvergisting, maar dit heeft uiteindelijk niet geleid tot een substantieel aantal installaties. In Denemarken hebben de experimenten in dezelfde periode geleid tot meer dan vijftig vergistingsinstallaties. Het meestoken van biomassa in elektriciteitscentrales is gekozen als replicatie casus. In beide landen is er sinds begin jaren 90 geëxperimenteerd met meestoken, hetgeen in beide landen geresulteerd heeft in een capaciteit van ongeveer 170 MWe. De data die gebruikt is voor dit onderzoek bestaat voornamelijk uit geprinte documenten en informatie uit interviews, aangevuld met een aantal bezoeken aan vergistingsinstallaties en meestook installaties, en deelname aan een bijeenkomsten van operators van vergistingsinstallaties in Denemarken.

Hoofdstuk 2. Conceptueel kader

Een overzicht van relevante literatuur

Vervolgens wordt een multi-level perspectief geïntroduceerd, waarin een derde concept (socio-technisch landschap) wordt toegevoegd aan regimes en niches. De drie concepten (of niveaus) verhouden zich tot elkaar doordat ze een verschillend niveau van structurering bieden aan lokale praktijken. Een socio-technisch landschap vormt daarbij de relatief harde materiële en immateriële context van samenlevingen. Het landschap bestaat uit (de aanwezigheid van) natuurlijke hulpbronnen, politieke coalities, infrastructuren, macro-economische aspecten etc. Het maakt sommige trajecten meer voor de hand liggend dan andere. De belangrijkste bijdrage van het multi-level perspectief aan de discussie over radicale innovaties is dat de uitkomst van een innovatietaject het resultaat is van koppelingen tussen de verschillende niveaus.

De paragraaf eindigt met een discussie over stabiliteit in regimes. In voorgaand onderzoek is stabiliteit van regimes als belangrijke variabele naar voren gekomen om verschillende routes in regime veranderingen te begrijpen.

Het tweede deel van het literatuuroverzicht behandelt Constructief Technologie Assessment (CTA). CTA is een benadering die tracht technologie ontwikkeling te sturen door een inschatting te maken van de maatschappelijke effecten van een technologie, en deze inzichten vroegtijdig te integreren in de ontwikkeling van die technologie. Hierbij zijn drie zaken belangrijk. Ten eerste het vroegtijdig betrekken van alle relevante actoren in het ontwerpproces. Ten tweede het stimuleren van maatschappelijk leren en het anticiperen van mogelijke toekomstige effecten. Ten derde het stimuleren van reflexiviteit, d.w.z. het inzicht dat technologisch en maatschappelijk ontwerp onlosmakelijk met elkaar zijn verbonden.

**SNM: het onderzoeksmodel**

In SNM wordt het niche concept verder uitgewerkt. In deze benadering worden maatschappelijke experimenten gezien als de drager van een niche. Voorgaand SNM onderzoek heeft laten zien dat bij experimenteren met technologie in een maatschappelijke context drie processen een belangrijke rol spelen. Ten eerste het uiten en vormen van verwachtingen. Actoren hebben verwachtingen over de functionaliteit of haalbaarheid van een technologie; verwachtingen vormen de legitimatie om met technologie aan de slag te gaan die nog niet marktrijp is. Uit voorgaand onderzoek is gebleken dat de bijdrage van experimenten aan verwachtingen gering is en dat een verschuiving in verwachtingen met name een proces van niche vertakking (‘branching’) tot gevolg heeft. Het tweede proces is het ontstaan van een sociaal netwerk rondom de innovatie. Voorgaand onderzoek heeft inzichten opgeleverd over de invloed van de netwerksamenstelling en de afstemming binnen een netwerk op de uitkomsten van niche ontwikkeling. Het derde proces is leren. Leerprocessen vormen het kernproces in experimenten en niche ontwikkeling. Leren zou vooral breed en diep moeten zijn. Breed leren verwijst naar het leren op een groot aantal domeinen (techniek, gebruikers context, maatschappelijke context, industriële ontwikkeling, overheidsbeleid en regulering). Diep leren (tweede-orde leren) verwijst naar het leren over onderliggende normen, regels en uitgangspunten. Tezamen vormen de dynamiek in verwachtingen, de vorming van een sociaal netwerk en het type leerprocessen de basis voor experimenten.
Aanvulling op het onderzoeksmodel

Het onderzoeksmodel wordt op drie punten bekritiseerd. Ten eerste is er te weinig aandacht voor de ontwikkeling van technologische niches in markt niches. Op basis van aanvullende literatuur wordt in dit onderzoek een uitbreiding voorgesteld. De uitbreiding houdt in dat het onderscheid tussen technologische en markt niches niet alleen is gebaseerd op bescherming, maar ook op stabilisatie. De combinatie levert een assenkrans op dat gebruikt wordt in de empirische hoofdstukken om niche ontwikkeling in kaart te brengen (zie figuur 1). De hypothese is dat een lineaire ontwikkeling van technologische niche naar markt niche een te simplistische representatie is van daadwerkelijke ontwikkelingspatronen.

Het tweede punt van kritiek gaat in op verwachtingen. Uit voorgaand onderzoek is gebleken dat dynamiek in verwachtingen met name door externe veranderingen worden, maar dit punt wordt daarin niet verder uitgewerkt. In dit onderzoek wordt dynamiek in verwachtingen uitgebreid met dynamiek in visies en worden de oorzaken van de dynamiek expliciet aan de orde gesteld. De hypothese is dat veranderingen in visies en verwachtingen met name het resultaat zijn van niche-externe ontwikkelingen.

![Protection - Stabilisation Diagram](image)

Figuur 1. Vier typen niches in relatie tot het niveau van bescherming en het niveau van stabilisatie.

SNM: de beleidstool
Strategisch Niche Management wordt gepromoot als een tool om bestaand beleid mee aan te vullen. Drie verschillende beleidsstrategieën worden onderscheiden op basis van het coördinatiemechanisme, namelijk een ‘top-down centralised planning’ strategie, een ‘market-based bottom-up’ strategie, en een ‘policy and network management’ strategie. Ik verwacht dat in het geval van de mee- en bijstoken casussen met name de eerste strategie is toegepast, terwijl in het geval van de mestvergisting cases in Denemarken met name de laatste strategie is toegepast. Strategieën gebaseerd op marktwerking zullen in de meeste gevallen een onderdeel vormen van de strategie.

Hoofdstuk 3. Mestvergisting in Nederland

Historisch overzicht

Analyse van niche dynamiek
De casus wordt eerst geanalyseerd vanuit de niche processen. Uit de analyse blijkt dat verwachtingen en visies de verschuiving van boerderij vergisters naar centrale vergisters kan verklaren. Boerderijvergisters werden vooral gebouwd met een visie en verwachtingen op energie opwekking; centrale vergisters werden veelal gebouwd met een visie op mestverwerking.

Het netwerk dat betrokken is geweest bij mestvergisting in Nederland is sterk veranderd gedurende de drie perioden. In de eerste periode waren vooral boeren, technologie ontwikkelaars en onderzoeksinstituten uit de landbouwsector betrokken; afstemming is goed doordat ervaringen uitgewisseld en vergeleken worden en het netwerk voortbouwt op
bestaande relaties in de landbouwsector. Een deel van dit netwerk bleef grotendeels betrokken bij de vergistingsinstallatie in Deersum. Het netwerk in Helmond wordt gedomineerd door dominante actoren uit het landbouwregime. De individuele boeren zijn echter uitgesloten van het netwerk en oefenen geen invloed uit op de ontwerp keuzes; er is geen afstemming tussen de wensen van boeren en de ontwerpkeuzen van Promest. In de derde periode is het netwerk klein en gefragmenteerd. Er is weinig afstemming tussen de verschillende projecten en er is een gebrek aan ervaren actoren.

De betrokken actoren hebben verschillende zaken geleerd van de experimenten. In de eerste periode was er nauwelijks kennis en ervaring op het vlak van mestvergisting. Het meeste leren ging uit naar technisch-economische optimalisatie. Het leerproces was goed georganiseerd en werd ondersteund door wetenschappelijke input en participatie van boeren en onderzoekers in het netwerk. In de tweede fase is het leerproces in Deersum interessant. Deze installatie blijft in gebruik ondanks slechte biogas opbrengsten, omdat er geleerd wordt over andere voordelen van mestvergisting, zoals vermindering van kunstmestgebruik en voordelen van gezamenlijk opslag. In Helmond is het leerproces van lage kwaliteit. Er is grote politieke druk om de installatie te laten slagen en ondanks de vele problemen wordt de installatie toch opgeschaald. In de laatste fase is het leerproces matig georganiseerd. Er wordt geleerd van buitenlandse ervaringen door middel van het lezen van internationale publicaties en deelname van buitenlandse technologie leveranciers. Het belangrijkste leerproces is dat het vergisten van mest met organische afvalstoffen een belangrijk middel is om de biogas opbrengst te vergroten en een aantal functies (afvalverwerking, duurzame energieproductie, landbouwkundige voordelen) met elkaar te combineren. Covergisten blijkt echter niet mogelijk binnen het bestaande juridische kader.

Nederlandse regime dynamiek
In het tweede deel van het hoofdstuk wordt de dynamiek op regime niveau geanalyseerd. In de eerste periode krijgt het electriciteitsregime in toenemende mate te maken met problemen door stijgende olieprijzen, toenemende aandacht voor het milieu en ingrepen van de Nederlandse overheid. Het regime blijft echter stabiel en de oplossingen worden vooral gezocht in regime optimalisatie zoals het vervangen van olie door kolen en energie besparing. Niche technologieën zoals mestvergisting worden nauwelijks overwogen.

Na 1985 neemt de stabiliteit in het electriciteitsregime af, met name door aandacht voor de klimaat problematiek (met name CO2 emissies), de eerste stappen richting liberalisering en de opkomst van decentrale producenten. Alhoewel dit potentiële kansen creëert, maakt de daling van de energieprijzen mestvergisting onrendabel, terwijl de decentrale producenten oplossingen vooral zoeken in het ontwikkelen van decentraal vermogen op aardgas. Belangrijker is dat het landbouwregime zeer instabiel wordt door de erkenning van het mestoverschot. Het mestoverschot is in Nederland zeer groot in vergelijking met andere Europese landen en de overheid introduceert verschillende wetten en regels om het probleem aan te pakken. Dit creëert een gevoel van urgentie bij dominantante landbouwactoren; deze bestempelen grootschalige mestverwerking als de oplossingen van de problemen, gesteund
door de Nederlandse overheid. Een belangrijk gevolg van de nieuwe regels is dat covergisten (al toegepast in sommige boerderij vergisters) niet meer mogelijk is.


Conclusies
De conclusie is dat de kwaliteit van niche processen gering is geweest. In de eerste periode is er veel geleerd, ondanks een beperkte hoeveelheid bestaande informatie. Na 1985 is de kwaliteit echter laag geweest, met uitzondering van de centrale vergister in Deersum. Eind jaren 90 blijft de kwaliteit van niche ontwikkeling beperkt door een gebrek aan ervaren actoren en een beperkt aantal experimenten waarin beperkt wordt geleerd. De belangrijkste leerrvaringen komen uit het buitenland.

Met betrekking tot regime ontwikkelingen concludeer ik dat deze zeer belangrijk zijn geweest om de niche ontwikkeling te begrijpen. In de eerste periode wordt niche ontwikkeling beïnvloed doordat problemen op regime niveau verwachtingen op niche niveau creëren. In de tweede periode is de grote instabiliteit in het landbouw regime een belangrijke verklarende factor voor een vergroting van de niche doordat landbouw regime actoren gaan investeren in de niche; ze zien het als een ‘probleemoplosser’. In de derde periode zorgt instabiliteit in het electriciteitsregime voor hernieuwde aandacht en zien actoren van het electriciteitsregime mestvergisting als ‘beloeftevolle technologie’. Het landbouwregime creëert echter een grote barrière op niche niveau doordat covergisten niet mogelijk is en mestvergisting en – verwerking niet langer wenselijk worden geacht binnen dit regime.

Hoofdstuk 4. Meestoken in Nederland

Historisch overzicht
Nederlandse productiebedrijven begonnen met het meestoken van biomassa in de vroege jaren 90. De meeste experimenten waren gericht op het direct meestoken van biomassa, zonder enige aanpassing aan de centrale. Het productiebedrijf UNA experimenteerde met rioolslib, het productiebedrijf EZH met speciale pallets gemaakt uit verschillende organische
Samenvatting

afvalstromen en productiebedrijf EPZ experimenteerde met het direct meestoken van papierslib. EPZ onderzocht ook de bouw van een vergassingsinstallatie voor het vergassen van afvalhout, maar ging niet over tot de bouw. Het vierde productiebedrijf (EPON) experimenteerde met het indirect meestoken van afvalhout, waarbij het hout apart werd vermalen en verstookt in aparte branders in de ketel. De experimenten zijn succesvol en de meeste bedrijven besloten na 1995 over te gaan tot het permanent meestoken van biomassa tot een percentage van 5% van de energy input van de centrale. De bedrijven vragen daarvoor vergunningen aan bij de provincies. EPZ besluit om toch verder te gaan met de bouw van de vergasser. Over het algemeen zijn er weinig problemen, met uitzondering van de vergasser die met grote technische problemen kampt. Na 2000 worden de bedrijven geconfronteerd met toenemende druk vanuit de overheid om de emissies van CO2 te reduceren. De overheid sluit met de bedrijven een kolenconvenant af, waarin de bedrijven beloven een totale biomassa capaciteit van 475 MW te realiseren middels het meestoken van biomassa. De energiebedrijven onderzoeken allerlei nieuwe biomassa stromen en meer radicale ingrepen zoals pyrolyse en vergassingsinstallaties. De elektriciteitsproductie door biomassa verbranding in bestaande elektriciteitscentrales neemt snel toe, maar hoofdzakelijk door het uitbreiden van (in)directe meestook.

Analyse van niche processen

De verwachtingen en visies in de vroege jaren 90 waren voornamelijk gericht op afvalverwerking en goedkope elektriciteitsproductie. Elektriciteitsproducenten participeerden in de experimenten omdat ze konden besparen op de brandstofkosten; afvalleveranciers waren op zoek naar nieuwe mogelijkheden om afval te verwerken. Dit veranderd na 1995. De visies zijn nu meer gericht op het produceren van duurzame energie en het creëren van een ‘groen’ bedrijfsprofiel. Na 2000 worden de verwachtingen met name beïnvloed door het kolenconvenant, dat hoge verwachtingen creëert over de toekomstige toepassing van biomassa in elektriciteitscentrales.

Het sociale netwerk dat betrokken is bij de experimenten bestaat voornamelijk uit traditionele regime actoren. Dit verklaart voor een deel waarom de meestook niche zo snel kon groeien: de actoren konden voortbouwen op bestaande relaties en bestaande kennis gebruiken. Wanneer tegen het einde van de jaren 90 de onderzoeksrelaties onder druk komen te staan, zoeken de actoren uitvlucht in internationale onderzoeksnetwerken. De provincies spelen ook een belangrijke rol in de ontwikkeling van de niche. Ze zijn verantwoordelijk voor het verlenen van vergunningen. Het Ministerie van VROM geeft hen de mogelijkheid zelf emissie standaarden vast te stellen, gebaseerd op een combinatie van regels uit het electriciteits- en afval regime. De oplossing creëert echter ook een hoop onduidelijkheid, hetgeen omwonenden en milieuorganisaties stimuleert om zich te verzetten tegen de meestook installaties.

De betrokken actoren leren in het begin vooral over technische en economische optimalisatie. De kwaliteit van deze leerprocessen is hoog, met name doordat de actoren kunnen voortbouwen op bestaande netwerkrelaties en door de participatie in internationale netwerken. Tegen het einde van de jaren 90 ontstaat steeds meer het besef dat de
maatschappelijke inbedding van de installaties het grootste probleem vormt, met name de acceptatie van de installaties bij omwonenden en milieuvluchtigen. Deze problematiek stimuleert actoren om een aantal aannames in heroverweging te nemen, zoals emissie standaarden en de duurzaamheid van bepaalde afvalstromen. Ondanks dat emissie standaarden stabiliseren op Europees niveau, zijn de actoren niet in staat om de problemen met maatschappelijke inbedding op te lossen.

**Nederlandse regime dynamiek**

In de vroege jaren 90 is in het electriciteitsregime de stabiliteit aan het afnemen door toenemende aandacht voor het klimaatprobleem en de toenemende concurrentie met decentrale producenten. De bestaande elektriciteitsproducenten zijn daarom op zoek naar mogelijkheden om de economische en milieuprestaties van de bestaande centrales te verbeteren. Het meestoken van organisch afval past binnen deze doelstellingen. Ontwikkelingen in het afvalregime (overheidsbeleid) benadrukken in toenemende mate de noodzaak om de efficiëntie van energieopwekking uit afval te verhogen en stimuleren de verbranding van afval buiten de bestaande afvalinfrastructuur. De overlap tussen afval- en electriciteitsregime creëert de locale kansen voor de meestoken niche in de vroege jaren 90.

Na 1995 is met name de liberalisering van het electriciteitsregime een belangrijke bron van instabiliteit in het regime. Door horizontale en verticale integratie ontstaat een nieuw type elektriciteitsbedrijf dat een veel bredere focus heeft dan de traditionele productiebedrijven hadden. Afvalverwerking wordt in veel bedrijven een belangrijk onderdeel van de bedrijfsactiviteiten, terwijl voormalige distributiebedrijven gaan participeren in grootsculptuurlijke elektriciteitsproductie. De interactie met het afvalregime neemt hierdoor toe. Afval wordt in toenemende mate gezien als een duurzame energiebron, een ontwikkeling gesteund door de Nederlandse overheid en actoren uit het afvalregime. Door de opkomst van de groene stroom markt voor duurzame elektriciteit gaan de energiebedrijven meestoken in toenemende zien als een ‘beloftevolle’ technologie.

Na 2000 gaan de ontwikkelingen in het electriciteitsregime door, de stabiliteit neemt verder af door nieuwe regelgeving, het uiteenvallen van sociale netwerken in het regime, de veranderende rolverdeling in het netwerk, met name op het vlak van innovatie, en de toenemende overheidsdruk om CO2 emissies tegen te gaan. Dit creëert in toenemende mate onzekerheid en de wil om te investeren in radicale innovaties neemt af. Tegelijkertijd accepteren regime actoren meestoken als ‘probleemoplosser’ voor de CO2 problematiek. In het electriciteitsregime blijft er onduidelijkheid bestaan over de definitie van biomassa en afval, ondanks stabiliseren van een brede definitie (inclusief verontreinigd afval) op Europees niveau. Milieugroepering steunen de definities niet.

**Conclusies**

Mijn conclusie is dat de kwaliteit van niche processen in deze casus redelijk hoog was, met name op het vlak van technisch leren. Het bestaande netwerk is echter nog niet in staat gebleken de maatschappelijke problemen op te lossen. Deze problemen komen met name voort uit de overlap tussen het electriciteitsregime en het afvalregime.
Samenvatting

Met betrekking tot het niche-regime interactie concludeer ik dat regime veranderingen hebben geleid tot een groei van de meestook niches in Nederland, met name het beleid om afval in toenemende mate te verwerken buiten de bestaande afvalinfrastructuur, de opkomst van een groene stroom markt en het ontstaan van een nieuwe type energiebedrijf door horizontale en verticale integratie. Hierdoor werd meestoken in toenemende mate gezien als een ‘beloftevolle technologie’. Na 2000, accepteren regime actoren meestoken als ‘probleem oplosser’, maar zijn er ook in toenemende mate problemen vanuit het regime. Deze ontstaan met name door het liberaliseringsproces en de overlap met het afval regime.

Hoofdstuk 5. Mestvergisting in Denemarken

Historisch overzicht


Analyse van niche processen

Visies en verwachtingen legitimeerden de bouw van vergistingsinstallaties in de jaren 70. Externe ontwikkelingen zoals energieprijzen en milieubeleid zijn een belangrijke oorzaak van de veranderende visies. Maar ook experimenten droegen in Denemarken bij aan visie vorming en veranderingen van verwachtingen. De slechte resultaten met boerderijvergisters was een van de oorzaken voor een verschuiving naar centrale vergisters; resultaten uit het Biogas Actie Programma droegen bij aan nieuwe regels en gebruik. Veranderende visies en verwachtingen verklaarden ook het proces van niche vertakking naar covergisten van huishoudelijk afval.

Het sociale netwerk betrokken bij de experimenten in Denemarken bestaat met name uit boeren, een actieve ‘grassroot’ beweging, verschillende overheden, onderzoeksinstanties, energiebedrijven en leveranciers van biogas installaties. In de eerste periode (boerderijvergisters in de jaren 70/80) waren met name de boeren en de grassroot beweging belangrijk. De ontwikkeling van de centrale vergisters is gekenmerkt door het ontstaan van een sterk sociaal netwerk, waarin een groot aantal actoren intensief met elkaar samenwerkt en contact heeft. Dit resulteert in een breed sociaal netwerk met een hoge mate van afstemming. Een belangrijke acteur is het ‘Folkecenter voor Duurzame Energie’. Dit centrum gaat door met de ontwikkeling van boerderijvergisters, ondanks afnemende steun van de Deense overheid, en ontwikkeld twee typen vergisters die aan de basis staan van de herintroductie van boerderijvergisters in het eind van de jaren 90.

Het leerproces was goed georganiseerd in Denemarken, met name binnen het Biogas Actie Programma. Regelmatige bijeenkomsten van leveranciers, boeren, wetenschappers, plant operators en beleidsmakers maakten een breed en diep leerproces mogelijk. De actoren leerden op veel dimensies, zoals technisch, economisch, landbouwkundig, regelgeving, milieuaspecten. Sommige van deze leerprocessen kunnen als tweede-orde worden aangeduid, omdat ze leiden tot het aanpassen van bestaande praktijken en regels.

Deense regime dynamiek

De Deense electriciteits- en warmteregimes begonnen te veranderen na 1973, met name door de hoge olieprijzen en een toenemend ingrijpen van de Deense overheid. Denemarken was in hoge mate afhankelijk van olie en had geen eigen aardgas infrastructuur. Nieuw beleid van de overheid was name gericht op het reduceren van de afhankelijkheid van olie door het vervangen van olie door kolen en door het realiseren van energiebesparing. De verwachting was, gesteund door de Deense overheid en de energiebedrijven, dat op de lange termijn kernenergie een grote rol ging spelen. De focus op regimeoptimalisatie en kernenergie resulteerde in minimale aandacht voor vergistingsinstallaties en deze bleven onzichtbaar voor regime actoren.

Na 1984 neemt de instabiliteit in het electriciteitsregime toe door een toenemende decentralisatie en toenemende verbindingen met het warmteregime. De overheid stimuleert decentrale warmtekracht eenheden om een markt te creëren voor een nieuw aangelegd aardgasnetwerk. Centrale vergistingsinstallaties kunnen inhaken op deze ontwikkeling in termen van belastingvrijstellingen, investeringssubsidies en beleidsdoelen. De gecombineerde


Conclusies
De belangrijkste conclusie in deze casus is dat de kwaliteit van niche processen zeer hoog is geweest, met name in het geval van centrale vergisters. De kwaliteit van de processen was hoog vanwege de frequente interactie tussen verschillende sociale groepen en het vermogen van de actoren om te leren van experimenten en deze lessen te vertalen in ontwerpkeuzen voor nieuwe experimenten.

Met betrekking tot niche-regime interactie concludeer ik dat in de eerste periode de problemen in de electriciteits- en warmte regimes niet direct leidden tot kansen voor vergistingssystemen, maar wel verwachtingen en visies van niche actoren beïnvloedden. Deze verwachtingen waren de basis voor de eerste niche experimenten. In de tweede periode versterken veranderingen in verschillende regimes elkaar en creëren veel mogelijkheden voor de ontwikkeling van centrale installaties. Centrale vergisters worden door actoren uit verschillende regimes gezien als een ‘beloftevolle’ technologie. In de laatste periode, tot slot, bepaalt de instabiliteit in het electriciteitsregime het einde van de ontwikkeling van centrale vergistingssystemen, terwijl ontwikkeling in het landbouwregime en afvalregime nieuwe kansen generen, met name voor boerderijvergisters en het covergisten van huishoudelijk afval.

Hoofdstuk 6. Meestoken in Denemarken

Historisch overzicht
De eerste meestook installaties werden in Denemarken in begin jaren 90 gebouwd. In de eerste periode (1990-1992) bouwt ELSAM (het overkoepelend orgaan voor energiebedrijven in west Denemarken) twee decentrale meestook installaties. Één installaties wordt al snel nog slechts gebruikt als afvalverbrander. De tweede installatie in Grenå verbrandt kolen en stro. De ervaringen met deze installatie zijn positief, maar er doen zich een aantal problemen voor, met name door de specifieke eigenschappen van het stro.

In de laatste periode (2000-2003) stelt ELKRAFT de installatie in bedrijf, maar begint meteen met een verbouwing, zodat ook het meestoken van hout in de aardgas centrale mogelijk wordt. ELSAM besluit om terug te keren naar indirect meestoken, ondanks de problemen van deze technologie. In totaal is er in 2002 een biomassa meestook capaciteit gerealiseerd van 177.3 MWe.

Analyse van niche processen
De verwachtingen ten aanzien van meestoken zijn in Denemarken sterk gerelateerd aan politieke afspraken in eind jaren 80 en begin jaren 90. In begin jaren 90 hebben de energiebedrijven nog geen sterke visie op meestoken, maar richten ze zich (in beperkte mate) op decentrale eenheden. In 1993 maken politieke partijen een afspraak waarin vastgelegd wordt dat ELSAM en ELKRAFT in 2000 1,2 miljoen ton biomassa moeten verstoken. Dit creëert hoge verwachtingen en visies ten aanzien van meestoken in centrale eenheden. ELSAM richt zich op indirect meestoken omdat ze verwacht dat dit de laagste kosten oplevert. ELKRAFT heeft een sterke visie ten aanzien van recycling van restproducten en focust op parallel meestoken. Op basis van experimenten vinden er verschuivingen plaats in verwachtingen, met name van indirect meestoken naar parallel meestoken.

Het sociale netwerk bestaat voornamelijk uit de energiebedrijven en het Deens Energie Agentschap (DEA), maar ook biomassa leveranciers, onderzoeksinstituten en technologie leveranciers spelen een rol. Het netwerk bestaat voornamelijk uit traditionele regime actoren, al zijn ook nieuwe sociale groepen bij de experimenten betrokken (bijvoorbeeld boeren die het stro leveren). Deze groepen hebben echter al ervaring met biomassa verbranding, omdat
ze participeerden in decentrale niches voor biomassa verbranding in stadsverwarming en decentrale elektriciteitsproductie. De afstemming in het sociale netwerk is daarom relatief hoog. Politieke afspraken zetten het bestaande sociale netwerk onder druk om technologieën te ontwikkelen en toe te passen die betere milieuprestaties hebben. De afspraken dwingen energiebedrijven meer radicale ingrepen als parallelle installaties te ontwikkelen, omdat biomassa met name wordt gedefinieerd als stro (een moeilijke brandstof). Alhoewel energiebedrijven zich verzetten tegen deze definitie, blijft het DEA dicht bij de oorspronkelijke afspraken gedurende de jaren 90.

Het leerproces is vooral technisch-economische en sterk verweven met het leerproces voor stand-alone biomassa eenheden in Denemarken. Stro en hout worden al toegepast in decentrale elektriciteitsproductie en warmte productie en de centrale meestookprojecten kunnen profiteren van standaarden, praktijken en kennis die daar zijn ontwikkeld.

Deense regime dynamiek
In de eerste periode is de stabiliteit in het electriciteitsregime aan het afnemen door toenemende aandacht voor CO2 emissies en klimaatverandering en door politieke afspraken. De afspraken resulteren in een sterke groei van decentrale producenten die elektriciteit opwekken met behulp van aardgas. Deze dynamiek creëert niet in een specifieke stimulans voor meestook eenheden, maar wel in een aantal locale mogelijkheden zoals in Grenå.

In de tweede periode neemt de stabiliteit in het electriciteitsregime verder af, met name door toenemende (politieke) aandacht om kolen te verbannen uit het electriciteitsregime. Dit resulteert in een sterke groei van de meestook niches. Het resulteert echter ook in een verbod voor de bouw van nieuwe kolencentrales, waardoor een aantal nieuwe meestook installaties niet gebouwd kunnen worden.

Na 2000 creëert liberalisering in toenemende mate instabiliteit in het regime. Door liberalisering verandert de organisatie van het regime waardoor er betere mogelijkheden ontstaan voor het realiseren van meestook projecten. Aan de andere kant benadrukt het nieuwe beleid economische efficiëntere oplossingen, waardoor de bedrijven zich meer gaan richten op indirecte meestook in plaats van parallelle meestook.

Conclusies
De conclusie is dat de kwaliteit van niche processen relatief hoog was, omdat politieke afspraken een sterke visie creëerden en actoren konden voortbouwen op leerprocessen uit voorgaande biomassa niches. Ook de invloed van regime veranderingen is in deze casus goed te zien. Door afnemende stabiliteit in het electriciteitsregime groeit de meestook niche in Denemarken. De rol van de Deense overheid is hierin belangrijk, omdat ze het electriciteitsregime gedurende lange tijd onder druk hebben weten te zetten.

Hoofdstuk 7. Analyse en conclusie
In hoofdstuk 7 beantwoord ik de drie onderzoeksvragen van dit onderzoek. De eerste onderzoeksvraag luidde: hoe en waarom verschilt de ontwikkeling van bioenergie van
**Samenvatting 313**

*mestvergisting en meestoken in Nederland en Denemarken?* De eerste stap in het beantwoorden van deze vraag is het maken van een vergelijking tussen mestvergisting in Nederland en Denemarken en meestoken in Nederland en Denemarken. Deze vergelijking is een samenvatting van de casussen zoals in het bovenstaande beschreven. De vergelijking laat de belangrijke rol van zowel niche als regime ontwikkelingen zijn in het begrijpen van een innovatie traject. De vergelijking gebruik ik vervolgens om de twee resterende vragen te beantwoorden. In de volgende paragrafen focus ik op twee zaken in het bijzonder, namelijk cruciale factoren in het ontstaan van markt niches en niche-regime interacties.

**Cruciale factoren voor het ontstaan van markt niches**

De tweede vraag was: *wat zijn de cruciale factoren voor het ontstaan van markt niches?* Om deze vraag te beantwoorden geef ik eerst de ontwikkelingspatronen weer van de niches in Nederland en Denemarken in termen van stabiliteit en bescherming (zie figuur 2).

![Figuur 2. Niche ontwikkeling patronen voor mestvergisting in Nederland (a), mestvergisting in Denemarken (b), meestoken in Nederland (c) en meestoken in Denemarken (d).](image)

Ik concludeer dat het patroon in het geval waarin geen markt niche ontstond (onsuccesvol) en de patronen waarin wel een markt niche ontstonden (succesvol), op drie cruciale manieren verschillen. Het eerste verschil is dat de onsuccesvolle cases een sequentieel
ontwikkelingspatroon laat zien, terwijl de succesvolle casussen een parallel ontwikkelingspatroon laten zien. Het tweede verschil is dat in de succesvolle casussen, een continue ontwikkelingspatroon te zien, terwijl in de onsuccesvolle casussen een discontinue ontwikkelingspatroon is te zien. Het derde verschil is dat in de succesvolle casussen er sprake is van toenemende stabiliteit, terwijl in de niet succesvolle casus er sprake is van een periode van afnemende stabiliteit.

Rol van interne niche processen in het ontstaan van markt niches
Visies en verwachtingen spelen een cruciale rol in het ontstaan van marktniches. Op basis van mijn casussen concludeer ik dat een brede set van verwachtingen cruciaal is in het begin, maar dat verwachtingen getest moeten worden in experimenten gedurende het innovatie traject. Brede verwachtingen zijn met name cruciaal voor een parallelle ontwikkeling, omdat ze actoren aanzetten te experimenteren van verschillende trajecten (parallelle ontwikkeling). In mindere mate zijn ze ook van belang voor een continue ontwikkeling (zoals bijvoorbeeld in het geval van Deense boerderijvergisters).

Met betrekking tot mijn hypothese dat verwachtingen en visies op niche niveau vaak veranderen door externe omstandigheden, concludeer ik dat mijn casussen deze hypothese bevestigen. De link tussen resultaten van experimenten en een veranderende visie op niche niveau is minder sterk en is met name aanwezig wanneer resultaten van een experiment zeer tegen vallen, of wanneer actoren veel tijd en moeite stoppen in het monitoren en leren van experimenten.

Ik concludeer ook dat een breed netwerk met een hoge mate van afstemming belangrijk is, met name voor het verklaren van een continue versus discontinue ontwikkeling (en in mindere mate voor het verklaren van een parallel versus sequentiële ontwikkeling). Brede sociale netwerken zijn belangrijk voor continuïteit in niche ontwikkeling, omdat actoren de niche dragen; zij ontwerpen experimenten en leren en behouden lessen; zij dragen de verwachtingen en visies uit. Als er niet langer een actief netwerk aanwezig is, sterft een traject uit en kunnen ervaringen en lessen verloren gaan.

Tot slot concludeer ik dat brede leerprocessen op veel dimensies belangrijk zijn voor stabilisering in de niche en daarmee per definitie het meest cruciale proces in het ontstaan van markt niches is. Leren is ook belangrijk voor het verklaren van een continue versus discontinue ontwikkeling, omdat leren verwachtingen kan beïnvloeden.

Ter conclusie, mijn case studies resulteren in twee bijdrages aan de SNM literatuur. Ten eerste, ze bevestigen het Gros van de bevindingen van voorgaand SNM onderzoek, maar nu in een ander empirisch domein. Dit versterft SNM als onderzoeksmodel. Ten tweede, de case studies hebben laten zien waarom interne niche processen belangrijk zijn voor het ontstaan van markt niches. De relatie tussen interne niche processen en het ontstaan van markt niches is weergegeven in tabel 1.
Tabel 1. Relatie tussen interne niche processen en het ontstaan van markt niches.

<table>
<thead>
<tr>
<th>Characteristics of emerging market niches</th>
<th>Parallel development</th>
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<tbody>
<tr>
<td><strong>Internal niche processes</strong></td>
<td>++</td>
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<td>Broad set of expectations, but tested in experiments</td>
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<td>Learning at many dimensions and second-order learning</td>
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Bovenstaande processen zijn belangrijk, maar niet voldoende. Regime veranderingen spelen ook een belangrijke rol in de ontwikkeling van markt niches.

**Niche-regime interactie**

De tweede onderzoeksvraag was: *hoe werken niche en regime ontwikkeling op elkaar in?* Mijn hypothese was dat afnemende stabiliteit in het electriciteitsregime zou leiden tot grotere niches. Ik concludeer dat mijn casussen deze hypothese bevestigen en dat er drie manieren zijn waarop regime instabiliteit kunnen leiden tot grotere niches. Ten eerste kan instabiliteit in het regime verwachtingen creëren of beïnvloeden op niche niveau, waardoor niche actoren nieuwe experimenten opzetten. Ten tweede kan instabiliteit regime actoren stimuleren om te participeren in niche ontwikkeling, omdat ze de techniek zien als een ‘beloftevolle technologie’. De participatie van regime actoren kan de beschikbare resources voor niche ontwikkeling vergroten. Ten derde kunnen regime actoren participeren in niche ontwikkeling, omdat ze de niche technologie zien als ‘probleemoplosser’. In het laatste geval kan de niche veel sneller en sterker toenemen in grote dan in het tweede geval.

Regime instabiliteit is echter geen afdoende voorwaarde, ook de kwaliteit van niche processen is belangrijk. Ik combineer dit in een matrix, waarin op de horizontale as de kwaliteit van niche processen staat en op de verticale as de stabiliteit van regimes. Dit levert een twee-bij-twee matrix op die een inschatting weergeeft van het potentieel van een niche om door te breken op basis van de kwaliteit van niche processen en de stabiliteit in het dominante regime.
Met betrekking tot het effect van experimenten in niches op regime dynamiek concludeer ik dat in mijn casussen experimenten vooral geleid hebben tot aanpassing in de formele regelgeving of standaarden. In het algemeen is er echter weinig effect geweest op het bestaande regime. Met betrekking tot de aanwezigheid van meerdere regimes concludeer ik dat in alle casussen meerdere regimes een rol hebben gespeeld. De aanwezigheid van meerdere regimes kan zowel een positieve als een negatieve invloed hebben op niche ontwikkeling. Met betrekking tot bronnen van instabiliteit concludeer ik dat instabiliteit met name is veroorzaakt door veranderingen in het socio-technisch landschap, waarbij het overheidsbeleid een belangrijk mechanisme is.

**Rol van overheid in niche ontwikkeling**
Met betrekking tot de rol van de overheid in niche ontwikkeling concludeer ik dat voor succesvolle niche ontwikkeling tenminste een aantal elementen van de proces en netwerk management benadering nodig zijn. Zonder het stimuleren van experiment, het mogelijk maken van breed en diep leren, het creëren van nieuwe sociale netwerken en actieve deelname van overheden bij experimenten is de kans op succesvolle niche ontwikkeling gering. Maar ook een aantal elementen van de top-down central planning strategie zijn noodzakelijk, om het combineren en uitwisselen van ervaringen te stimuleren en de activiteiten van verschillende actoren op elkaar af te stemmen. Onderdelen van de marktgestuurde bottom-up strategie zijn belangrijk voor het financieel aantrekkelijk maken van deelname in niches, maar deze moeten wel specifiek zijn in plaats van generiek. De relatie tussen beleidsstrategieën en uitkomstscenario’s is weergegeven in tabel 2.
Samenvatting

Tabel 2. Optimale mix van beleidsstrategieën versus verschillende uitkomstscenario’s.

<table>
<thead>
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Short summary

This book compares the experimental introduction of two bioenergy technologies in the Netherlands and Denmark. In the Netherlands, the contribution of bioenergy to the total domestic energy supply is limited to 1.3%, while in Denmark the total contribution is about 8.4%. Two cases were used in this study to investigate the difference, i.e. the digestion of manure in biogas plants and the co-firing of biomass in power plants. Despite many experiments since the 1970s, only a few plants were in operation in the Netherlands in the early 2000s. In Denmark, the number was substantially higher. Co-firing, on the other hand, reflected a different situation: In the Netherlands, co-firing gained a substantial role in renewable energy generation, while Denmark implemented an equivalent capacity. The main research question of this thesis is: how and why does the Danish development of bioenergy from manure digestion and co-firing differ from the Dutch development?

I have used the Strategic Niche Management (SNM) approach to answer this question. SNM emerged from the observation that many sustainable technologies fail to succeed. SNM perceives the development of new technologies against the backdrop of a dominant regime, i.e. a set of rules embedded in a dominant design and social network. To make new technologies flourish, it is necessary to create protected environments (technological niches), in which actors can experiment with technologies and rules that deviate from the dominant regime. When actors learn to improve the technology and societal embedding, protection can be lowered and the technological niche can evolve into a market niche. In this thesis, two elements are added to the SNM approach. First, this thesis investigates what the crucial factors are for the emergence of market niches. Second, it investigates how niche development interacts with regime dynamics. In addition, this thesis discusses the role of public authorities on the basis of SNM insights and the case studies.

The main conclusion is that in the Dutch manure digestion case, the initial technological niche remained a technological niche, while in the Danish manure digestion case, the Dutch co-firing and Danish co-firing cases, the initial technological niches evolved into either protected market niches or regular market niches. On the basis of the case patterns, three crucial characteristics of these emerging market niches are distinguished. First, in cases of emerging market niches, the patterns show a continuous development, while in the case where no market niche emerged, the pattern shows a discontinuous development. Second, a parallel development of niches is characteristic for the emergence of market niches, versus a sequential development pattern in the case where no market niche emerged. The third crucial characteristic for the emergence of market niches is increasing stability. On the basis of the case studies it is argued that a continuous and parallel development pattern with increasing stability can emerge: if the set of expectations is broad at the beginning of the innovation journey but tested through experimentation along the trajectory; if the social network is broad
and has a high level of alignment; and if learning occurs in many dimensions and is of second-order quality (learning about underlying norms and ideas).

Table 1. Relation between the characteristics of emerging market niches and internal niche processes

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With respect to interaction between niches and regimes, the conclusion is that decreasing stability at the regime level can result in larger niches. Combining the stability level at regime level with the quality of niche processes (visions and expectations, network formation and learning) results in a two-by-two matrix for assessing the potential of niche breakthrough (see Figure 1).

Figure 1. Relation between regime stability and quality of niche processes

With respect to the role of public authorities, the main conclusion is that if the intended outcome is a regime shift, the focus should be on a process and network management strategy, complemented with a top-down planning strategy and market-based, bottom-up
strategy (Table 2). However, if the intended outcome is regime optimisation, the focus should be on top-down planning, complemented with a market-based, bottom-up, and process and network management strategies. On the basis of the case studies, this thesis argues that a third outcome scenario is possible, i.e. a regime reconfiguration. The necessary strategy is a combination of strong top-down, and planning, process and network management, complemented with market-based, bottom-up strategies. This outcome will most likely occur when regimes are already unstable.

Table 2. Optimum mix of policy strategies versus different outcome scenarios

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Curriculum Vitae

Rob Raven was born on 17 February 1975 in Geleen, The Netherlands. After receiving his secondary education in Geleen, he studied Technology and Society (Innovation Sciences) at the Eindhoven University of Technology and took extended courses in electrical engineering. Rob worked at the Energy Research Centre of the Netherlands (ECN) and for that received his masters degree in 1999. The thesis subject was about the modeling of energy standards for utility buildings. After graduation Rob started working on his doctoral thesis in the field of innovation studies and energy sectors. This work resulted in the present thesis. He participated in the inter-disciplinary 'Biomass Working Group' of the Eindhoven University of Technology as well as in the research schools 'Eindhoven Centre for Innovation Studies' (ECIS) and the 'Netherlands Graduate Research School of Science, Technology and Modern Culture' (WTMC). Since August 2004, Rob is working as a post-doctoral researcher at the Eindhoven University of Technology. His current work is about long-term transitions in energy sectors and teaches the course 'System Innovations and Strategic Niche Management'.


