Pathways for sustainability transitions in the electricity sector : multi-level analysis and empirical illustration.

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Pathways for sustainability transitions in the electricity sector: Multi-level analysis and empirical illustration

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Abstract—**This paper analyses sustainability transitions in the electriciy sector. Using a Multi Level Perspective on transitions, three transition pathways are briefly elaborated and indications for the consequences for the infrastructure are given. The transformation pathway is characterised by a further hybridisation of the infrastructure; in the reconfiguration pathway, internationalisation and scale increase in renewable generation can lead to the emergence of a Supergrid. The de-alignment and re-alignment pathway is dominated by distributed generation and a focus on more local infrastructures. This pathway involves a major restrcuturing of the elecitricty system, but our conclusion is that this pathway is less likely than the other two. The de-alignment and re-alignment pathway is therefore more dependent on external developments and/or strong policy interventions. However, in all pathways major investments in infrastructure and innovative technologies are needed.**

I. Introduction

THE energy sector faces serious problems, e.g. oil dependency, reliability and climate change. Large jumps in environmental efficiency may be possible with sustainability transitions, i.e. shifts to new energy systems. Hence, NGOs and policy makers show increasing interest in energy transitions. The Dutch government gave transitions a central place in its fourth National Environmental Policy Plan, as did the Ministry of Economic Affairs in its recent Energy Report [1], [2].

The research question in this paper is: 1) how can we analyse sustainability transitions for the electricity sector, with a particular focus on electricity generation and infrastructure? 2) who are the main actors in different transition pathways? Traditional scenario analysis falls short to answer these questions, because: a) it does not have a good theory of transition dynamics, b) technology and system innovation are poorly conceptualised (either as exogenous 'manna from heaven' or as linear model). Hence, the paper aims to: a) describe a better transition theory, b) apply this theory to think about future sustainability transitions in the electricity system (not full scenarios, but brief indications).

II. Multi-level perspective on transitions

Academics show increasing interest in the dynamics of transitions and system innovations [3], [4] and governance aspects [5]. An important theory in this respect is the multi-level perspective (Geels, 2002), which understands transitions as the outcome of interactions between radical niche-innovations, an incumbent regime, and an external landscape.

Transitions are about changes at the meso-level of *socio-technical regime*, which consists of three dimensions: a) material and technical elements; in the case of electricity systems, these include resources, grid infrastructure, generation plants, etc, b) network of actors and social groups; in the electricity regime important actors are utilities, the Ministry of Economic Affairs, large industrial users, and households; c) formal, normative and cognitive rules that guide the activities of actors (e.g. regulations, belief systems, guiding principles, search heuristics, behavioural norms). Existing socio-technical regimes are characterised by path dependence and lock-in, resulting from stabilising mechanisms, e.g. vested interests, 'organizational capital', sunk investments, stable beliefs [6].

Niches form the micro-level, the locus where novelties emerge. Small market niches or technological niches act as 'incubation rooms', shielding new technologies from mainstream market selection. Such protection is needed because new technologies initially have low price/performance ratio. Protection comes from small networks of actors who are willing to invest in the development of new technologies. The macro-level is the *socio-technical landscape*, which forms an exogenous environment that usually changes slowly and influences niches and regime dynamics. The relationship between the three levels is a nested hierarchy (Fig. 1).

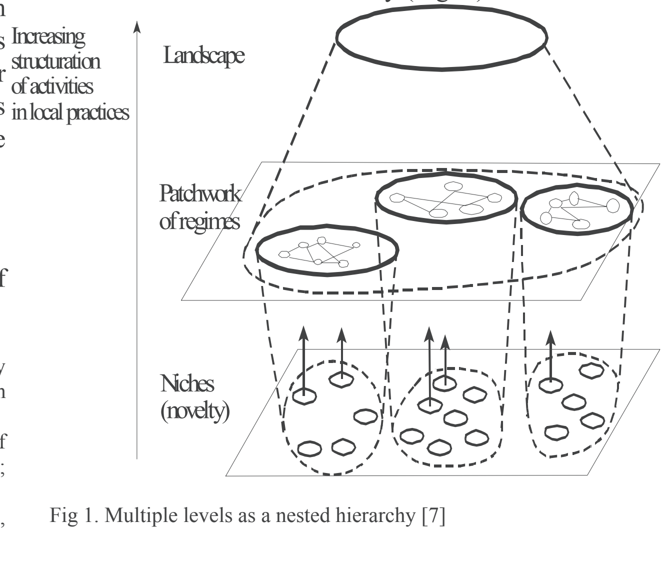

Fig 1. Multiple levels as a nested hierarchy [7]

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Pioneers and innovators always work on novelties, but these usually remain restricted to niches (e.g. R&D projects or small market niches). New technologies have a hard time to break through, because the existing regime is stabilised and entrenched. Historical studies have shown that transitions only come about when developments at all three levels link up and reinforce each other.

Early multi-level studies suggested that radical innovations emerge in niches, break through and overthrow the existing regime. While this pattern does exist, it is less likely in systems with large infrastructures, where sunk investments and high entry barriers are important. To analyse electricity systems, we therefore use a more refined typology of transition pathways, which distinguishes four ideal-typical paths, based on different *kinds* and *timing* of multi-level interactions [8]. These pathways are::

1) Transformation

Increasing landscape pressure leads to internal regime problems. This is followed by endogenous re-orientation of regime trajectories. Regime actors make modest changes in their search heuristics, guiding principles and R&D investments, which lead to gradual changes of direction. Radical innovations remain restricted to niches.

2) Reconfiguration

The regime faces problems because of external landscape pressures. In response, the regime adopts certain niche-innovations in the system, leading to gradual reconfiguration of the basic architecture and changes in some guiding principles, beliefs and practices.

3) Technological substitution:

The regime faces problems because of landscape pressures. Promising radical niche-innovations arise, which eventually replace the existing regime.

4) De-alignment and re-alignment

Major landscape changes lead to huge problems in the regime. Regime actors lose faith in the future of the system, and do not invest (much) to improve its performance. Multiple niche-innovations arise and co-exist, leading to a period of uncertainty and experimentation. Eventually one option becomes dominant, leading to a major restructuring of the system (new guiding principles, beliefs and practices).

III. TRANSITION PATHWAYS IN THE ELECTRICITY SYSTEMS

We will apply this conceptual framework to the electricity regime (see also [4]), which experiences not only pressures from liberalisation and Europeanization, but also from climate change, resource depletion and supply security concerns (Russia, Middle East). Moreover, rapid economic growth in China, India and other economies is putting pressure on the availability of resources and is leading to higher prices for fossil fuels. These developments have caused several tensions in the electricity regime. The introduction of a market mechanism in the electricity system has made balancing demand and supply and planning of capacity much more complicated. The 1990s saw the rapid rise of decentral cogeneration of heat and power (CHP) by large industrial firms. In some countries (such as the Netherlands), CHP now produces more than 50% of all electricity, *de facto* leading to a hybrid central-decentral system [4]. The electricity infrastructure has to adapt to the resulting two way flows in the system; also increasing international electricity flows present potential problems for the stability of the system [9], [10]. Actors like utilities, producers, network operators and regulators are grappling to come to terms with the new institutional configuration introduced in the 1990s in Europe. The utilities have become more short term, cost competition oriented, but on the same time public pressure to 'green' the production is increasing [11].

We will distinguish and discuss three different transition pathways. The technological substitution pathway is less likely, as we do not foresee the complete replacement of the electricity system. In all pathways the need for 'greening' the system is acknowledged and substantial gains in environmental efficiency can be achieved, despite a large increase in demand. Meeuwsen assumes for the Netherlands a 100% increase in demand and a 50% reduction of CO_2-emission in 2050) [9].

1) Transformation: further towards hybrid grids

In this pathway, the existing regime actors react to the outside pressure and the internal regime tensions by modifying the direction of development. In particular, they respond to increasing demand and pressure from outsiders, articulated by environmental pressure groups and social movements. These groups demand a significant greening of the generation of electricity. However, the pressure groups remain outsiders and most of the regime actors survive although some changes can occur in the social network as some regime actors are being replaced or others redefine their roles and strategy. Only modest changes in the search heuristics, guiding principles and R&D investments of the regime actors will occur. The utilities focus on constructing large scale offshore wind farms and large scale biomass gasification and combustion plants, but coal or multi-fuel fired plants (co-combustion of biomass) in combination with Carbon Capture and Storage (CCS) and nuclear power plants remain important. All options fit well within the existing system, although some adaptations are needed, e.g. the construction of a CO_2 transport infrastructure.

The market mechanism, introduced in the 1990s remains the dominant organising principle. National and European policies focus on market based instruments, e.g. the expansion of the carbon emission trading system in Europe. Cost-effectiveness is the most important criterion in the scenario. The share of small scale (renewable) energy technologies, like PV panels, urban wind turbines in the built environment, small scale biomass plants and micro-cogeneration, increases, but remains confined to specific niches, in particular in the built environment. These niche-innovations do not disrupt the basic architecture of the regime, but stimulate reorientation in a more sustainable direction.

In this scenario, the generation capacity consists of a few large scale generation units as well as a large number of small units nearby consumers. Hence the hybrid character. The average size of the production units decreases slightly and balancing and load management take place at the national level. The utilisation degree of the generation capacity will decrease significantly (because of low load factors of distributed generation plant). For the network: increasingly bidirectional flows will occur at both the transmission and the distribution level. Dominant issues will be the need for sufficient network capacity and system balancing facilities. The balancing difficulties are mainly caused by offshore wind farms. Except for balancing via generation, also strong demand management will be needed [9].

2) Reconfiguration: towards a Supergrid

In this transition pathway the regime faces major external landscape pressures, in particular security of supply issues because of global competition for resources and markets and geopolitical instability in regions with major reserves of fossil fuels. These developments and the impacts of climate change induce more cooperation on the European level. In a response to the challenges EU integration and policies becomes more dominant. The regime actors also are increasingly becoming international players. There emerges a strong collaboration between regime actors and outsiders [11].

The adoption of a set of niche-innovations in the system leads to a gradual reconfiguration of the basic architecture of the system. In this case, an up scaling of the system takes place: management and control of the system shifts to the European level, to European load control and dispatch centres. The new guiding principles, beliefs and practices are a partial return to the more top-down control and management philosophy that was dominant before the introduction of the market mechanism. This is reinforced by the large scale increase in the renewable energy technologies. Very large wind farms offshore, very large solar power plants (both PV and Concentrated Solar Power) in southern Europe and in the Sahara are being linked to hydropower stations in Scandinavia and the Alps. Part of the base load is still provided by large coal fired power plants (with CCS).

The integration of these large scale renewable power plants requires a strengthening of the transmission grid and gradually a European Supergrid emerges. At the same time such a powerful grid, partially consisting of HVDC lines, enables the further development of a more sustainable and more self-supporting electricity system. In this situation wind power transforms from a "walk on extra to the star of the show" [12].

In this pathway the system is characterised by few very large scale generation units, which are in general located far from consumption centres. Despite the fluctuating nature of some of resources (in particular) wind the power production is well predictable and controllable. Balancing via generation and some demand management will suffice for balancing demand and supply in the system. The main issue is to create sufficient network capacity [9].

3) De-alignment and re-alignment: towards distributed generation

In this pathway regime actors are not capable of dealing with extreme landscape pressures on the electricity sector. These pressures might come from very high oil prices (e.g. accelerated Peak Oil, war in the Middle East) or gas scarcity (e.g. Russia cutting of gas supplies because of escalating international tensions). The regime actors increasingly lose faith in the usual solutions. This would aggravate the regime problems and lead to a period of uncertainty about the direction of the system. It would stimulate and accelerate experimentation with multiple niche-innovations and more local or regional based systems. These local/regional systems use renewable resources and efficient technologies, e.g. onshore wind, PV panels, small scale biomass power plants, and micro cogeneration. Production takes place near to the consumers.

These experiments e.g. start in specific niches like new urban areas and gradually spread to other applications. These experiments are supported by new networks of actors. These 'new entrants' can include local utilities and companies, consumer cooperations, housing associations and municipalities, gradually take the place of the old incumbents and a new regime emerges. The guiding principle now is a strong preference for (predominant) local or regional generation and balancing [11].

This pathway leads to a major restructuring of the system. The new system could be dominated by a set of loosely coupled regional and local grids (micro grids). If necessary, these micro grids can operate in island operation, but exchange of electricity with other systems increases reliability and enables cost optimisation. Therefore, completely isolated and autonomous operated networks are not probable. A few large scale generation units provide back up capacity and can supply large consumers, e.g. heavy industry; they also will help in balancing supply and demand. In this situation, the utilisation degree of the composite system is quite low (this means that there will, c.q. has to, be a lot of redundant capacity in the system). Poor predictability and controllability and bidirectional flows in the distribution grids make balancing demand and supply the main issue, but power (voltage) quality also can be a problem. Storage facilities will be essential to warrant balancing in the local and regional systems. Also, the development and application of ICT for monitoring and control and the use of more flexible components (FACTS) in the system will be essential for a smooth operation of the system [9]. Making the grid 'smarter' is important in all pathways, but it is pre-eminently of importance in a situation dominated by distributed generation.

IV. CONCLUSIONS

The three pathways show different responses to the pressures on the current electricity regime and the resulting tensions, but there are clear differences in priorities contributed to the various pressures, the main dynamics and the role of niches. In the *Transformation* pathway, regime actors keep control over the system. Reorientation occurs through the greening of centralised production (cofiring of biomass, CCS) and the adoption of large scale renewable options (e.g. wind parks). These options fit reasonably well within the system, although adaptations and changes are needed to integrate these options. The dynamic is predominantly *economic*, that is producers operate mainly under a market regime and prices and costs play a crucial role in the competition. As a consequence, cost-effectiveness of alternatives is a major criterion when evaluating alternative options. Policy interventions and regulations can mitigate a lack of competitiveness, but many options remain niche applications because they are perceived as too expensive.

In the *Reconfiguration* pathway, the outside pressure on the regime is perceived as a major threat to the very existence of the regime. Regime actors decide to join forces to create a more sustainable European system (Supergrid). Coordination and guidance at the European level play a major role in this scenario. In a way, this a reversal to the dominant development pattern before the 1980s, although there have been major changes in the generation part of the system. *Political* dynamics are important drivers. Some large scale renewables have been integrated completely in the Supergrid, while small scale alternatives are marginalised.

Finally, in the *De-alignment and re-alignment* pathway, regime actors lose faith in the 'normal' solutions and the regime crumbles under the severe landscape developments. Gradually, new configurations emerge around local or regional based power plants, linked together in new networks, e.g. *micro grids*. These configurations are carried by a network of (partly) new actors and a completely new set of rules has to be implemented. *Cultural* dynamics (regionalism, autarky) are important. Because of major changes in social networks, regime rules and infrastructure, this pathway entails the most radical shift.

Which of the pathways is the most likely? In fact, elements of all three pathways can be distinguished. The Transformation pathway remains closest to the current situation, but proposals for large distance high voltage lines (including HVDC) are regularly articulated and some of those plans are already being implemented, e.g. the link from the Netherlands to Norway and to the UK. Also, expectations about the potential of wind offshore are very high. A large scale implementation of wind farms on the North Sea will inevitably lead to the expansion of the high voltage grid. At the same time distributed generation is being promoted and stimulated by national and European policies. Germany is a world leader on PV, both in production and implementation [13]. Gas utilities in the Netherlands are pushing micro cogeneration systems [14]. Also, R&D of new grid configurations are taking place, supported by national and EU R&D grants [15]. Because all three pathways are technologically feasible, future sustainability transitions are mainly determined by economic, institutional dynamics and cultural dynamics. However, we conclude that the de-alignment and re-alignment pathway is less likely than the other two pathways, which stay to closer vested interests and are more in line with ongoing dynamics. The de-alignment and re-alignment pathway is therefore more dependent on external developments and/or strong policy interventions.

Investments and infrastructure innovations are needed in all pathways, not only for the Supergrid and hybrid system, but also for the decentralized scenario (microgrids). Contrary to the common belief (and promise) that distributed generation will reduce the need for transmission and distribution infrastructure, microgrids also require expansions and improvements of the central infrastructure, e.g. to provide back-ups and balancing supply and demand [16]. A shift towards distributed generation will also require more emphasis on local distribution grids. These will acquire the characteristics of HV grids, requiring a change of operation principles. Also, new innovative components and technologies are needed [9]. Infrastructure thus remains crucially important in all transition pathways.

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