What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production

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Original research article

What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production

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ABSTRACT

Keeping global mean temperature rise well below 2 °C requires deep emission reductions in all industrial sectors, but several barriers inhibit such transitions. A special type of barrier is carbon lock-in, defined as a process whereby various forms of increasing returns to adoption inhibit innovation and the competitiveness of low-carbon alternatives, resulting in further path dependency. Here, we explore potential carbon lock-in in the Dutch chemical industry via semi-structured interviews with eleven key actors. We find that carbon lock-in may be the result of (i) technological incompatibility between deep emission reduction options over time, (ii) system integration in chemical clusters, (iii) increasing sunk costs as firms continue to invest in incremental improvements in incumbent installations, (iv) governmental policy inconsistency between targets for energy efficiency and deep emission reductions, and (v) existing safety routines and standards. We also identify barriers that do not have the self-reinforcing character of lock-in, but do inhibit deep emission reductions. Examples include high operating costs of low-carbon options and low risk acceptance by capital providers and shareholders. Rooted in the Dutch policy setting, we discuss policy responses for avoiding carbon lock-in and overcoming barriers based on the interviews, such as transition plans for individual industries and infrastructure subsidies.

1. Introduction

Keeping global warming below 2 °C requires a 85–90% reduction in global greenhouse gas (GHG) emission between 2015 and 2050 [1] and the 1.5 °C limit in the Paris Agreement even requires global CO_2-neutrality in 2050 [2]. Such emission targets are hereinafter referred to as deep emission reductions (DER). The chemical industry, including petrochemicals, is one of the most GHG-intensive industries, and globally accounts for 16% of industrial direct CO_2 emissions and approximately 7% of total GHG emissions [3]. Direct emissions from the chemical industry arise mainly from fuel combustion to produce electricity and high-temperature heat, and also as by-products directly from chemical processes. A relatively small group of base chemical outputs, in particular ammonia, ethylene and chlorine, are responsible for two-thirds of the chemical industry's GHG emissions. The products of these base chemicals are used in various sectors. For example, fertilisers are used in agriculture and plastics in the packaging industry [4].

The Netherlands is one of the world's largest producers and exporters of chemicals [5]. The chemical industry makes a significant contribution to the Dutch economy with a share of 1.6% of GDP [6] and 18% of total Dutch export in 2016 [7]. The turnover of the Dutch chemical industry (DCI) in 2015 was €45 billion [8], and 43,000 people were directly employed in the sector in 2015 [9]. At the same time, the DCI accounted for approximately 8% (18 $MtCO_2$-eq) of the Netherlands' total GHG emissions (233 $MtCO_2$-eq) in 2015 [10]. Energy intensity in the DCI improved by 39% between 2000 and 2012, which put it amongst the most energy efficient chemical industries in Europe [11]. In 2013, an Energy Agreement was signed by the Dutch government and more than forty societal organisations, including the Association for the Dutch Chemical Industry (VNCI). The Energy Agreement included a goal to save a total of 100 petajoule (PJ) by 2020 in industry [12,13]. Moreover, in May 2019, a Climate Law was passed by the Dutch Senate, committing the Netherlands to a 49% GHG emission reduction in 2030 and 95% in 2050, compared to 1990. A Climate Agreement has been proposed with measures for different sectors, including industry [14].

Current obligations and past achievements notwithstanding, many reports and studies indicate that achieving DER in the chemical industry requires measures beyond current energy efficiency improvements [15,16] and even an 'industrial system transition' [2]. According

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to these studies, a combination of various DER measures is required, including novel technologies related to radical options. Those DER options are categorised by IPCC [2] as well as the Dutch Ministry for Economic Affairs and Climate Policy [17] as full electrification and hydrogen, circularity and substitution, bio-based, carbon dioxide capture, utilisation and storage (CCS/CCU), and process and energy efficiency, where the latter one is not considered DER unless combined with one of the other categories.

Adoption of several of those options, however, may be inhibited by lock-in. Their uptake depends path-dependency based on historical preferences and development of existing technologies in the system [18]. Arthur [19] argued that existing complex technologies exhibit increasing returns to adoption; the more they are implemented, the more experience is accumulated, and, consequently, the more they are improved.

Several studies have identified general barriers that energy-intensive industries face to reach DER, including the lack of end-user demand for low-carbon products due to the business-to-business character of basic industry products, the high capital costs and long investment cycles and payback times, the risk of losing competitive advantage in the global market, and the lack of sufficient prioritisation and policy effort [4,9,16]. Carbon lock-in has been investigated in sectors such as energy [30], transport [31], agriculture and infrastructure [32]. However, potential carbon lock-in in the industry sector, and how to respond to that, has to our knowledge only been characterised in the concrete industry [33], and largely remains an open question [16].

We hypothesise in this paper that, in addition to general barriers, the DCI is at risk of carbon lock-in, given its existing path-dependent, highly optimised and integrated system that has exhibited strong increasing returns to past adoption. Similarly to other sectors, those increasing returns and the high reversal costs to a new system stimulate firms to try safeguarding their vested interests [34], hampering implementation of the DER technologies. Failing to deal with carbon lock-in in a timely and adequate manner makes a low-carbon transition even more difficult or economically unsustainable for the DCI in the long run. In this paper, we investigate whether such potential carbon lock-in exists for the DCI, and if so, what are the components of such a potential carbon lock-in and what could be possible policy responses.

This paper is structured as follows: Section 2 describes the conceptual framework, data collection and the analysis. In Section 3, we present and discuss our results on carbon lock-in and other barriers and compare our findings with carbon lock-in studies in other sectors. In Section 4, our findings on policy responses to avoid such carbon lock-in and barriers will be presented and discussed. Finally, Section 5 provides conclusions, recommendations for future work, and discusses limitations of our research.

2. Methods

2.1. Conceptual framework

In general, increasing returns to adoption resulting in path dependence [18,19] of fossil fuel-based technologies is the main criterion for carbon lock-in. When actors have gained vested interests in a sector or technology, and the system enabling it, [33,35], they tend to continue down a specific path, following initial steps taken in that direction [36]. Moving down such a path makes it difficult to reverse course as the costs of reversal are very high [36,37]. This situation can lock the system in a particular technology [37–39] and any old or new alternatives, even when superior, could become locked-out [19]. Path dependence and increasing returns to adoption have been emphasised as core concepts in the lock-in literature [18,19,31,40–48].

Lock-in can also be related to the challenge of implementation of new low-carbon technologies, constraining institutional, technological, social, and economic efforts towards DER [42,44]. For example, Seto et al. ([44], p. 426) define carbon lock-in as "a path-dependent process (…) whereby initial conditions, increasing economic returns to scale and social and individual dynamics act to inhibit innovation and competitiveness of low-carbon alternatives". Wesseling and Van der Vooren [33] give carbon lock-in a slightly different spin by demonstrating the interaction between system components in the concrete industry. They map structural components in the technological innovation system of the concrete industry, analyse system functions, and then identify systemic problems that inhibit the functioning of the innovation system that could move towards low-carbon innovation. They argue that lock-in emerges when a set of interdependent systemic problems and vested interests reinforce each other in one or more closed feedback cycles.

The approach taken in our paper complements Wesseling and Van der Vooren [33] and others discussing carbon lock-in [30,49]. We follow Arthur [41] and Unruh [43], who argue that carbon lock-in emerges "through combined interactions among technological systems and governing institutions" ([43], p. 817) and operationalise path dependence in four types of increasing returns to adoption (see below). Lock-in emerges because actors try to maintain and upgrade the dominant design by incremental improvements that do not jeopardise continuity of the production. An example in industry is energy efficiency measures. Such incremental improvements increase returns for the incumbent system, but at the same time increase reversal costs to a carbon-saving system leading to inertia to implement any disruptive technologies [36,37,50], such as DER options.

Based on Arthur [42] and Unruh [43], in this paper, we distinguish four types of increasing returns to adoption: Economies of scale, learning effects, adaptive expectations, and network economies. "Economies of scale" refers to reduced unit production costs due to the spread of fixed costs over increasing production volume. "Learning effects" improve performance by gaining more knowledge and experience from a technology over time. "Adaptive expectations" arise when increase in adoption of a technology reduces uncertainty, and as a result increases confidence of users and producers in quality, performance and permanence of the product and process. And finally, "network economies" occur when there are advantages in adopting the same technology that others apply.

Not all barriers to DER in the chemical industry can be characterised according to these four categories of lock-in.[1] Hence, we differentiate between 'normal' barriers and a special category of barriers which are (carbon) lock-ins. This distinction is relevant as carbon lock-in requires a different policy response [49,51].

2.2. Data collection

We conducted eleven semi-structured interviews with key actors involved in the transition of the DCI towards DER. The interviewees (see Table 1) were selected from different types of organisations to provide a diverse set of perspectives and insights on the subject. All interviews were recorded, transcribed and sent to the interviewees for review. Eight interviewees reviewed the transcripts and of those, seven gave additional information. This additional information was included as an addendum to the transcripts. The duration of the interviews was on average around 60 min with variations between 30 and 90 min.

We described views of the interviewees and refer to one, several (2–4), many (5–7), most (7–10) and all (11) interviewees expressing the same view on a certain topic. When few interviewees commented on a particular issue (e.g. because some of the interviewees did not feel sufficiently qualified to comment on technical issues), this is represented in the results section.

The interview data were triangulated with a document analysis of

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[1] We assume that all lock-in associated with DER is carbon lock-in, and apply the same characteristics.

Table 1
List of interviewees. All interviews except for the Urgenda interview were in-person. The interviews took place in November 2017. All interviewees were either high-level managers or senior advisors of the organisation.

Type of organisation	Organisation	Position in the organisation
NGOs	Urgenda (by phone)	High-level manager
Industry association	VNPI (The Dutch Petroleum Industry Association)	High-level manager
	VNCI (The Dutch Chemical Industry Association)	High-level manager
Industry	Royal Dutch Shell	Senior advisor
	AkzoNobel	High-level manager
	Chemelot	High-level manager
Government	Ministry of Economic Affairs and Climate Policy	Senior policy advisor Senior policy officer
Public Limited Company	Port Authority of Rotterdam (group interview)[a]	High-level manager, two senior advisors
Research institute/Consultancy	PBL (Netherlands Environmental Assessment Agency)	Senior advisor
	Quintel	High-level manager

[a] The interview was planned to take place with a high-level manager at the Port Authority of Rotterdam, but two colleagues were also available at the time of the interview and were invited to participate in the interview as well.

roadmaps, policy documents and public statements of relevant industries, governmental and non-governmental organisations.

2.3. Data analysis

We took a thematic analysis approach to analyse the interviews. Transcripts were coded using the four types of increasing returns [42] to identify which barriers are carbon lock-in. Out of eleven interviews, six were coded independently by two researchers to ensure consistent treatment and remove bias, five more were coded by one researcher, and all the coded interviews were discussed in details amongst the researchers until consensus about the coding was reached. This resulted in a list of factors that could be sources of carbon lock-in for the DCI. Any problem mentioned by the interviewees that met one or more of the four characteristics (economies of scale, learning effects, adaptive expectations, and network economies) was classified as a carbon lock-in. Other factors mentioned by the interviewees were categorised as barriers. Policy responses to carbon lock-in were coded openly and are discussed separately in Section 4. The codes were finally grouped into three broad categories: carbon lock-in, other barriers, and policy responses.

Table 2
Overview of five carbon lock-in themes, resulting from the thematic analysis of the interviews, and what type of increasing returns to adoption are observed per theme.

Theme	Type of increasing returns to adoption
Technological incompatibility	● Economies of scale ● Learning effects ● Adaptive expectations
System integration	● Economies of scale ● Learning effects ● Adaptive expectations ● Network economies
Sunk costs	● Economies of scale
Policy inconsistency	● Economies of scale ● Learning effects ● Adaptive expectations
Safety routines	● Learning effects ● Adaptive expectations

3. Carbon lock-in and barriers

In this section, we present the results of the thematic analysis in the interviews, and a document review. The results are organised by type of barrier. The first section discusses the barriers that show carbon lock-in characteristics, and the second section the other barriers arising from the interviews are discussed. The thematic analysis led to a list of nine barriers that relates to DER in the DCI. From the nine factors arising from the thematic analysis, five are considered to be carbon lock-in. They are: 1) technological incompatibility, 2) system integration, 3) sunk costs, 4) policy inconsistency, and 5) safety routines. The remaining four types are classified as other barriers, i.e. 6) cost competitive fossil fuel and feedstock, 7) turnaround and payback times, 8) low risk acceptance by capital providers and shareholders, and 9) customers behaviour and choice. Table 2 shows the classification of the carbon lock-in types, and associated types of increasing returns to adoption.

3.1. Barriers with carbon lock-in characteristics

3.1.1. Technological incompatibility

We refer to technological incompatibility when a DER technology is incompatible with another DER option, or with existing technology, in the chemical industry. Technological incompatibility means a DER technology cannot be operated alongside the other technology. While several technological (in)compatibilities could be identified, the interviewees tended to focus on the incompatibility between electrification and CCS[2] in the chemical industry.

Many interviewees pointed out the incompatibility between electrification and CCS technologies (aside from CCS applied to hydrogen or energy production). This incompatibility will emerge when electrification (by renewable electricity) is implemented, and no CO_2 is emitted anymore by the installations, rendering CCS inapplicable. Yet, many interviewees mentioned that CCS is an inevitable option to reach DER in the DCI, because it is the most viable and easy option in the short term, and emissions need to go down without delay. Several interviewees noted that CCS will be a temporary measure, operating for a limited but sufficient period of time for companies to recuperate their investments in CCS. However, several other interviewees flagged that the combination of CCS with current hydrogen production (through the steam methane reforming (SMR) process) will make low-carbon electrification harder to realise. The same interviewees argued that CCS is currently more attractive than electrification, because it is cheaper and more compatible with current installations, especially in the petrochemical industry, allowing continuity of current production processes while reducing CO_2 emissions but without moving to a truly sustainable chemical industry. According to them, CCS will therefore be a lock-in, inhibiting electrification to be applied in the DCI. Another interviewee pointed out that in the longer run, CCS may run out of CO_2 if it is used

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[2] One reflection on why only the CCS/electrification trade-off appeared in the interviews may have had to do with the timing: a new Government Agreement had just come out which included a proposal to implement 18 $MtCO_2$ of CCS in industry per year by 2030 [76], quite a sizeable amount that spurred much discussion and that may have dominated the moods of the interviewees at that time.

for power-to-gas, in which CO_2 emitted when making hydrogen through SMR would be used to produce methane, which is then used as a fuel. Some interviewees pointed at the possibility of hybrid boilers, as those would allow for partial electrification and could become a bridge to full electrification.

Consistent with the point several interviewees made on the potential role of CCS to become a source of carbon lock-in, CCS has been framed as hampering implementation of other more sustainable options in several stakeholder sources. A common point made against CCS is that CCS will provide the possibility to perpetuate fossil fuel consumption and distract society form realising more sustainable technologies required for a fully renewable industry and energy system [45,52–55]. The compatibility with current business routines and lower costs, also because electrification would increase costs for renewable electricity generation, are reasons for industry associations to look at CCS favourably [9]. Environmental NGOs, such as Greenpeace, however argue that CCS will divert investments away from more sustainable options required for a fully renewable-based energy system [51,56]. Alternatives for CCS and their potential estimated CO_2 emissions abatement and costs are investigated in a Greenpeace-backed report [57]. Those options are presented to be part of sustainable solutions while CCS is explicitly excluded [57].

Technological compatibility matters for companies to maintain continuity of production, to avoid additional fixed costs. Thus, technological incompatibility of DER options with current systems is a carbon lock-in, as investments are made in incumbent production systems lead to increasing returns to adoption through economies of scale as well as adaptive expectations. In addition, many of the learning effects of the current technologies over time may become obsolete, while for any new DER technology, learning and knowledge accumulation has to start from scratch.

3.1.2. System integration

The DCI, for example in the Rijnmond (Rotterdam harbour), in Chemelot (the former DSM complex near Geleen in the southeast of the country) or in Zeeland (in the southwest around Terneuzen and Vlissingen) is often co-located in highly integrated industrial clusters. Regarding the interaction of such chemical industry clusters with the DER options, many interviewees expected that the residual heat grids, which are being constructed now to supply excess industrial heat to households, will be at risk of becoming stranded assets if future technologies produce less or zero residual heat. One of the interviewees commented that the technical integration of the chemical clusters in the Netherlands has been an advantage for energy efficiency improvements, but this highly optimised integration reduces the economic attractiveness of DERs. Another interviewee felt that the cluster integration, implying centralisation, would limit companies' options for switching feedstock and technologies. It was also claimed by another interviewee that the replacement of the current installations with alternative options would throw the existing integrated, optimised system out of balance, leading to wasting of materials and energy.

System integration in general has been seen as an advantage rather than a barrier to reach DER in industry reports [9]. Even further integration to improve circularity is advised in one of the site plans for climate neutrality [58]. However, potential system integration lock-in, specifically on the waste heat exchange between chemical companies and their vicinities, has also been explicitly flagged [59]. Moreover, it is indicated that the lock-in effect of such cross-sectional waste heat exchange may prevent further efficiency improvements at the plant level [4]. Others expect that some of this type of lock-in also might be applied to hybrid boilers as it is not easy to implement them in every industrial setting and replacement of an individual piece of an industrial facility may require a big change in the entire system [24], bringing new sunk costs to the system and increasing the switching costs to the fully renewable industrial system. This point has been also discussed by Bataille et al. [22]: there are potential transition pathways (e.g. through using hybrid technologies) that allow industry to minimise stranded assets while reducing emissions through a gradual shift from limited contribution of renewables to fully renewable options, however they express doubt of whether such transition pathways would make economic sense in contrast with the option of direct use of renewables in new low-carbon facilities. This implies the potential risk of future lock-in in such transition models, hampering the DER achievement.

System integration shows carbon lock-in of all four types of increasing returns. The existing clusters obviously thrive on economies of scale and network effects, which both reinforce the incumbent system. In addition, learning about integration may not be transferrable to low-carbon chemical clusters, and actors show confidence in the performance of the cluster, using incumbent technologies and processes (adaptive expectations).

3.1.3. Sunk costs

According to several interviewees, high capital costs of existing long-lived installations means that the DCI is incentivised to continue running current assets, which deters it from investing in DER. One of the interviewees mentioned that any investment in current installations will mean those installations remain in operation for 20 to 30 years or more.

Several interviewees also argued that further energy efficiency optimisation of the existing installations could present a lock-in situation, especially when payback times of such investments are long. They indicated that such sunk costs would also be increased in industry's efforts to meet the energy saving target of 100 PJ by 2020 in the Dutch Energy Agreement [12] (see also the next section). Sooner or later the existing installations will have to be replaced with DER technologies, which would render the energy savings investments as stranded assets.

The large scale of chemical industry installations and associated high capital (and sunk) costs are driven by economies of scale that have been built up over a long period of time. Any replacement of the installations due to fast adoption of DER technologies deprives companies of significant income out of the current system, making sunk costs a source of carbon lock-in.

3.1.4. Policy inconsistency

The Dutch Energy Agreement (2013) aimed at saving 100 PJ by 2020. At the same time, the government is determined to achieve an emission reduction target of 95% below 1990 levels in 2050. Most of the interviewees observed a discrepancy between DER and the energy saving target, as they argue achieving the DER goal requires higher energy consumption, particularly in case of CCS deployment. Furthermore, several interviewees pointed out that limited resources and constraints in time would lead to economic and temporal trade-offs between meeting energy and DER targets.

Several interviewees indicated the potential consequences of policy inconsistency for the DCI as an entity. The same interviewees expressed concern that the discrepancy between policy targets might lead to business outflow from the Netherlands to elsewhere, especially of the companies headquartered outside the Netherlands, and consequently potentially to carbon leakage. Nonetheless, one of the interviewees argued that the business outflow would be difficult for the companies since they are operating in highly integrated and inter-dependent chemical clusters. It should also be noted that the Dutch government is not blind to this inconsistency: one of the interviewees indicated that the Dutch government is aware of the conflict between the energy and DER targets and policies, but indicated that attempts to modify EU regulation have not been successful up to now.

The VNCI [9] explicitly flags the potential lock-in resulting from short-term emission reduction measures in existing fossil-based technologies. It is argued that such short-term improvements will lead to higher sunk costs, impeding DER technology implementation. As for many chemical processes and companies only one investment cycle remains until 2050, the window for investments into DER options, as long-term solutions, is closing, in favour of short-term improvements in existing installations. DECHEMA [4] suggests that investments in the efficiency measures in the current fossil fuel-based plants will be in competition with the DER options and create a source of carbon lock-in.

Policy inconsistency, in many cases, is just a normal barrier, but in the case mentioned by the interviewees, it is a carbon lock-in resembling the "sunk cost" carbon lock-in discussed in the previous section. Any energy efficiency improvements in the exiting fossil-based technologies of DCI to achieve the energy efficiency goal will add more sunk costs to the current incumbent system, leading to higher reversal costs to a lower-carbon system. In addition, the learning effects for knowledge to reach the earlier target (for instance legal, registration and monitoring skills) can become obsolete if an inconsistent policy is eventually made consistent.

3.1.5. Safety routines

According to several interviewees, the chemical industry puts much emphasis on safety considerations, given the risks associated with chemical plants. One of the interviewees indicated that, for the DCI, applying new technologies entails new safety risks as safety tests need to be redone, new safety routines need to be developed, and the accident risk is potentially temporarily higher. Conducting new safety tests will also slow the production rate once a DER technology is up and running, leading to additional higher costs. Another interviewee explained that the engineers at the plant need to be convinced of the safety of the new equipment.

Applying the new DER technologies safely also demands a workforce with relevant expertise. This need could be met either by retraining existing personnel or hiring new experts. According to several interviewees, this would bring extra personnel costs to the chemical companies, though they did not perceive the personnel costs as challenging.

Regarding the potential safety risks associated with applying DER options, the IPCC [60] confirms that process safety is a major concern in the chemical industry that should be carefully considered in implementation of DER options. On safety concerns and considerations, there is similarity between the chemical industry and air traffic control. Bruce and Spinardi [35] explain that the air traffic control sector is reluctant to adopting other technologies, particularly due to a highly developed safety culture [49]. Any radical change in the innovation system is discouraged because of the high sunk costs to design a new system and certify the safety requirements, and the perceived associated risks [35].

The need for a new set of safety standards and routines for DER is a carbon lock-in because of the learning effects, adaptive expectation and network effects in the safety routines serving the existing system. The current safety routines have been built up over decades and have been successful because of continuous, cumulative learning, and adoption of DER technologies may nullify some of those experiences and knowledge. In addition, different safety routines may initially reduce confidence in safe performance of the new technologies.

3.2. Other barriers

3.2.1. Cost-competitive fossil fuel and feedstock

The current DCI system runs based on fossil fuel for both energetic and non-energetic use, but reaching DER requires abundant renewable electricity (for electrification and electricity-based hydrogen) and/or biomass (for high temperature heat and alternative carbonaceous feedstock). According to many interviewees, the cost of renewable electricity, heat and feedstock would be the main determinants for the total cost of low-carbon production of chemical products. Most interviewees flagged uncertainties about availability and cost-competitiveness of renewable electricity and biomass. Uncertainty about future electricity prices (partly related to uncertainty of future CO_2 prices) was highlighted by several interviewees as one of the most crucial difficulties in the realisation of renewable electrification.

In the IPCC Fifth Assessment Report [60], insufficient availability of bio-based and waste materials as substitutes for fossil-based fuels and feedstock is listed as one of the main concerns to reach emission reductions in the chemical industry. In addition, uncertainties around the operational costs, mainly related to prices of alternative fuels, has been highlighted as one of the biggest challenges that the DCI faces [9,24]. This uncertainty makes it difficult for companies to reliably predict the payback time of their investments in the DER technologies, making the investment riskier [24]. The VNCI [9] estimates that costs of renewable feedstock and fuels in the cheapest pathway is at least 50 percent higher than those of the fossil fuels currently used. Affordability and availability of sustainable biomass is highlighted as one of the main challenges in the "Biomass and CCS" scenario for the Port of Rotterdam [25].

As operational and feedstock costs themselves are not increasing returns on adoption, we consider this a normal barrier. Although for some renewable energy options the fossil advantage is shrinking [61], in the current chemical industry system, as in many other industries, fossil-based fuels and feedstock are cost competitive compared to renewable energy.

3.2.2. Turnaround and payback times

Many chemical processes require continuous operation in which all operational steps run simultaneously. Major system overhauls cannot be done while the plant is operational. Thus, chemical plants schedule time periods to shut down operations. Such scheduled events are called 'plant turnaround'. They are kept to a minimum as lost production hours while the industrial units are offline are costly, in addition to higher labour, equipment and materials costs during the turnaround. The turnaround interval in the chemical industry typically varies between four and six years. Several interviewees stressed the importance of the timing of turnarounds for implementation of DER measures, especially as the planned measures to be implemented in the next turnaround are decided on shortly after the last turnaround has been finalised. According to the same interviewees, if the opportunity for implementing DER at the next turnaround is missed, either the installation replacement will take place during the later turnaround, which may be too late to meet DER target in 2050, or extra costs are incurred for an additional turnaround.

Turnaround relates to payback times, an aspect not mentioned much by interviewees but highlighted in sector documents. The chemical industry's assets are high-value and have very long lifetimes. For instance, a boiler is expected to work for 30 years [24]. Consequently, payback time for replacing such an asset is long. The DCI has an interest in running the current assets as long as possible [9,24]. A plant often has a short window of opportunity to invest in DER as there will be only one investment cycle for many chemical processes until 2050. It implies that if a required DER technology is not ready to be implemented for the next investment round, the system has to make a new replacement with a non-DER option which brings more sunk costs to the current system, creating carbon lock-in [9].

However, this factor is a normal barrier and not a carbon lock-in, as the existence of long payback times and turnaround in itself does not lead to increasing returns to adoption. Once the investment with the long payback time is made, it is considered a sunk cost (see Section 3.1.3). The limited amount of plant turnarounds (which are more frequent than major re-investments in the full installations) limits the number of investment windows for DER, but also for investments in potentially lock-in-enhancing energy efficiency.

3.2.3. Low risk acceptance by capital providers and shareholders

Implementation of DER technologies bears high investment costs, leading some companies to seek external financing for at least part of the investment. Several interviewees indicated that most DER technologies have never been applied at industrial scale, therefore, the first company or investor will face the largest risk. Regarding the external financing, several interviewees expected that due to the high risk of investment in DER projects, banks are also unlikely to finance first-of-a-kind DER projects. On the governmental side, many interviewees mentioned the potential of Invest-NL, a new institutional impact-investor in the Netherlands, to provide insurance for financial risk and to support investors in risky projects. Nonetheless, several interviewees argued that the risk acceptance of Invest-NL is uncertain. Invest-NL was announced by the Dutch Government in 2017, and the starting date of Invest-NL has been planned for 2019 [62].

Several interviewees stated that due to the lower short-term returns of low- or zero-carbon products, shareholders are likely to react negatively towards DER investments, and favour investment that have a high-value track record. The same interviewees mentioned that the DCI is risk-averse in general as typically shareholders in the chemical industry expect stable profits and dividends, which is reflected in the industry avoiding financially risky DER. Confirming the same point, one of the interviewees mentioned that compared to radical and intermediate DER options, incremental energy saving projects make attractive business cases for the shareholders because those projects have higher short-term economic returns.

The VNCI [9] emphasises the key role of companies' high-level leadership to mobilise resources and actions for moving towards a decarbonised industry. Visionary leadership can decide to go ahead with riskier DER business cases that currently are not sufficiently profitable. Regarding the contribution of the leadership of chemical companies in realising the DER targets, the report points to top management and shareholders that reside outside the Netherlands [9]. In other words, decisions on the climate-neutral future of companies are being taken outside of the Dutch political landscape. The report emphasises the key role of leadership to improve business cases for several main DER technologies, by upscaling them and as such de-risking them [9]. Highlighting this management challenge is consistent with the interview results on the risk aversion of the shareholders who have benefited from stable profits. Cecere et al. [37] explain that one of the main reasons for the attractiveness of incremental improvements for shareholders is the lower investment costs associated with such projects compared to the higher costs of radical changes.

Risk aversion on the part of capital providers and shareholders is part of an engrained system and leads to the perpetuation of the current situation. However, it does not increase the strength of the incumbent system as it persists and no increasing returns to adoption in the form of increased economies of scale, adaptive expectations, learning effects or network effects could be identified. Hence, low risk acceptance is qualified as a normal barrier and not as carbon lock-in.

3.2.4. *Customer behaviour and choice*

According to most interviewees, customer buying behaviour is driven mainly by price and, secondly, by the product quality. It was argued that, although customers regard low-carbon products favourably, the willingness to pay a higher price is low. While several interviewees indicated that a small but growing group of business customers buys low-carbon products to meet internal sustainability goals, this is not expected to drive the DER agenda sufficiently.

Generally, the chemical industry supplies bulk chemicals to other manufacturing companies, which produce final products, usually multiple steps down the supply chain. Therefore, the chemical industry is not much exposed to direct pressure of end-users to produce low-carbon products. Our interview results are in line with other papers that also find a lack of willingness to pay on the part of customers (businesses) for low-carbon materials, because customers cannot pass through the higher price to the end-users [25,63]. Contrary to adaptive expectations in the concrete industry (see below in the comparison with other sectors), according to our results, customer behaviour in the chemical industry does not meet any of the characteristics of carbon lock-in.

3.3. *Comparison with other sectors*

We compared our findings with carbon lock-in studies in other sectors. Seto et al. [44] indicate that lock-in may not be coincidental: they explain that institutional lock-in can be "an intended feature of institutional design, not an unintended by-product of systemic forces … to reinforce a status quo trajectory" ([44], p. 433). Wesseling and Van der Vooren [33] also attribute carbon lock-in to vested interests. Our results imply that such institutional lock-in indeed exists, but we found no evidence of intentionality.

We do identify unintentionally counter-productive policy inconsistency: by investing in energy efficiency of the existing assets prone to lock-in, investors and policy makers increase the transition costs. Here, we may find a difference between industry and, for instance, efficiency in coal-fired power, where studies indicate that efficiency improvement increases future flexibility to reduce emissions [40]. We could not locate quantitative cost estimates of such dynamic interplay between short- and long-term mitigation options specifically for industry, but as an illustration, the International Energy Agency in 2013 estimated that continuing investment through to 2020 to make incremental changes in the current fossil fuel-based technological system instead of investing in low-carbon alternatives could quadruple investment costs for decarbonisation in 2035 [64].

Seto et al. [44] also describe behavioural lock-in (individual, cultural and social practice) in various sectors. Our interviewees confirmed Seto et al's findings of multidirectional causation among the carbon lock-ins and barriers; these lock-ins and barriers affect each other and can reinforce each other. Seto et al. explain that techno-institutional lock-in can be strengthened through individual decision-making (mainly driven by habits, norms and routines) [40,44]. A similar conclusion was reached by Unruh [43], who explains how reinvestments in current technologies can lead to positive feedbacks, and consequently lock DER options out.

The behavioural lock-in considers the individual consumer behaviour as the focal point. In the chemical industry, however, the products are not directly connected with the end-users in the supply chain. While companies also show behavioural traits [41], our results indicate that their behaviour is more driven by price. We therefore identify customer behaviour as a barrier and not a carbon lock-in.

Wesseling and Van der Vooren [33] note an absence of demand for cleaner production in their case study on the Dutch cement industry. They observe such reluctance to buy low-carbon concrete not only with companies but also with the government, one of the largest cement procurers. But the price sensitivity of customers may not be the only explanation of the lack of a market for low-carbon industrial products. Wesseling and Van der Vooren [33] highlight that procurers are conservative about the quality of the clean concrete, leading to risk aversion and delayed diffusion and application of clean concrete in the Netherlands. This is the adaptive expectation characteristic of carbon lock-in. However, as this is not found in the interviews on the chemical industry, this is not included in the carbon lock-ins in our paper. Chemicals have some characteristics, such as more straightforward measurement of the chemical qualities of the products, that may lead one to believe that this is less of an issue for the chemical industry, but its appearance in concrete could mean this could be a topic of further research.

Klitkou et al. [31] investigated lock-in in energy production and road transportation in the Nordic countries. They arrive at nine lock-in mechanisms based on previous scholarly work on lock-in: learning effects, economies of scale, economies of scope, network externalities, informational increasing returns, technological interrelatedness, collective action, institutional learning effects, and the differentiation of power. There are similarities with our findings in the chemical industry in learning effects, technological interrelatedness, informational increasing returns, economies of scale, network externalities and collective action. Because of the relatively large scale and slower turnover of capital goods, and specificity of chemical industry installations, we could, however, not identify economies of scope (lowering total costs of production by producing a variety of products together rather than separately) as a relevant source of carbon lock-in in the chemical industry.

To what extent are our results generalisable? The technological incompatibility between electrification and CCS was emphasised and, with regard to CCS, may also apply to sectors such as fossil-fuelled electricity [65]. Our work reinforces earlier studies [4,59] that identify system integration incompatibility, especially in heat exchange networks, as a source of carbon lock-in. As illustrated by a case on district heating, CCS, as well as industry-based residential heat grids, may become cases of “rolling path dependencies” [66]. It would be worth investigating this concept further in the context of decarbonisation of energy-intensive industry.

Industry seems to be a special case for inconsistencies between (energy) efficiency and low-emission technology, highlighted by carbon lock-in due to policy inconsistency. Such inconsistency also appears in personal vehicles; investments in improving internal combustion vehicles means that these investments are not done in low-emission alternatives. However, personal vehicles tend to have shorter lifetimes than industrial assets. Buildings can have very long lifetimes, but any investment in energy efficiency (e.g. insulation) assists low-emission technology. Hence, carbon lock-in through policy inconsistency seems to be fairly specific for energy-intensive industry.

4. Policy implications and responses

All interviewees were asked about policy responses to escape carbon lock-in and resolve the barriers. Their suggestions are discussed below in two categories: long-term targets and transition planning, and mixes of policy instruments, and are related to current policy developments in the Netherlands, in particular those around the Dutch Climate Agreement [14].

4.1. Long-term targets and plans

Several interviewees stressed the need for strategic back-casting studies for companies to spot potential lock-in and barriers. One interviewee proposed the preparation of technology-specific transition plans for the 12 largest CO_2 emitting companies in the Netherlands (which the interviewee indicated are jointly responsible for 75% of the Dutch industrial CO_2 emissions). Such transition plans would serve to find windows of opportunity for viable implementation of options that avoid carbon lock-in. Another interviewee highlighted the unknowns on industrial symbiosis that make it difficult to make such transition plans.

In an earlier draft version of the Dutch Climate Agreement [67], transition plans resembling this suggestion, along with an arrangement that financially assists industry in realising such plans, was included. However, upon of a public outcry that this would violate the ‘polluter pays’-principle, this arrangement was replaced by a carbon tax for energy-intensive industry.

One interviewee suggested the consideration of policies that roll back chemical industry cluster integration in favour of decentralised production of chemicals. The current government plans in the Climate Agreement signal no such developments or intentions as it still explicitly mentions the industrial clusters [14].

Many interviewees stressed that the government should have a clear long-term target focusing on DER to make the transition happen, to resolve the inconsistency (such as between energy saving and DER), also between different governments. In the Dutch Climate Agreement, this is addressed by the mention of a soft aim of climate neutrality in 2050 for industry and the harder target, also in the Climate Law, of a 49% emission reduction in 2030 compared to 1990, with a possibility of increasing this 2030 target to 55% [14]. Another interviewee emphasised that policy consistency and continuity is vital for trust between the DCI and the government. The current response to this concern is that the Dutch Climate Agreement is designed to have broad stakeholder support, including industry [68], although several environmental NGOs decided to withdraw [69,70].

4.2. Mixes of policy instruments

Many interviewees agreed that the government should apply various policy instruments to accelerate the industrial transition. A combination of market pull-types of instruments, such as standards, pricing or taxes, and technology push instruments, such as innovation subsidies and public investments, was advised by several interviewees.

Most interviewees highlighted that the risks of first-of-a-kind projects need to be reduced to overcome barriers related to risk aversion (Section 3.2.3) and sunk costs (Section 3.1.3). According to the interviewees, for DER, it is unavoidable that the government subsidises DER piloting, demonstration and scaling up. One interviewee pointed out that innovation subsidies can lower risk for the financiers of the investments. The Dutch Climate Agreement [14] and the Climate Plan [17] both mention innovation subsidies as an important instrument for industry.

Several interviewees indicated that in the short-term, operating costs will go up, which would increase the total cost of production. The same interviewees indicated that an appropriate policy instrument could compensate for additional operating costs for a limited period of time. For this, one of the interviewees suggested that the government provides subsidies for the near-market technologies that still have high operating costs. The same interviewee indicated that this kind of support will accelerate commercialisation of DER technologies by bringing the operating costs down for the companies. This can be done through financing DER infrastructure, especially for CCS, hydrogen and electricity. Besides the government, the utility provider companies were also mentioned as key actors to invest and build required infrastructures for electricity, fuel transport and CO_2 transportation. Several interviewees named the Port Authority of Rotterdam, as a public limited company, as willing to invest in energy, CCS, steam and heat grid infrastructures. As a specific suggestion, one interviewee indicated that Invest-NL, a new public investment fund, could be helpful to invest in the needed infrastructure, and hence shorten the payback time of the DER projects.

In addition, several other interviewees indicated that the DCI should receive compensation for the difference between the CO_2 price in the EU Emissions Trading Scheme (ETS) and the additional operating cost of DER measures. The same interviewees, although aware of strong opposition from NGOs, recommended that the government extends the current subsidy scheme on renewable energy to a subsidy on CO_2 reductions, including CCS. This wish was included in the Dutch Climate Plan [17] which indeed includes an extension of the SDE+ scheme to CO_2-reducing measures in industry. Given resistance against much CCS, industrial CCS is limited to an annual 7.3 $MtCO_2$.

One of the interviewees indicated that customer buying behaviour will not change unless the tax system changes in favour of low-carbon products. Several interviewees advised that the government should help to develop a market for low-carbon products to provide the appropriate setting for potential interested customers to buy climate friendly products. The Dutch Climate Plan partly foresees in this: it announces that public procurement will take into account climate friendliness [17]. In addition, a carbon tax will be imposed on industry that will be well-connected with the EU ETS [17], but for which details are not yet available.

5. Conclusion and recommendations

Based on stakeholder interviews and literature, we found sources of carbon lock-in in the Dutch chemical industry in five areas:

technological incompatibility, system integration, sunk costs, policy inconsistency and safety routines. The existing installations of the chemical industry are large-scale and long-lived assets, involving high sunk costs, leading the chemical industry to continue using the current installations [71]. At the same time, the existing installations cannot be operated alongside the new technologies (particularly electrification). If DER is to be achieved, existing installations would face early retirement and hence become stranded assets [44]. A considerable share of the sunk costs belongs to partly policy-induced incremental energy efficiency improvements that have been implemented over the past decades [30].

Along with the current technologies that have to be replaced, safety standards and routines need to be partly developed for new technologies. Apart from the uncertainties on the safe performance of the new technologies (which in many cases, have not yet been used at a large scale), it requires time, new expertise, and investments in new systems. When DER options are incompatible with existing interconnected technologies and infrastructures within and outside of the chemical clusters, a further barrier or even carbon lock-in appears. In industrial clusters, network effects create greater initial inertia for the incumbent system, compared to when only a single firm were involved. However, when the transition is decided, it could go faster in industrial clusters. Overall, our results are consistent with earlier studies on carbon lock-in, including those in other sectors. Our findings indicate, however, that for the chemical industry, the carbon lock-ins of system integration and safety routines are more prominent and others, including those related to behavioural lock-ins, don't appear because of specific technological and institutional characteristics of the DCI.

As for other barriers, operating costs are currently high and so are uncertainties around those operating costs, in particular costs of feedstock and renewable electricity. Moreover, risk acceptance of capital providers and shareholders is low, therefore they tend to invest on the existing incumbent technologies due to the uncertainties and high risk of DER projects. Furthermore, shareholders (and hence the company boards) are risk-averse and want to see dividends, and, for that reason, demand low payback times, stable profits and low risks.

We identified several limitations to our study, which point to directions for further research. First, the fairly small set of interviews gives a partial image at a particular time; a repeat of the interviews, possibly involving a broader set of stakeholders could provide more detailed information. Additional research methods that could be deployed include more structured expert elicitation to explore industrial carbon lock-in and identify effective and acceptable policy options [72]. To address the potential role of system integration in carbon lock-in, further work on the particular regional and industrial characteristics of chemical industry clusters could be insightful for long-term investment planning, e.g. for the implementation of renewables-based electrification. Policy instrumentation to respond to carbon lock-in and barriers needs to be specified for various industries in addition to different sectors, and further work beyond Pollitt et al. [73] and Munnings et al. [74] on policy instrumentation specific to industry, often exposed to international trade, would fill a knowledge gap. In terms of innovation system analysis, sectoral innovation system assessment [75] might be a suitable tool for identifying suitable policy actions, especially in combination with functional analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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