International Journal of Greenhouse Gas Control 105 (2021) 103235

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Understanding contrasting narratives on carbon dioxide capture and storage for Dutch industry using system dynamics

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ARTICLE INFO

Keywords:
Carbon dioxide capture and storage
Climate change mitigation
System dynamics
Carbon lock-in
Just transition
Netherlands
Energy-intensive industries

ABSTRACT

Carbon dioxide capture and storage (CCS) can reduce CO_2 emissions, but there is disagreement on its role. The disagreement is reflected in stark differences in stakeholders' narratives on CCS. In the Netherlands, one extreme narrative focusses on CCS as part of a just transition and another on CCS as contributing to carbon lock-in. These narratives reflect different expectations of dynamic feedbacks around CCS deployment in the specific Dutch industrial context. This paper describes an alternative narrative that can advance the debate on what role CCS may play. Qualitative system dynamics based on interviews with experts is applied to identify the systemic feedback mechanisms that drive the dynamics of CCS in the Dutch industrial system transition, according to the two narratives. We find that CCS may reinforce carbon lock-in through the feedback mechanisms of legitimising, crowding out, and integration, and that CCS may play a part in a just climate transition through employment, economic, and environmental mechanisms. We combine these mechanisms into our alternative framing of CCS that could align the interests of different stakeholders: regulating CCS carefully to maximise its social and climate benefits and minimise the build-up of vested interests and carbon lock-in.

1. Introduction

Carbon dioxide capture and storage (CCS) is a technology that can capture CO_2 emissions produced by the use of fossil fuels or biomass in electricity generation or industrial processes (IPCC, 2005). In the capture process, CO_2 is separated from other exhaust gases. The captured CO_2 is then compressed for transportation, injected and stored in deep porous geological formations, over about a kilometre underground (Global CCS Institute, 2019a). CCS can most efficiently be applied to large stationary CO_2 sources such as power plants and energy-intensive industries like oil refining, cement, steel, and chemical plants (Global CCS Institute, 2019b; IEA, 2019). In the Netherlands, it is mainly seen as a mitigation option for industry as the coal-fired power plants are due to shut down in 2030 (Dutch Government, 2019a).

CCS can avoid a significant share of energy-related and industrial CO_2 emissions (IEA, 2017; IEA, OECD, 2004; IEA, UNIDO, 2011; IPCC, 2018). Over the past decade, CCS has been framed as an indispensable part of the climate change mitigation portfolio, as reducing Greenhouse Gases (GHG) in line with limiting warming to well below 2 °C while maintaining industrial productivity is thought to be very costly and hence nearly impossible without CCS (IEA, 2017; IEA, UNIDO, 2011; IPCC, 2018). For instance, the Intergovernmental Panel on Climate Change (IPCC) has estimated a 138 % increase in the marginal abatement costs, for the period 2015–2100, in case of CCS absence in the mitigation portfolio (IPCC, 2014a). The International Energy Agency (IEA) estimates that the exclusion of CCS would increase the mitigation costs by 40 % (US$2 trillion) by 2050 (IEA, 2012). Although these results reflect that a functioning economy without fossil fuels is difficult to imagine (and therefore to model), the reality is that CCS is seen as a key option in the low-carbon transition.

This vision of CCS, however, is far from reality. Progress on CCS has been limited (IPCC, 2018). Since it started featuring prominently in the global mitigation portfolio in the early 2000s, its contribution has grown to only around 40 $MtCO_2$ annually in 2019 (Global CCS Institute, 2019a), which is only a fraction of its potential and its need according to studies. Reasons include public resistance as well as a lack of incentives and political will (de Coninck and Benson, 2014; IPCC, 2018).

The stalling of CCS and its association with the fossil fuel-based

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https://doi.org/10.1016/j.ijggc.2020.103235
Received 28 February 2020; Received in revised form 4 December 2020; Accepted 8 December 2020
Available online 29 December 2020

system have led to a debate on what actually can be expected of CCS in addressing climate change. What will be the systemic (indirect) impacts of large-scale CCS implementation on the dynamics of the transitions needed to address climate change? This debate takes place both in society (Boyd et al., 2017; Feenstra et al., 2010; Greenpeace, 2008; Karimi et al., 2016; Terwel et al., 2012) and in research (Blackford et al., 2009; Ha-Duong and Loisel, 2009; Shackley and Thompson, 2012; Stephens et al., 2011; Vergragt, 2012; Vergragt et al., 2011). Narratives vary from CCS as a cost saver (IPCC, 2014b) and recently a contributor to a just transition (Swennenhuis et al., 2020), to CCS as 'false hope' (Greenpeace, 2008) and reinforcing existing fossil fuel-based carbon lock-ins (Vergragt et al., 2011).

Whether for or against CCS, the state of the debate at the moment paralyses climate action in industry. Deployment of CCS is too slow for the Paris Agreement goals, but policymakers[1] and industry actors are still relying on CCS in their projections of deep emission reductions and are consequently not investing as much in other mitigation options as would be needed if CCS were not part of the mix. At the same time, the few CCS projects that are happening are often insufficiently legitimised by the general public and parts of civil society.

This paper explores two narratives of the role of CCS in the Dutch industrial climate transition with the aim of describing an actionable, more unifying narrative that can clarify CCS's role in the Dutch climate transition. Qualitative system dynamics is used based on interviews with stakeholders and industrial experts in the Netherlands (with a focus on the Rotterdam harbour area, the country's largest industrial cluster emitting 17 % of Dutch GHG emissions) to identify the feedback and systemic mechanisms that drive the dynamics of CCS in the climate transition. The two selected narratives, "CCS as part of a just transition" and "CCS as contributing to carbon lock-in", can be seen as two extremes in the spectrum and are further explained in section 2.1.

Our contribution to the academic debate is an exploration into an alternative framing of CCS that takes into account the concerns expressed across the full spread of CCS narratives. We do this by unpacking the two extreme narratives of CCS in climate transitions through a system dynamics method (Forrester, 1961; Sterman, 2000) based on interviews with experts. Such an approach can reveal the substance of different viewpoints on CCS and elucidate how they interrelate and interact over time. A system dynamics approach is typically applied in settings where information from different stakeholders with different viewpoints needs to be synthesised (de Gooyert et al., 2016). The approach looks at many variables and their mutual interdependencies. In our research, this allows us to consider the richness of the various co-existing understandings of CCS and to explore the potential indirect (long-term, second/third order, non-linear) effects (of large-scale CCS) that are suspected to play a role.

After the conceptual framework and methodology (Section 2), we dissect the two juxtaposed narratives, uncovering the underlying mechanisms, which leads to an inventory of elements that comprise the two narratives in Section 3. We then, in Section 4, explore a potential CCS narrative that incorporates the concerns of both frames, we explain limitations of our research and provide recommendations for future research. In Section 5, we present the research conclusions.

[1] Global CCS Institute reported the global CCS readiness index in 2018. The index basically identifies the countries that are leading in creation of enabling environment and support for large-scale CCS implementation. By monitoring the progress of CCS deployment through a series of indicators, including poly development and legal and regulatory frameworks, the Global CCS Institute ranked Canada, USA, Norway, United Kingdom, Australia and the Netherlands respectively as the six leading countries that support large-scale CCS implementation (Havercroft and Consoli, 2018).

2. Conceptual framework and method

Our conceptual framework consists of carbon lock-in and just transition notions as overarching lenses to analyse our data. We accept both perspectives as legitimate and assume that with them, we cover most of the spread of relevant stakeholder views on CCS in industry in the Netherlands. We regard our data, two sets of interviews with experts, through those lenses and evaluate the dynamic mechanisms at work using system dynamics. We discuss the core concepts in our conceptual framework in more detail in Section 2.1. The data collection (interviews) are discussed in Section 2.2, and the data analysis method in Section 2.3.

2.1. *Carbon lock-in and just transitions*

Carbon lock-in has been defined as a path-dependent process whereby reinforcing feedback and increasing returns to the adoption of a technology act to inhibit development, deployment, and diffusion of possibly superior alternative technologies (Arthur, 1994, 1989; Seto et al., 2016; Unruh, 2000). In a mature technological innovation system, various structural components of the system, i.e. actors, institutions, and networks, align themselves with the incumbent socio-technical regime (Bergek et al., 2015; Malerba, 2002). It is argued that this leads to path dependencies (Arthur, 1994; Carlsson and Jacobsson, 1997) which, along with increasing returns to adoption of certain technologies, establishes a firm's vested interest of maintaining existing technologies. Any radical innovation that jeopardises this vested interest and stability encounters systemic problems by the interdependent structural components of the system, as explored for the concrete industry by Wesseling and Van der Vooren (2017).

Several authors have presented criteria to evaluate CCS's role in reinforcing carbon lock-in. Shackley and Thompson (2012), inspired by Collingridge (1992;, 1980), developed a list of organisational (including technical and social) indicators for this. They state that CCS will create an unavoidable technological lock-in, but it will not necessarily be a problem as long as CCS is kept as a flexible option. They argue that a problem emerges when the technology is designed inflexibly, deepening and thereby strengthening carbon lock-in. Vergragt et al. (2011) adapted Shackley and Thompson's framework in their research and presented a list of criteria to investigate how CCS may strengthen carbon lock-in. The criteria include: "Heaviness (including scale, infrastructure, capital intensity and lead time), interrelatedness among/between technologies, legitimation (including hyping, hubris and being closed to criticism), learning effects of users, producers, and other stakeholders (such as regulators and the public), expectations, and interests." To measure the risk of "fossil fuel energy CCS" locking out "bioenergy CCS" via their lock-in criteria, they applied the functional approach of the Technological Innovation System (TIS) framework (Bergek et al., 2008; Hekkert et al., 2007; van Alphen et al., 2009) to assess the factors influencing the development, diffusion, and deployment of these two technologies. They concluded that there is a risk of CCS strengthening carbon lock-in unless CCS is coupled with bioenergy rather than fossil fuel (Vergragt et al., 2011). CCS is also identified as a potential contributor to a carbon lock-in by making renewable-based electrification harder to realise as operations of these two technologies alongside in a single installation are in most cases incompatible (Janipour et al., 2020).

In contrast to the framing of CCS around carbon lock-in, CCS is also envisaged to have potential for making the climate transition more just. The term 'just transition' originates from a superfund for workers in toxic materials. Early on, its primary focus was on sustained employment for workers (Mazzochi, 1993). Later, the concept attracted the attention of trade unions, academics, and national and regional governments to understand what the meaning of just transition could be in the context of climate change, e.g. for coal transitions (Adams et al., 2016; Evans and Phelan, 2016; ILO, 2015; Simmons et al., 2018; Weller, 2019). More recently, the concept of a just transition has also been brought in connection with climate justice (Jasanoff, 2018; Okereke, 2010; Swilling et al., 2016). Just transition has been presented as a mobilising term for providing green jobs as an important element of the transition away from the fossil-fuelled economy (Heffron and McCauley, 2018). Newell and Mulvaney (2013) indicate equity and justice as the core of a just transition toward a low-carbon economy in which those who are currently living in energy poverty and the ones whose livelihoods depend on the fossil fuel economy will not be disregarded, and also indicate that the pursuit of climate justice for the current and future generations exposed to the negative effects of climate change is another key element. Linking environmental goals with social and economic development goals is at the core of a just transition. The notion of just transition has popularised as a result of a lack of attention to social justice in the process of moving towards a low-carbon future (Jasanoff, 2018). In that view, just transition should encompass *"a fair and equitable process of moving towards a post-carbon society"* (Heffron and McCauley, 2018), promoting distributional, procedural and restorative justice (Heffron and McCauley, 2018).

In the 'employment' framing of just transitions, CCS could be seen as a technology to help create and maintain jobs in fossil fuel industries in both the power and manufacturing sectors. It is argued that CCS could also create jobs in construction and maintenance as the required skills from both employees and companies relate to existing onshore and offshore industries (Patrizio et al., 2018; Swennenhuis et al., 2020).

Heuberger et al. (2017) argue that, if CCS reduces the total system cost of a low-carbon energy and industrial system, it could create opportunities for regions by creating productive industrial ecosystems. It is reasoned that in such regions, existing industries may reduce their emissions at relatively low costs through new low-carbon technologies such as blue hydrogen and carbon dioxide capture and utilisation (CCU). From a climate justice perspective, it is argued that CCS may help mitigate distributional impacts of the energy transition by lowering the cost of the transition (Zachmann et al., 2018), although that will depend on how it is implemented, especially as process- and justice-wise, CCS does not have a strong track record in the Netherlands (Brunsting et al., 2011; Terwel et al., 2012; van Egmond and Hekkert, 2015). CCS could further help by maintaining a level international playing field for industry, avoiding carbon leakage and maintaining industrial activity within regions (Swennenhuis et al., 2020), although funding would be needed to cover additional costs.

In general, what makes CCS attractive in the just transition framing is that it provides the possibility to continue using fossil fuels, and not scrapping existing infrastructure and social systems at great economic and social cost, while at the same time addressing climate change (Spreng et al., 2007). This argument is countered by the carbon lock-in narrative, which indicates that precisely this point will reinforce the carbon lock-in (Greenpeace, 2008; Spreng et al., 2007; Vergragt, 2012, 2009). It is argued that CCS creates a false sense of safety, directing the system onto a wrong path that will entail high sunk costs (Stephens, 2015). Depending on their lifetime, some of the future CCS projects might become stranded assets and thus increase the transition costs (Janipour et al., 2020).

2.2. Interviews

In order to explore the room for an alternative narrative between the diametrically opposed views on CCS as a carbon lock-in or CCS as an enabler of a more just transition, we have combined two existing sets of interviews conducted in the Netherlands, a country with a long-standing societal debate on CCS (Ashworth et al., 2015; Brunsting et al., 2011; De Best-Waldhober et al., 2012; Terwel et al., 2012). The total set of interviews comprises a variety of viewpoints on CCS. The interviews in both sets were semi-structured to allow interviewees to bring up and discuss any issues that they considered relevant for the realisation of the deep GHG emission reductions in the Dutch chemical and petrochemical industries. Table 1 shows the number of interviewees by interview set and the organisation type. The interview question lists of both interview sets are in Appendix 1.

Table 1
Number and organisational type of the 'Carbon lock-in' and the 'Just transition' interviews.

Type of organisation	Number of interviews (Carbon lock-in)	Number of interviews (Just transition)
Non-Governmental Organisation (NGO)	1	2
Industry association	2	1
Industry	3	2
Government	2	2
Public company[a]	1[b]	3
Research institute/ consultancy	2	2
Total	11	12

[a] The Rotterdam port authority.
[b] Three experts were present for the interview. One of these experts, a senior advisor, was also one of the interviewees in the 'Just transitions' set.

The carbon lock-in interviews were held at a time when a new government had just proposed ambitious CCS plans and a lively societal debate was taking place on CCS. They were held for a case study on carbon lock-in in the Dutch chemical industry, and the interviewees were asked questions about potential conflicts and discrepancies among different deep emission reduction options for the Dutch chemical industry. Because of the societal debate at the time (see below), CCS was discussed extensively by all interviewees (Janipour et al., 2020). The interviewees were identified from the invitation list of a July 2017 meeting of the Transition Path High Temperature Heat (THT2050) in The Hague (NL). The THT2050 was a consultation process organised by the Dutch government in 2017 to discuss the energy-intensive industries' contributions to the Paris Agreement goals. About half of the interviewees in this set had a relation to the Rotterdam harbour area.

The 'just transition' interviews were conducted as part of a comparative study on the role of CCS in a just transition in the Rotterdam area, Scotland and Norway (Swennenhuis et al., 2020). The Dutch interviewees were selected based on their roles in the national CCS debate. The Rotterdam area was chosen as the focus of this study as this region has been the CCS hub in the Netherlands and will be heavily affected (relevant for the justness of the transition) by industrial decarbonisation.

The interviewees for both sets were active in the national rather than the local debate, including the Rotterdam interviews. The reason is that the Rotterdam industrial area has large national significance in the Netherlands, as by far the biggest industrial cluster, including for the chemical and refining industries, which was the topic of the carbon lock-in interviews.

The interviews took place in November 2017 (carbon lock-in focused) and in July and August 2018 (just transition). The interviews were conducted eight months apart, but we did not note any influence of the time lapse on the narratives claimed by the parties. This is confirmed by several announcements and reports relevant to CCS released by different parties during that period of time. In October 2017, the coalition agreement 'Confidence in the Future' (Dutch Government, 2017) was presented, which raised much debate among CCS and industrial stakeholders because of the proposal to implement 18 $MtCO_2$ of CCS in industry annually by 2030. Because of this, all carbon lock-in interviews discussed CCS. In February 2018, the national government started negotiations for a national Climate Agreement (Dutch Government, 2019a). The negotiations took place for four months among representatives of the government, NGOs, industry and labour unions to implement the 49 % national GHG emission reduction in 2030 compared to 1990. The negotiations led to a draft Climate Agreement in July 2018 (Dutch Government, 2018). The draft presented CCS as an unavoidable but intermediate mitigation option. NGOs, however, emphasized their previous criticisms about reliance on CCS and expressed their concerns about CCS potential risks and negative consequences (Kalavasta, 2018). The positions of the diverse stakeholders (NGOs, industry, government) over the eight-month period spanned by the two sets of interviews were consistent.

The duration of the interviews varied between 30 and 90 min. The interviewees were either high-level managers or senior advisors. All interviews were recorded, transcribed, and sent to the interviewees for confirmation. To show diversity of interviewees, expressing the same idea on different topics, we gave each interviewee a unique number and added those numbers to the end of the associated quotations in the text in Section 3 and Appendix 2.

2.3. Data analysis

Following recommendations of Kim and Andersen (2012), we coded and analysed our interview textual data to develop a system dynamics model. We deviated from the original methodology suggested by Kim and Andersen (2012) by instead of taking a grounded theory approach, using previous studies to create the framework to code our interviews. The framework is presented in Table 2 and is based on (1), the main criteria applied by Vergragt et al. (2011) to investigate carbon lock-in effects of large scale CCS deployment, and (2), the findings of Swennenhuis et al. (2020) on what the contribution of CCS to a just transition could be. We made this change because the existing (though very recent and still developing) literature on the topics that we study allow for a deductive approach, where Kim and Andersen (2012) describe settings in which research is more exploratory and hence inductive.

To reduce bias, two interviews from the carbon lock-in set were coded independently by two researchers, including the interviewer of the set and another (non-interviewer) co-author of the research; two interviews from the just transition set were coded independently by the interviewer of that interview set and the same co-author who coded the two carbon lock-in interviews (non-interviewer). The codes were discussed among them to reach the same coding strategy. For all interviews, we coded any excerpts that could make a clear link within the theoretical frameworks of carbon lock-in and just transition described in section 2.1 and summarized in Table 2. The remaining 19 interviews were coded by the respective interviewer based on the same coding strategy. Some of the concepts and mechanisms of carbon lock-in and just transition narratives overlap or interact, which is highlighted in Appendix 3.

During the coding process, we identified main stocks[2] and their associated flows[3] (see Fig. 2), other relevant auxiliary variables and their causal relationships. Therefore, we derived individual causal links from different coded data segments (= the interviewees' arguments + the supporting rationales). Next, we transformed and visualised the text (data segments) into words-and-arrows diagrams within each theme. To give an example of such a process, the following data segment transformation into the words-and-arrows diagram is shown in Fig. 1.

> "*If you look at the cost per ton avoided (CO_2), it's a relatively good way to get rid of your CO_2.*" (Interviewee number 19)

In the next step, we applied axial coding to identify relationships between themes. In this step, all the words-and-arrows diagrams were generalised and merged into one stock and flow map to show the system structures and dynamics (this is presented at the end of the results section in Fig. 8). These stock and flow maps draw from the causal relationships as emerged during the interviews with experts, as well as from earlier studies on carbon lock-in and just transition. This integration allows for the development of a more comprehensive narrative that is in line with the expert interviews and embedded in existing knowledge. While the single causal relationships depicted in word-and-arrow diagrams still have a one-on-one relationship with the interviews, the integrated stock and flow maps discuss systemic mechanisms that go beyond the level of individual data sources. Appendix 2 shows the empirical foundation for the systemic mechanisms in the stock and flow maps for each mechanism, how it is supported by excerpts from interviews, as well as related earlier studies.

For the sake of simplicity and readability, we present the developed system dynamics diagram stepwise in Sections 3.2 and 3.3, explaining the carbon lock-in and just transition framings. While some illustrative quotes are included in the text in Section 3, a more comprehensive list of interview excerpts is shown in Appendix 2.

Table 2
Main themes to categorise codes relevant to the potential contribution of large scale CCS to carbon lock-in and just transition.

Groups	Themes
Carbon lock-in	Heaviness (including scale, infrastructure, capital intensity and lead time)
	Interrelatedness
	Legitimation
	Learning effects
	Expectations and interests
Just transition	Skills for a just transition
	Transition as opportunity
	Responsibility
	Scale of action
	Viability

Adapted from (Vergragt et al., 2011) and (Swennenhuis et al., 2020).

3. Results

In this section, we introduce the results in the form of a stock and flow diagram. We present the results of our analysis on the carbon lock-in narrative in section 3.2, and on framing CCS as a contributor to a just transition in section 3.3. We describe views of the interviewees and refer to one, some (2–6), several (7–11), many (12–17), most (18–22) and all (23) interviewees expressing a similar view on a certain topic.

3.1. The base stock and flow diagram and the systemic mechanisms

Our stock and flow diagram starts with four stocks (see Fig. 2). First, GHG concentration is fed by GHG emissions and leads to global warming. Sinks of GHG other than CCS are considered outside the scope of this study. Second, fossil fuel-based industries are one of the main sources of GHG emissions: investments that flow into fossil fuel-based industries lead to more GHG emissions. Third, we also include low-carbon industries with lower or zero GHG emissions: investments that flow into such industries leads to lower industrial GHG emissions. The fourth stock is the CCS capacity which abates GHG emissions and prevents a higher GHG concentration in the atmosphere.

The stock and flow diagrams depicted in this paper may be read as follows: each loop comprises variables connected by arrows indicating cause-effect relationships. A plus sign on an arrow means a change in the same direction: if variable A increases or decreases, variable B increases or decreases respectively as well (ceteris paribus). A minus label on an arrow means change in the opposite direction, thus if variable A increases, variable B drops, and if variable A drops, variable B increases (ceteris paribus). The sign "R" in the middle of a closed circle of causal relationships indicates the reinforcing characteristic of the loop, or a "B"

[2] In system dynamics modelling, stocks represent states of the system that may be changed, accumulated or depleted, by the actions of flows.

[3] Flows are the entities changing the states of the stocks over time.

Theme	Cause	Effect	+/-	Words-and-arrow diagrams
Viability	Cost CCS	Investments in CCS	-	[Cost CCS -→ Attractiveness CCS +→ Investments in CCS]

Fig. 1. An example of words-and-arrows diagram of causal arguments extracted from the analysis of the interviews.

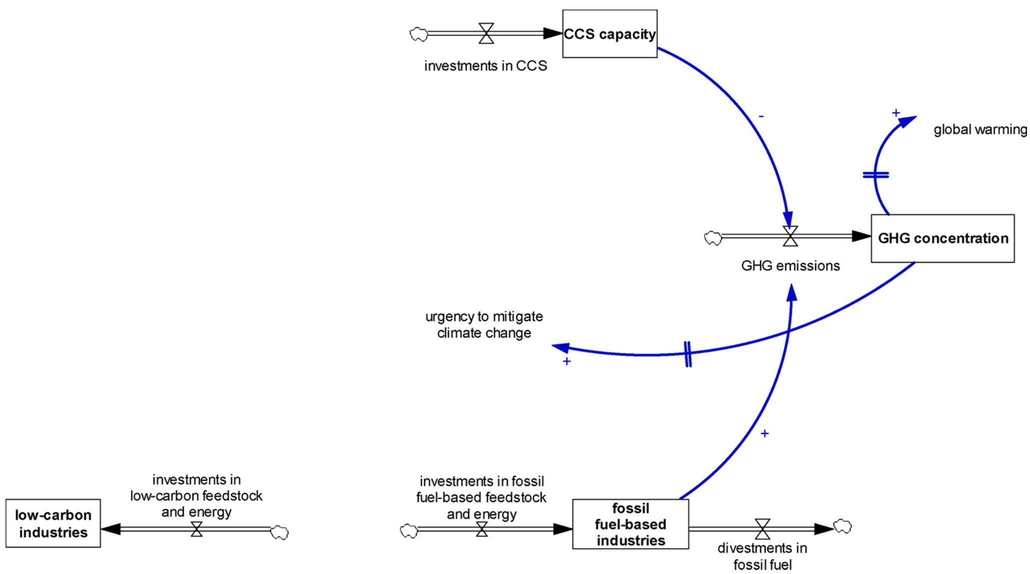

Fig. 2. Three main industrial contributors in the volume of GHG concentration. These main stocks change by their associated in- and outflows. Legend of the diagrams: 1) stocks are shown in rectangles. 2) Flows are depicted as double lined black arrows with one end connected to a stock and another end connected to a little cloud that can be either a source or a sink. 3) A source is shown as a little cloud where a flow originates from (outside the model). 4) A sink is shown as a little cloud where a flow sinks (outside the model). 5) Thick blue arrows show new added causal links between two variables. 6) Double lines perpendicular to the arrows indicate a substantial time delay in that causal relationship.

indicates the balancing characteristic of the loop. The following diagrams can be read as follows: 1) Stocks are shown in rectangles. 2) Flows are depicted as double lined black arrows with one end connected to a stock and another end connected to a little cloud that can be either a source or a sink. 3) A source is shown as a little cloud where a flow originates from (outside the model). 4) A sink is shown as a little cloud where a flow encounters the boundary of the scope of our study (outside the model). 5) Thick blue arrows show new added causal links between two variables, compared to the previous diagram. 6) Double lines perpendicular to the arrows indicate a substantial time delay in that causal relationship.

The results of the interview analysis following the themes in Table 2 and the stock-and-flow diagramming as introduced are consequentially converted into systemic mechanisms for the carbon lock-in and just transition narratives, which form the structure of Sections 3.2 and 3.3, and which are the relations added to the system dynamics diagram as it develops into Fig. 8. The systemic mechanisms for carbon lock-in are the crowding out mechanism, the legitimising mechanism and the integration mechanism. Those for the just transitions narrative are the employment mechanism, the economic effects mechanism, and the environmental effects mechanism.

3.2. CCS strengthening carbon lock-in

The potential of CCS strengthening carbon lock-in will be discussed across the three themes of crowding out, legitimising, and integration. The carbon lock-in mechanisms are driven by reinforcing feedbacks, where an initial investment in CCS makes it more attractive to invest even more in CCS in the future.

3.2.1. Legitimising mechanism

The first argument expressed by several interviewees for the role of CCS in strengthening carbon lock-in was that CCS will legitimise the fossil fuel-based industries and therefore fossil fuel consumption: *"For certain industrial processes with current technology there is probably a good user case. CCS on Steam-Methane Reforming (SMR) for example. That will give it a 10, 15, 20 years social license to operate."* (19) Some interviewees indicated that CCS is an end of pipe solution, and that CCS operates as a means to perpetuate current fossil fuel production. It may result in a situation where the emitters will only apply the easier option that is CCS and will not deploy the more difficult but more sustainable low-carbon options. One interviewee mentioned that NGOs have concerns that CCS will reduce the pressure (urgency of radical emission reductions) on fossil fuels production and consumption: "*some NGOs have some doubts that they go on with the fossil fuel system if we use CCS.*" (12) Fig. 3 depicts the balancing feedback mechanism that fossil fuel-based industries encounter. In this figure, it is shown how CCS helps the fossil fuel-based industries to reduce its emissions and consequently legitimise its continued production. The carbon lock-in effect in this case comes from the CCS that weakens the balancing effect that would otherwise help to shift away from fossil fuels. Via the legitimising effect, investments in CCS may lead to increased legitimacy of fossil fuel-based industries, therefore to more investments in fossil fuel production, which increases reliance on CCS even more. The legitimacy that CCS could bring for fossil fuels may increase attractiveness of fossil fuels, negatively influencing the relative attractiveness of low-carbon options for investors.

3.2.2. Crowding out mechanism

Several interviewees contemplated that large scale CCS implementation would crowd out other low-carbon options, especially electrification[4] . Stressing the scarcity of financial resources to mitigate climate change effects, one of the interviewees flagged that there would

[4] Our reflection on why only the CCS/electrification trade-off was brought up in the interviews is that it may be relevant to the new Government Agreement that came out in the period when interviews were done. The Agreement had a proposal to implement 18 MtCO_2 of CCS in industry per year by 2030 (Dutch Government, 2017). That sizeable amount raised discussions among actors and that may have dominated the thoughts of the interviewees at that time.

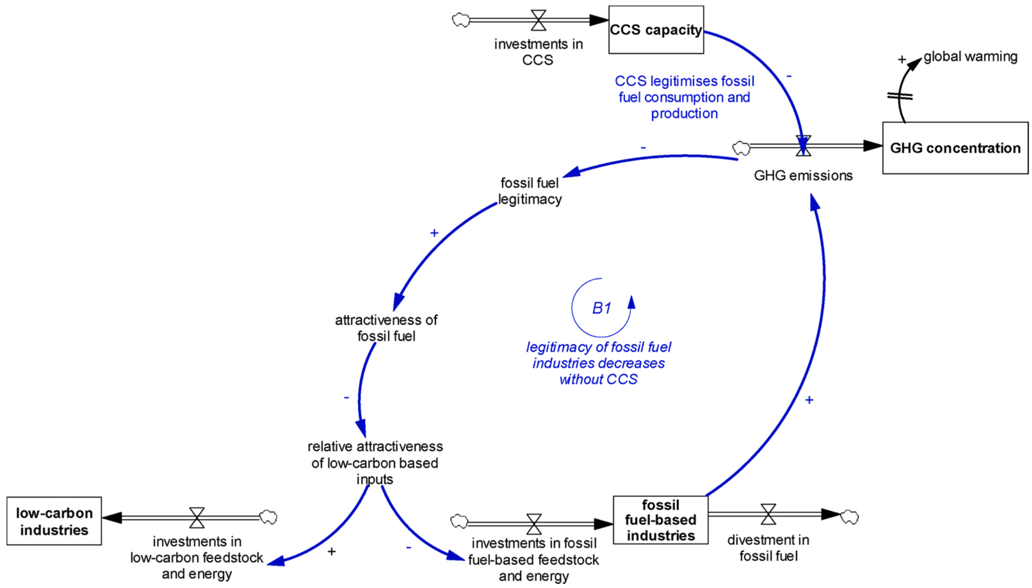

Fig. 3. Large scale CCS may legitimise fossil fuel production as it can abate the associated emissions. by storing it underground, leading to increased fossil fuel production/consumption and more reliance on CCS to abate CO_2 emissions. (For the diagram legend, see Fig. 2 caption).

be a trade-off between investing in CCS and in renewable-based electrification: *"CCS costs billions and it's an end of pipe solution .... I would then rather spend billions on the hydrogen solution and then you have solution for the next generations. And you can only use your money once ... It prevents using the same money for real industrial innovations, so I think CCS is preventing larger investments in the things we really need to do. So, it slows down innovation."* (1) The crowding out mechanism of CCS on electrification was also elaborately explained by another interviewee, describing the situation where development of CCS comes at the cost of progress in renewable electricity production and lowering the speed of the innovation required to drop the costs of renewable electricity: *"On the more macro scale of course if we would move too quickly to CCS and we would not make sufficient progress in developing the electrification path, both in terms of arranging for sufficient supply of affordable electricity on the one hand and doing enough innovation and bringing down the cost of, let's say, electrolysers of water to produce hydrogen from water rather than natural gas then you get some kind of lock-in, then you would stick with CCS much longer than needed."* (4) Some interviewees raised concerns on allocating (a part of) current subsidies on renewable energy to CCS implementation.

The crowding out mechanism has knock-on effects: it would hinder progress in learning curves[5] of other low-carbon options, hamper cost reductions and decrease the speed to market for those technologies. This situation can consequently bring "success to the successful" and result in more reliance on CCS to cut the emissions. This constellation of reinforcing mechanisms is shown in Fig. 4. The crowding out mechanism comprises three learning curves that are in competition with each other: 1) investments in CCS will lead to innovations in CCS and therefore increase the attractiveness of CCS compared to other mitigation options, 2) implementation of CCS will decrease GHG emissions, lowering the urgency to mitigate climate change, which may result in increasing attractiveness of investing in fossil fuel-based industries, leading to more innovation in fossil fuel-based industries, 3) and the learning that takes place on CCS and fossil fuel-based industries may crowd out learning that the same investments could have generated for the low-carbon options instead.

As the main counterargument of the crowding out mechanism, several interviewees indicate that CCS is an intermediate option which will not stand in the way of electrification as there are investments on both CCS and electrification because both technologies will be needed. This argument may refer to the depth of lock-in explained by (Shackley and Thompson, 2012) and (Vergragt et al., 2011) in a way to imply a shallow depth for the potential lock-in caused by large-scale CCS implementation, but due to the uncertainties about the real capacity and scope of CCS projects in the future, it is not certain that such a carbon lock-in will be shallow enough to be escapable.

3.2.3. Integration mechanism

The third main carbon lock-in argument in the interviews pointed at the integration mechanism. Some interviewees stated that CCS is envisioned as the main technique to make blue hydrogen production possible: "*In the short-term, medium-term, hydrogen production, that's where you would apply CCS ... of course you can make hydrogen from electrolysis but you cannot wait for it*" (3). Several interviewees explained that CCS integration with fossil fuel-based hydrogen production (blue hydrogen) may not only increase the legitimacy of CCS applications but also raise switching costs to other, low-carbon options, particularly electrification, that cannot be integrated with fossil fuel-based systems. One of the interviewees framed it as follows: "*if you say OK, we have hydrogen production and we add a CCS installation then it will be harder for the coming years to say OK we stop that*" (12). Fig. 5 shows how the integration reinforcing mechanism works: investments in CCS could lead to more integration with fossil fuel-based industrial processes, decreasing attractiveness of the low-carbon options that cannot be integrated with the fossil fuel-based system. Then the main option that can abate fossil fuel-based industry's emissions would be CCS, increasing reliance on CCS.

3.3. The role of CCS in a just transition

The role of CCS in a just transition in the Netherlands will be discussed across three themes: employment, economic effects, and environmental effects. Justness of the transition in the diagrams of this section is a variable that can be influenced, whereas carbon lock-in is inherently an outcome as a result of feedback mechanisms, driven by a number of variables.

3.3.1. Employment

Interviewees were asked how the energy transition might affect

[5] Increase in learning of something (e.g. a particular technology) that comes from gaining the greater experience in that thing.

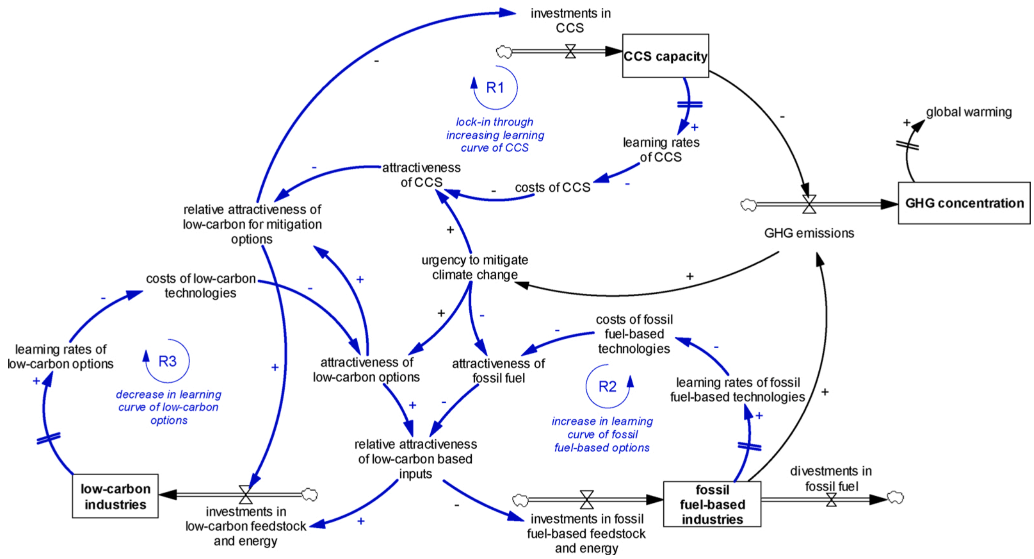

Fig. 4. Large scale CCS implementation may lead to lower learning rates for low-carbon options, and increase reliance on CCS deployment. (For the diagram legend, see the Fig. 2 caption).

employment in the Rotterdam area reliant on emission-intensive industries. Some interviewees did not think job loss in the industry, specifically in the Netherlands, would be a problem; while jobs may disappear, new jobs will be created. Some interviewees even expected a net gain in jobs, partially related to innovation activities. When asked about CCS specifically, it was recognised by some of the interviewees that technical skills in the fossil fuel-based industry are directly linked to anything CCS related and CCS could extend the lifetime of certain industries and make the transition more gradual *"CCS should mainly smoothen the loss of jobs in the fossil fuel industry."* (19) Emphasising the compatibility of technical skills in the fossil fuel-based industry with competences required for CCS, one interviewee added that *"if there is an industry that is able for example to cope with CCS in a very good manner that it should be the oil company, I think we are better equipped than the power companies to do that … So if you focus on CCS, the oil industry has a lot of qualities and engineering qualities which you require."* (2) This may have a positive outcome on job creation or at least it could help the fossil fuel-based industries to avoid job loss. Some interviewees did not believe that CCS and the related jobs are temporary, at least not for the foreseeable future.

When the interviewees were presented with examples of the closure of other industries (either the closure of coalmines in the past in Limburg, or the highly fossil fuel dependent areas such as Aberdeen, Scotland), some interviewees gave two major reasons why this probably would not happen in Rotterdam. Firstly, the industry in the Rotterdam area is very diversified: *"I think the situation in Rotterdam is different, because there are many types of industry and employers, as well as secondary and tertiary activities around that… It's not just a single coalmine or something."* (20) And secondly, the industry is highly capital intensive, rather than labour intensive: *"In all honesty, I worked at [energy company] for 5 years, and all there is at Maasvlakte 3 is a control room and 7 operators … However, in terms of capital expenditure (CapEx), the new coal plants cost*

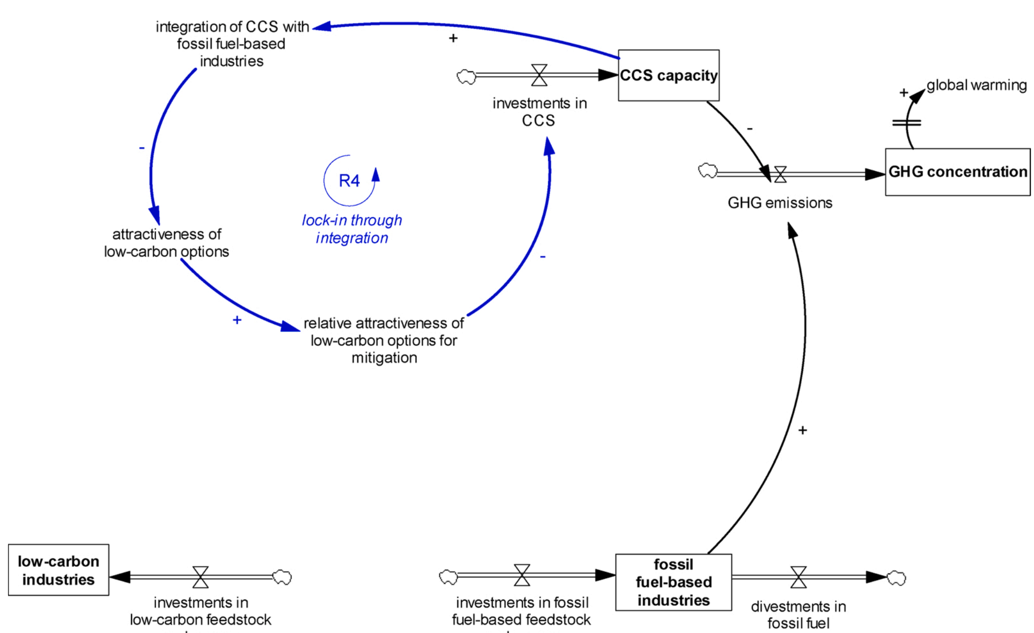

Fig. 5. More investments in large scale CCS may lead to more integration with the incumbent systems, lowering attractiveness of the other low-carbon options that cannot be integrated with the incumbent system. (For the diagram legend, see the Fig. 2 caption).

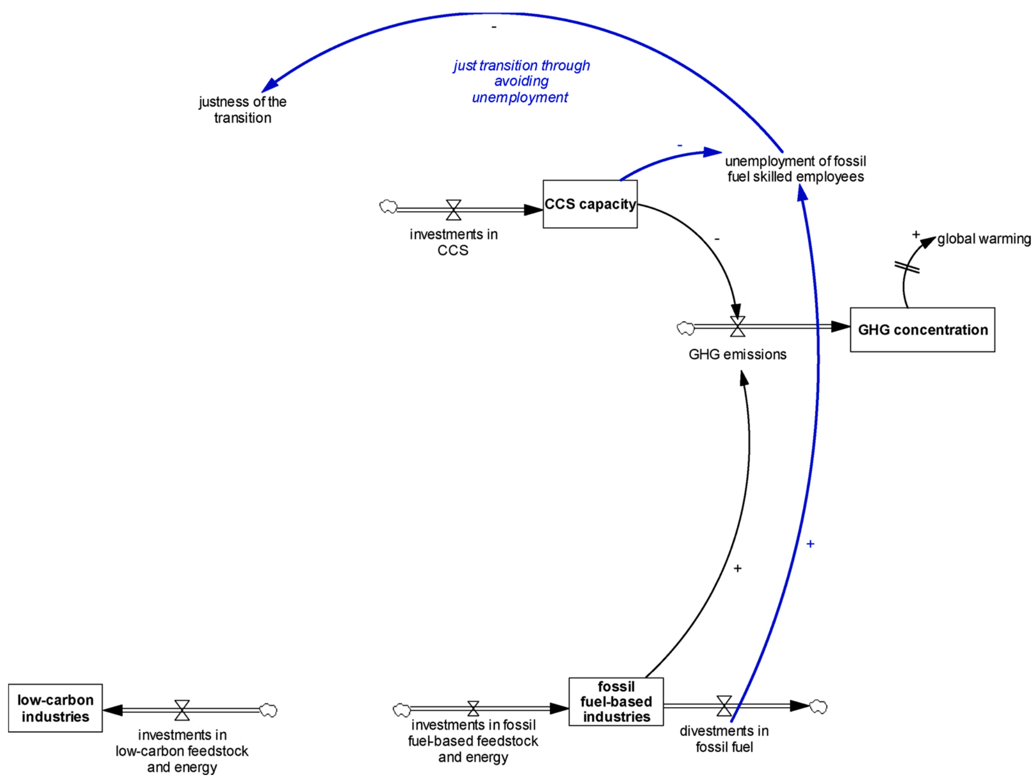

Fig. 6. CCS may make a small contribution to avoid job losses in fossil fuel-based industries (in the Rotterdam area, the Netherlands). (For the diagram legend, see the Fig. 2 caption).

insane amounts." (15)

Fig. 6 shows the mechanism through which CCS may help preventing job loss, even though our results indicate that this effect may be small in the Netherlands, particularly in the Rotterdam area. The mechanism explains that in case of divestments in fossil fuel-based industries, the workers will be unemployed, and this decreases the justness of the transition. In general, investments in CCS may help avoiding vast job losses in fossil fuel-based industries. It may even provide new CCS related jobs to those fossil fuel skilled workers who will become unemployed as a result of unavoidable divestments in fossil fuel industries.

3.3.2. Economic effects

The idea that CCS might be beneficial for the economy is predicated on the same reasoning as why it might cause carbon lock-in; it allows for continued operation of the fossil fuel-based industries. Whereas, without CCS, parts of the industry may disappear in the transition to a sustainable future, along with their economic benefits. Several interviewees also mentioned other ways in which it might have an impact on the economy. One elementary reason that was given was that CCS may be considered as a relatively cost-effective method to reduce emissions in the industry, therefore helping to lower costs of the transition.

Some of the interviewees explained that the Rotterdam industrial area was recognised as an area with unique advantages because of the location close to well-characterised storage reservoirs for CO_2 and a large number of stationary industrial point sources of CO_2 in close geographical proximity. The creation of a CCS network could in that sense add to an attractive industrial ecosystem by allowing existing and new industries to easily connect to a CCS network for relatively cheap emission reductions: *"We think that for clustered industry, CCS can offer an advantage."* (16) Considering CCS as an economic opportunity, some interviewees pointed to the financial gains that the owners of empty gas fields (as potential CO_2 storage sites) can incur: *"The people managing these gas fields are very happy that they can extend the life time of their assets there."* (6)

Some interviewees addressed potential negative impacts on employment and economic benefits of the port of Rotterdam on a macro level, if the transition is mismanaged. However, it was mostly argued by the same interviewees that the energy transition is an opportunity. In addition to the current benefits the area offers as the largest harbour and industrial complex of Europe, CCS specifically was envisaged by the same interviewees to be a key part of an appealing industrial ecosystem by providing the infrastructure for relatively cost-effective GHG emission reductions; they indicated that the Rotterdam harbour could be a hub for CO_2 storage, receiving shipments of CO_2 from locations without close access to viable storage.

Fig. 7 displays the three mechanisms through which CCS may support regional economic development and help avoiding regional economic loss. More investment in CCS may lead to further utilisation of the depleted gas fields and the development of related innovations. This may increase attractiveness of regional industrial investments, therefore helping the just transition by avoiding regional economic downturn as a potential result of the energy transition. In addition, CCS may decrease the costs of the transition, as it may be lower-cost than other low-carbon industrial options. The lower costs of the transition may impose a smaller economic burden on producers and especially consumers, and therefore contribute to a just transition.

3.3.3. Environmental effects

The direct environmental benefits of CCS were explained by many interviewees; it can be used to reduce industrial CO_2 emissions. In general, several interviewees perceived CCS as an intermediate term mitigation option but vital to reach the emission reduction targets. *"You need to do something now because there is this carbon budget and we already running very close to the limit … It is most likely a temporary measure as in a way industry involves you cannot live without it, because if you do not apply it you are running out of the time"* (3). However, one interviewee has concerns about risks during transport of CO_2 as well as long-term storage risks such as leakage. *"There are cracks in the Sleipner project according to*

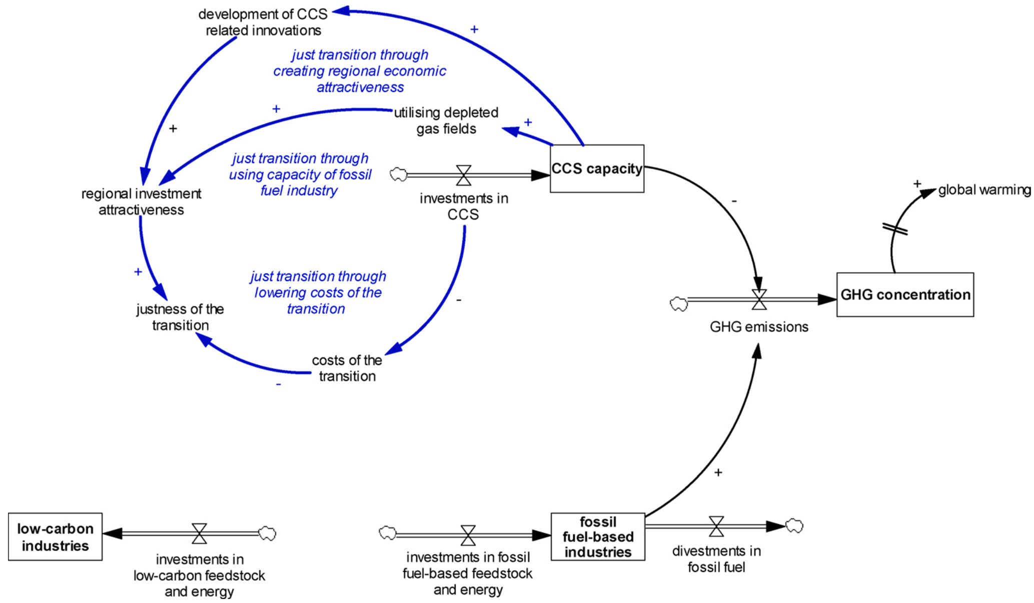

Fig. 7. CCS may provide regional economic opportunities, mainly in exploitation of CO_2 storage reservoirs. (For the diagram legend, see the Fig. 2 caption).

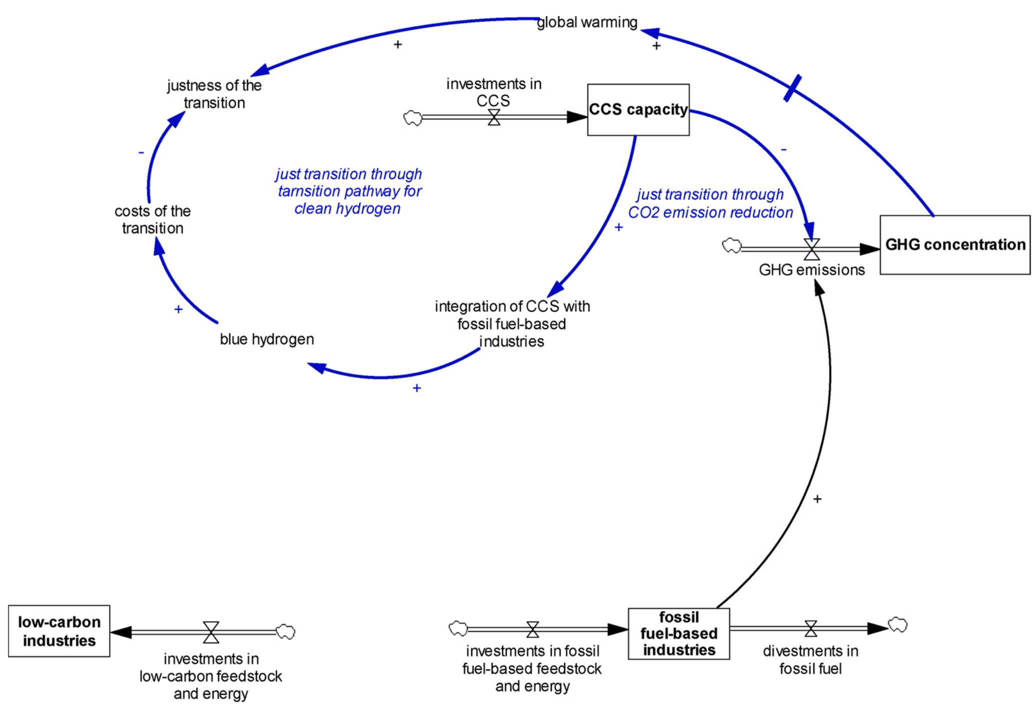

Fig. 8. CCS can be used to reduce industrial CO_2 emissions. In addition, integration of CCS with fossil fuel-based processes may facilitate clean hydrogen production and could lower costs of the transition and increase justness of the transition. (For the diagram legend, see the Fig. 2 caption).

a Nature article[6]*. No leakage has been found yet, but scientists say there will probably be some leakage"* (23). Though many interviewees are in agreement that CCS will play a key role in reaching the deep emission reduction target as other low-carbon options such as electrification are not yet available at scale, several interviewees flagged the risk of potential carbon lock-in and the necessity to avoid it: *"CCS is a transition technology…it is just an intermediate step in order to reduce emissions as quickly as possible because that's important. It is the carbon budget that counts in the end. But we must do it in a way in which we are working on moving to the next stage as well."* (4)

Some interviewees indicated that CCS is seen as a stepping stone on the way to green (electricity-based) hydrogen production. The current dominant hydrogen production method (SMR) produces a pure CO_2 waste stream, making CCS relatively cost-effective to produce 'blue' hydrogen. It is argued that this blue hydrogen could support the development of hydrogen infrastructure and knowledge for an eventual switch to green hydrogen: "*we need the hydrogen, and hydrogen from grey to blue to green hydrogen is kind of a transition pathway. CCS will need to play a role there. So in that sense, it will enable the chemical industry to decarbonise faster if we apply CCS*" (14). The same infrastructure could

[6] https://www.nature.com/news/seabed-scars-raise-questions-over-carbon-storage-plan-1.14386 (Monastersky, 2013).

also aid the development of CCU. In addition, it was mentioned by one interviewee that CCS is considered to be one of the main options for large-scale negative emissions. It is reasoned that CCS infrastructure may enable the development of other technologies that reduce GHG emissions such as blue hydrogen and expansion of CCU.

The mechanisms in Fig. 8 represent that investments in CCS will lead to a decline in CO_2 emissions, resulting in a lower atmospheric CO_2 concentration. The next mechanism explains that investments in CCS could also increase integration of CCS with other fossil fuel-based processes and facilitate the transition towards cleaner hydrogen production, leading to lower transition costs, thus increasing justness of the transition. The final argument for the contribution of CCS to a just transition is the same as the one used to argue that CCS may reinforce carbon lock-in by the integration mechanism.

4. Discussion

4.1. Addressing carbon lock-in and just transition

The systemic effects of large-scale CCS implementation are strongly debated in society and academia. According to the results of our interviews, three feedback mechanisms of crowding out, legitimising, and integration feed the arguments against CCS, explaining the claims on the potential role of CCS to strengthen carbon lock-in. In this framing, it is envisaged that the deployment of large-scale CCS in itself may lead to more CCS deployment that reinforces carbon lock-in. Once CCS is implemented at a large scale, it exhibits increasing returns to the adoption of CCS, which along with firms' vested interests may motivate actors to put more emphasis on CCS and less on other, more transformative options needed for the climate neutrality targets. On the other hand, the pro−CCS arguments are narrated in a way that CCS will contribute to a more just transition through three mechanisms of employment, economic, and environmental effects. The hypothesis is that the availability of CCS could mitigate fears of losing fossil fuel-based employment and economic competitiveness in a fossil fuel-dependent region, allowing time for the climate transition. While the contribution of CCS to avoid job losses and to create new jobs may be small in the Rotterdam area, it could play a role in other regions (Swennenhuis et al., 2020).

The lack of available data on transition plans of the Dutch energy-intensive industries makes it difficult to quantitatively triangulate the interviewees' perspectives and the mechanisms around large scale CCS implementation. We therefore only contrast our results with other case studies on carbon lock-in or just transitions of CCS. Shackley and Thompson (2012) investigated Research and Development (R&D) budgets for different energy technologies in the USA and Norway between 2000 and 2009. They concluded that while CCS R&D budgets had risen (for the period up to 2009), there was no evidence that CCS was substantially diverting R&D sources from other technologies, particularly renewable energy. However, R&D budgets have limitations as an indicator for assessing the potential crowding out effect, as the main rival technologies are already mature and require investments for demonstration, scale up, and deployment (based on our interviews), where the investments are larger and the competition for finance and public funding is fierce. It needs to be anticipated that CCS would result in a crowding out effect as high sunk costs and learning effects of large scale CCS projects may deter industry to invest in alternative low-carbon options, and there is competition for the same government funding and green financing sources (Dutch Government, 2019b). Implementation of CCS, like many other mitigation options, relies on government support or facilitation, implying that a government climate policy plan could incorporate safeguards to prevent CCS reinforcing carbon lock-in. For example, the Dutch government can make the subsidy allocations conditional on industry's actions on transformations in the longer run. If the crowding out mechanism is avoided, the legitimising mechanism may also be disabled as the alternative technologies' costs go down, their learning effect increases and they may become more attractive than the incumbent.

Vergragt et al. (2011) have warned about the role of CCS in creating a reinforced carbon lock-in. They presented Bio-Energy with CCS technology (BECCS) as the main way to escape such lock-in. However, they also flagged a potential BECCS lock-in in the future when CCS creates legitimacy for biomass use and reinforces the bio-based system in the same way as it does for the fossil fuel system. If CCS, also as part of BECCS, is envisioned to be part of the climate change mitigation portfolio and a facilitator to a just transition, it is vital that the government designs policy instruments in a way that CCS operates only for a certain period of time and that the storage capacity is put to the best possible use.

4.2. An alternative narrative: CCS as a regulated breathing space

Both narratives show the importance of understanding how industry can move from one set of carbon lock-in mechanisms to the next step of the transition towards a fully climate-neutral industry while ensuring maximum justness of the transition. To bridge the two extremes, an alternative narrative would need to emphasise the commonality in the need for realising a climate-neutral industry in the next thirty years, and the necessity of aligning interests to reach this climate neutrality goal. We do this by merging the feedback and systemic mechanisms in carbon lock-in and just transitions below (see Fig. 9).

This alternative narrative has as starting points that the costs of the transition are very high in case only renewable and low-carbon feedstock and energy are considered, but that those are the main and most desirable mitigation options. Such high costs negatively influence the justness of the transition, in other words, the higher the costs of the transition, the lower the justness of the transition for different stakeholders, including producers and consumers of industrial products. As the justness of the transition decreases, resistance against the expensive transition increases. As a result of such resistance against the whole transition plan, investments in low-carbon options could decline, leading to lower and slower learning effects for all low-carbon options and therefore the costs of large-scale low-carbon options remain high. In this situation, cheaper options such as CCS might be more attractive than the low-carbon options, therefore more investments in large-scale CCS implementation can be expected (see feedback loop B2 in Fig. 9).

In this narrative, CCS is expected to provide an in-between option, between a) a radical change, replacing all fossil fuel-based industries by low-carbon industries or b) no change at all because the powerful fossil fuel-based industries resist and the transition costs are too high. Therefore, this alternative narrative shows that CCS, through a well-managed transition, may make it possible to align interests to get the fossil fuel-based industries on board for the climate transition and allow for a slowly paced fossil fuel phase-out.

This phase-out is possible through a balancing mechanism. More investments in CCS would result in lower transition costs, which could lead to an increase in the justness of the transition and consequently less resistance against the whole transition. As a result of lower resistance to the whole transition, space emerges for more investments in alternative low-carbon options, accumulating the learning for such options over time and lowering the costs of their large-scale implementation. If there are both CCS and low-carbon-based capacities, and investments have been made, in a 'spot market' situation, the operational costs of CCS versus those of renewable electricity for blue or green hydrogen production may imply that CCS will be used less. Fig. 9 displays the balancing feedback mechanism B2 through which interests of the opposing groups may be aligned.

The alternative narrative we present tries to offer a 'mental model' about the carbon neutrality transition in which interests of climate advocates, industry, and society are aligned, and the aims of one group do not oppose other group's interests. The balancing feedback loops that limit the feedback mechanisms enhancing CCS through the justness of

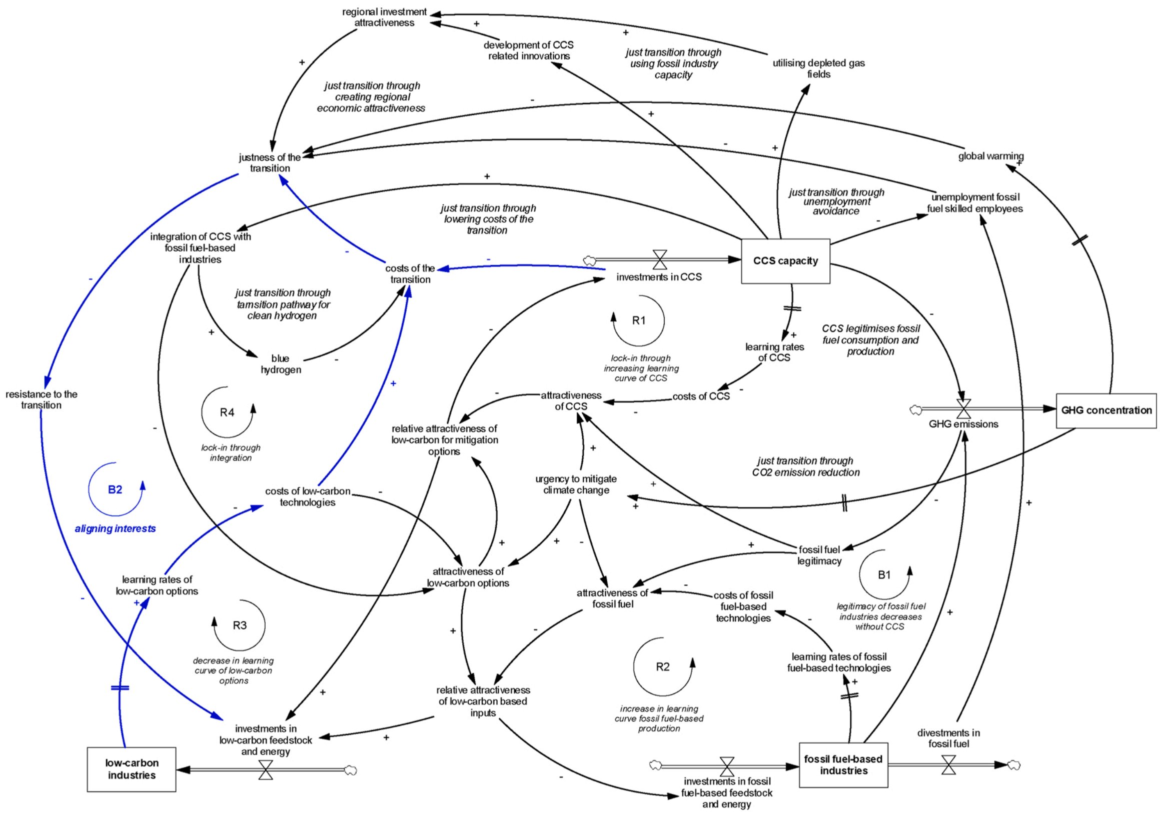

Fig. 9. Balancing feedback mechanism through interest alignment of CCS stakeholders (in blue). CCS may lower the costs and resistance for the transition. This may lead to more investments in low-carbon options over time and lower their large scale costs. (For the diagram legend, see the Fig. 2 caption).

the climate transition is in line with a shallower carbon lock-in as a useful step towards a fully sustainable system (Shackley and Thompson, 2012).

The alternative narrative hinges on whether the resistance against transition decreases as a result of lower costs of transition via applying CCS, and whether this would lead to more investments in low-carbon options, and this is where the public sector comes in. To make sure that support for the climate transition is translated into investments in low-carbon options for industry other than CCS, the public sector could consider policies like a portfolio obligation or a CCS ceiling.

Further, it is vital to consider CCS as a breathing space whilst other low-carbon options are supported to get fully market-ready for replacing CCS. Via a mismanaged energy transition, large-scale CCS may sustain CCS and an associated industry for many years to come (Asayama and Ishii, 2017), forming a vested interest that makes it difficult to take steps towards realising a zero-carbon, fossil fuel-free, or negative-emission economy. Another crucial part of a viable narrative, therefore, is that CCS needs an exit strategy to prevent vested interests from taking root. Policy instruments could be designed in a way to make sure that the costs of overuse of CCS outweigh the gains. For instance, as an exit strategy, the government can specify a timeline for the number of years CCS can be used as a mitigation option, and after that period captured CO_2 by CCS may not be accounted as abated emissions and levies could be charged.

4.3. Limitations of our research

We discuss several limitations to our study: the use of two interview sets, the time gap between those interview sets, and the geographical orientation. We also reflect on the generalisability of our results. First, as the data were taken from two earlier projects, the interview sets each had its own interview guide, and distinct people (except for one). This means almost half of the interviewees were guided to address carbon lock-in-related questions and the other half were guided towards just transition questions. This difference was resolved by common coding, but is still limiting the consistency in the methodology and therefore the robustness of the results. Using the same interview guide could also have enabled the exploration of more narratives beyond only carbon lock-in and just transition. The robustness of the findings would increase if the same interviewer team could interview all the interviewees with a same comprehensive interview guide, including both carbon lock-in and just transition questions explicitly.

Second, the time gap between the two sets of interviews could have impacted the results. We checked whether the events in that period of time had any influence on the viewpoints and narratives presented by stakeholder groups, and did not find any difference. However, without systematic research to prove such consistency, we cannot fully exclude the possibility that there might be time-related influences. Therefore, we acknowledge that the time gap between our interview sets is a limitation to our research.

Finally, going beyond the Rotterdam area for the just transition interviews would have enabled a more holistic view for the country.

Our findings are not generalizable as narratives on large-scale CCS depend on the regional context, as demonstrated by Swennenhuis et al. (2020). It is expected that in regions relying on fossil fuel-based industries with limited means to shift to non-fossil fuel industries, some of the mechanisms underlying the carbon lock-in narrative, such as integration, would not be brought up at all. So, such narrative analysis is more accurate if it is regionally or nationally focussed. Future research could continue to compare the results of regional analysis and investigate the possibilities of merging the narratives, could collect more empirical data and quantify the feedback loops identified, and could design policy instruments aimed at avoiding the potential CCS carbon lock-in while making the climate transition just.

5. Conclusion

In this study, we systematically analysed and unpacked two narratives, CCS as a carbon lock-in and as contributing to a just transition. Using 23 interviews in two sets, we identified six mechanisms that are envisaged to impact the potential systemic effects of CCS in the climate transition. We presented our results in the form of feedback and systemic mechanisms.

CCS may hinder the transition by reinforcing the existing carbon lock-in because investments in CCS could crowd out investments in other low-carbon alternatives, because CCS may legitimise the continuation of the fossil fuel-based industries, and because integration of CCS with other fossil fuel-based technologies (e.g. hydrogen production) make more radical changes costlier. CCS may contribute to a just transition by sustaining economic activities that would otherwise be lost, and by providing an intermediate technology to avoid CO_2 emissions from ending up in the air. CCS may also support a just transition through avoiding the job loss that would otherwise accompany phasing out the fossil fuel-based industries; however, our findings showed that CCS would have limited impact on employment in the Rotterdam area.

The narratives against and for CCS reflect contradicting views on the transition pathway to a low-carbon energy system, but both are characterised by a similar set of mechanisms strengthening carbon lock-in and contributing to a just transition. This means that there could be a zone of possible agreement.

We present an alternative framing of CCS by taking the different mechanisms into account and combining them. The focal point of this alternative narrative is the alignment of interests among parties on the path to climate neutrality. The main concrete recommendation is that policy instruments need to ensure that CCS only leads to a shallow carbon lock-in and that the industry remains flexibile in terms of options to reach climate neutrality. This can be done by keeping CCS as an intermediate mitigation option that will be phased out based on a specified time frame. In addition, the government needs to ensure that the development and deployment of CCS will not stand in the way of low-carbon options to become market ready. This can be done by making sure the investment in CCS is more than matched by investments in non-fossil fuel climate-neutral options.

The results of our analysis improve our understanding of the conditions for avoiding the negative and fostering the positive effects of CCS.

Role of the funding source

A part of data used for this research has been obtained from the work conducted as part of the ACT ACORN Project, which aimed to work towards delivering a low-cost carbon capture and storage (CCS) system in the North Sea by 2023.

ACT Acorn is funded by the Accelerating CCS technologies (ACT), the grant ID is ACT 691712, co-fund of ERA-NET under the Horizon 2020 programme. ACT comprises nine countries and the European Commission, who have collaborated in making funds available for CCS research and innovation. Our project has received funding from BEIS (UK), RCN (Norway) and RVO (The Netherlands).

The ACT Acorn consortium is led by Pale Blue Dot Energy and includes Bellona Foundation, Heriot-Watt University, Radboud University, Scottish Carbon Capture & Storage, University of Aberdeen, University of Edinburgh and University of Liverpool.

CRediT authorship contribution statement

Zahra Janipour: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Floris Swennenhuis:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Vincent de Gooyert:** Methodology, Investigation, Writing - review & editing, Software, Visualization. **Heleen de Coninck:** Conceptualization, Methodology, Investigation, Writing - review & editing.

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.

Appendix 1 Interview questions of the carbon lock-in and the just transition interviews

Interview set	Interview questions
Carbon lock-in	- Please explain what is your view on what the Dutch chemical industry is doing now for GHG emission reductions? - How do you envision the Dutch chemical industry in 2050? - What could be (or what is your company plan for) the lower-carbon measures to go beyond the current emission cut? - Where do you think discrepancy emerge? - Do you think they are technically compatible to be applied in the system? If changes are required, what would be the extent of change? - How would radical and intermediate options affect the energy efficiency of the process or how would those options affect energy intensity of production? - How about their impacts on total cost (euro) of production (per tonne of product)? - In terms of resource mobilisation, what type of resources do you think would be essential to implement the radical and intermediate options? - Do you think the resources are available? - What funding resources could be expected? - Do you think, if the resources were available, the actors (especially the chemical industry) would showed their willingness to pay? - Do you see any growth in the number and scale (in Euro or in % of total turnover in the sector) of R&D projects for radical and intermediate options since 2005? - How do you perceive the actors' willingness to participate in sharing knowledge and building networks? - Is there any research workforce (specialist in radical and intermediate options) in the chemical company? - How do you find entrepreneurial experimentation in the current chemical industry system in terms of the Dutch chemical industry's willingness to engage in new technology, and take risks? - How do find the company's culture in terms of innovativeness (are they open to change)? - When we look at international, European, and national targets, we notice sense of urgency to curb GHG emissions, but do you find this sense of urgency in the Dutch chemical industry? - How do you rank deep emission reductions in the Dutch chemical industry's priority list? - How do you perceive position of the Dutch chemical industry on GHG emission reductions? - Could you rank it against other industry sectors such as cement and steel? - Which forms of lobbying do you think the Dutch chemical industry has chosen? - Do you think the deep emission reductions in the Dutch chemical industry is a public society issue? - What do you think about social acceptance/support of radical and intermediate options compared to the incremental measures?

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(*continued*)

Interview set	Interview questions
	- Do you think that application of radical and intermediate options is legitimate in the Dutch chemical industry system? (e.g. workforce belief that radical and intermediate options could work) - How do you think the chemical industry customer base would react/change if they would engage in radical and intermediate options compared to the incremental measures? - Considering the potential discrepancies we talked about, do you think this situation would result in lock-in in the current system, that prevents radical and intermediate options to get in? - What do you think about the recently published Regeerakkoord that proposed 18 Megatons of CO_2 reduction by CCS? - Do you think that it will deepen discrepancy between radical options and the rest of measures and ultimately, reinforce carbon lock-in? - If so, what should be the (policy) response to prevent/resolve the lock-in? - What would you think the Dutch chemical industry need to go into lower-carbon options? - What do you expect from other actors?
Just transition	- Please tell me about what you think the future holds for the industries in this area? Why do you think this way? - What do you see the role of your own industry/area of activity being in the future (say, 15−20 years)? - What would you like life to be like here in 15−20 years' time? - What do you think life will be like here in 15−20 years' time? - How much do you know about the idea of a 'Just Transition'/justice in the context of climate change responses in an industrial region? If it is something you are familiar with, tell me what you know and what you think? - What do you think is needed to keep this area economically buoyant into the future? - What do you think is needed to keep the local society vibrant and resilient? - In your opinion, what are the major concerns and challenges for industries in this area from now into the future? - How do you think climate change will affect the local area, if at all? - Do you know anything about carbon dioxide capture and storage? If so, please tell me what you know… - More generally, what natural resources do you believe are important locally, and how do you feel they could be drawn on to benefit the area? - Who do you feel should be responsible for managing the future of this area as we renew our energy systems and face environmental challenges? (e.g. local government, national government, industry) - Do you feel the opportunities and challenges around managing a transition for an area like this have been communicated well to you? - Do you feel you have a forum/space where you can raise any concerns or suggestions about the future of the area and your needs/requirements? If so, where? - Even if you've not heard the term before, what would you think of when you hear the term 'Just Transition'/justice in the context of climate change at the regional level in a high-emitting area? What do you think 'fairness' or 'justice' means in the context of energy and climate issues locally? - Which group of people – if any – could be particularly vulnerable as industry declines or changes? - What do you think is needed to ensure local citizens are not disadvantaged as we act to respond to energy, industry and environmental issues?

Appendix 2 Illustrative selection of the list of the interview excerpts and earlier studies used to develop the feedback and systemic mechanisms

Framing	Systemic mechanism	Literature	Quotation	Interviewee number
Carbon lock-in	Legitimising (Fig. 3)	(Vergragt et al., 2011), (Hansson and Bryngelsson, 2009), (Spreng et al., 2007), (Stephens, 2015)	For certain industrial processes with current technology there is probably a good user case. CCS on SMR for example. That will give it a 10, 15, 20 years social license to operate.	19
			It (CCS) was kind of a sales trick in order to build those coal power plants.	23
			CCS, there might be some discussions not only because of discussions of the safety of the storage but also because some NGOs have some doubts, well they go on with the fossil fuel system if we use CCS.	12
			NGOs went crazy because they said … it will be a lock-in and people will only do CCS and not change.	3
	Crowding out (Fig. 4)	(Greenpeace, 2008), (Stephens et al., 2011), (Vergragt et al., 2011), (Stephens, 2015)	CCS costs billions and it's an end of pipe solution …. I would then rather spend billions on the hydrogen solution and then you have solution for the next generations. And you can only use your money once … It prevents using the same money for real industrial innovations, so I think CCS is preventing larger investments in the things we really need to do. So, it slows down innovation.	1
			What they say is that it prevents other types of measures from being taken which you would need in the end.	2
			On the more macro scale of course if we would move too quickly to CCS and we would not make sufficient progress in developing the electrification path, both in terms of arranging for sufficient supply of affordable electricity on the one hand and doing enough innovation and bringing down the cost of, let's say, electrolysers of water to produce hydrogen from water rather than natural gas then you get some kind of lock-in, then you would stick with CCS much longer than needed.	4
			If you are heavily betting on CCS, then other techniques … won't decrease in costs and develop as much as you'd like.	23
			[CCS] is way too expensive and they want to use money from investment funds that are supposed to be for scaling up solar and wind power, so, it is also taking money from wrong sources.	1
			Natuur & Milieu …. started an action to prevent funding from the SDE + which is for renewable energy to go into CCS.	11
				12

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Framing	Systemic mechanism	Literature	Quotation	Interviewee number
			There is now this the idea that we use the SDE + not only for renewable energy but also for other technologies like CCS …. now they said but you cannot use it for CCS because that's not renewable but then they said but it's that target is not renewable energy, target is CO_2 so we use same policy instrument also for other technologies like CCS.	
			that there is a risk of lock-in, because once you have made that investment, yes you will not simultaneously purchase an industrial heat pump and at the same time eliminate the teething problems.	23
			In the short-term, medium-term hydrogen production, that's where you would apply CCS and the reason there is even though of course you can make hydrogen from electrolysis but you cannot wait for it.	3
	Integration (Fig. 5)	(Janipour et al., 2020), (Vergragt et al., 2011), (Van de Graaf et al., 2020)	if you say OK we have hydrogen production and we add a CCS installation then it will be harder for the coming years to say OK we stop that"	12
			if you are going to invest in something (CCS) then you are doing that for a lot of years, 20 or 30 years, so what you invest now you would preferably would like to keep having until maybe 2050.	6
			I think that cluster formation will be very important, whether it's a CO_2-Cluster or hydrogen cluster.	23
			but you need to be aware of your chain dependencies.	14
			It looks like we will gain as much employment as we will lose. … the personnel are technically schooled, it (the new jobs) will remain technical.	22
			What we experience is that we do not struggle with the resources. In some areas maybe we need to get some new expertise or retrain people… we do not perceive that as a problem of lack of …or expertise.	3
			I doubt this of course will be a very quick radical transformation. If you know how refineries or big chemical industries how they operate and how they have to plan their maintenance, their big turnaround, I doubt whether we will need electrical engineers from overnight that is not going to happen. So, yes this might be different in 2050 but it will take time to adjust.	2
			CCS should mainly smoothen the loss of jobs in the fossil fuel-based industries.	19
	Employment (Fig. 6)	(Swennenhuis et al., 2020), (Zachmann et al., 2018), (Gough and Boucher, 2013), (Alcalde et al., 2019)	if there is some industry that is able for example to cope with CCS in a very good manner that it should be the oil company, I think we are better equipped than the power companies to do that … So if you focus on CCS, the oil industry has a lot of qualities and engineering qualities which you require.	2
			I know of course [oil company] is very much looking into CCS and they have been doing that for years in different settings and also one of the CCS projects … is a [oil company's] project. So, they have that experience there.	3
Just transition			That (BECCS) is something that will be necessary on the long-term if we find we can't reduce emissions as fast as we want.	17
			I think the situation in Rotterdam is different, because there are many types of industry and employers, as well as secondary and tertiary activities around that… It's not just a single coalmine or something.	20
			In all honesty, I worked at [energy company] for 5 years, and all there is at Maasvlakte 3 is a control room and 7 operators … However, in terms of CAPEX, the new coal plants cost insane amounts.	15
			You can give certain technologies a 'lease of life' (with CCS).	19
			If you compare to a lot of the other measures which we are taking into account, you could argue that CCS is not so expensive.	2
			If you look at the cost per ton avoided (CO_2), it's a relatively good way to get rid of your CO_2.	19
	Economic effects (Fig. 7)	(Heuberger et al., 2017), (Zachmann et al., 2018), (Alcalde et al., 2019)	So many industries on a relatively small scale can be advantageous for the transition because you can make one-time investments, such as CCS, to which many companies can connect… We think that for clustered industry, CCS can offer an advantage.	16
			The people manage these gas fields are very happy that they can extend the life time of their assets there.	6
			CCS which is particularly in the Netherlands a feasible option because we have a lot of gas fields at sea which are already empty or will be become empty, so we could use them to safely store the CO_2.	4
				3

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Framing	Systemic mechanism	Literature	Quotation	Interviewee number
			You need to do something now because there is this carbon budget and we already running very close to the limit so maybe in 20 or 30 years in time CCS will stop. It is most likely a temporary measure as in a way industry involves you cannot live without it because if you do not apply it you are running out of the time. we do see that CCS is an intermediate step. It's not the final solution but it's intermediate step in order to be able to make emission reductions in the shorter-term, substantial reductions in the shorter-term.	4
			There are cracks in the Sleipner project according to a Nature article. No leakage has been found yet, but scientists say there will probably be some leakage.	23
			You can do CCS before 2030 and it is affordable. Alternatives won't be ready before 2030 and are expensive.	15
	Environmental effects (Fig. 8)	(Shackley and Thompson, 2012), (Swennenhuis et al., 2020), (Sunny et al., 2020), (IEA, 2017), (Gough and Boucher, 2013)	CCS is a transition technology…it is just an intermediate step in order to reduce emissions as quickly as possible because that's important. It is the carbon budget that counts in the end. But we must do it in a way in which we are working on moving to the next stage as well.	4
			We can make it a bit more attractive to apply CCS because we can use it instead of leaving it underground. And the other thing is, as I said earlier, because we need the hydrogen, and hydrogen from grey to blue to green hydrogen is kind of a transition pathway. CCS will need to play a role there. So in that sense it will enable the chemical industry to decarbonise faster if we apply CCS.	14
			All scenarios show that if we continue like this, we will definitely need an incredible amount of negative emissions. That means biomass and CCS, that's the only option.	21
			We believe CCS is necessary in any case for whole global challenge. We even believe you need to do these negative emissions by biomass and CCS.	3
			we always say no the future is the more the combination of biomass with CCS not fossil fuel with CCS, so … you need to be aware of where you add the CCS system.	12

Appendix 3 Overlaps between the concepts of carbon lock-in and just transition narratives

Overlaps between concepts		Just transition systemic mechanisms		
		Employment	*Economic effects*	*Environmental effects*
Carbon lock-in systemic mechanisms	*Legitimising*	Avoiding job loss	Using fossil fuel-based industry capacity	CO_2-reduction
	Integration	Avoiding job loss	Lowering costs of the transition	Clean hydrogen transition pathway
	Crowding out	——	——	——

References

Adams, B., De Wel, B., Galgoczi, B., Hall, J., Camarero, C.M., Nelissen, G., Simeonova, Y., Snoeck, F., Starcheva, V., Szewczyk, R., Trefon, G., Vanselow, A., Antonio, J., 2016. Industrial Regions and Climate Policies: Towards a Just Transition? European Trade Union Confederation, Brussels.

Alcalde, J., Heinemann, N., Mabon, L., Worden, R.H., de Coninck, H., Robertson, H., Maver, M., Ghanbari, S., Swennenhuis, F., Mann, I., Walker, T., Gomersal, S., Bond, C.E., Allen, M.J., Haszeldine, R.S., James, A., Mackay, E.J., Brownsort, P.A., Faulkner, D.R., Murphy, S., 2019. Acorn: developing full-chain industrial carbon capture and storage in a resource- and infrastructure-rich hydrocarbon province. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.06.087.

Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Econ. J. 99, 116–131. https://doi.org/10.2307/2234208.

Arthur, W.B., 1994. Increasing Returns and Path Dependence in the Economy. University of michigan Press, Ann Arbor.

Asayama, S., Ishii, A., 2017. Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in the Japanese media. Energy Res. Soc. Sci. https://doi.org/10.1016/j.erss.2017.06.010.

Ashworth, P., Wade, S., Reiner, D., Liang, X., 2015. Developments in public communications on CCS. Int. J. Greenh. Gas Control 40, 449–458. https://doi.org/10.1016/j.ijggc.2015.06.002.

Bergek, A., Hekkert, M., Jacobsson, S., 2008. Functions in innovation systems: a framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policy makers. In: Foxon, T., Kohler, J., Oghton, C. (Eds.), Innovation for a Low Carbon Economy: Economic, Institutional and Management Approaches. Edward Elgar Publishing, Northampton.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transitions 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Blackford, J., Jones, N., Proctor, R., Holt, J., Widdicombe, S., Lowe, D., Rees, A., 2009. An initial assessment of the potential environmental impact of CO2 escape from marine carbon capture and storage systems. Proc. Inst. Mech. Eng. Part A J. Power Energy 223, 269–280. https://doi.org/10.1243/09576509JPE623.

Boyd, A.D., Hmielowski, J.D., David, P., 2017. Public perceptions of carbon capture and storage in Canada: results of a national survey. Int. J. Greenh. Gas Control 67, 1–9. https://doi.org/10.1016/j.ijggc.2017.10.010.

Brunsting, S., De Best-Waldhober, M., Feenstra, C.F.J., Mikunda, T., 2011. Stakeholder participation practices and onshore CCS: lessons from the Dutch CCS case Barendrecht. Energy Procedia 4, 6376–6383. https://doi.org/10.1016/j.egypro.2011.02.655.

Carlsson, Bo, Jacobsson, S., 1997. In search of useful public policies—key lessons and issues for policy makers. In: Carlsson, B. (Ed.), Technological Systems and Industrial Dynamics. Economics of Science, Technology and Innovation. Springer, Boston, pp. 299–315.

Collingridge, D., 1980. The Social Control of Technology. Frances Pinter, London.

Collingridge, D., 1992. The Management of Scale: Big Organizations, Big Decisions, Big Mistakes. Routledge, New York and London.

De Best-Waldhober, M., Brunsting, S., Paukovic, M., 2012. Public concepts of CCS: understanding of the Dutch general public and its reflection in the media. Int. J. Greenh. Gas Control. https://doi.org/10.1016/j.ijggc.2012.08.016.

de Coninck, H., Benson, S.M., 2014. Carbon dioxide capture and storage: issues and prospects. Annu. Rev. Environ. Resour. 39, 243–270. https://doi.org/10.1146/annurev-environ-032112-095222.

de Gooyert, V., Rouwette, E., van Kranenburg, H., Freeman, E., van Breen, H., 2016. Sustainability transition dynamics: towards overcoming policy resistance. Technol. Forecast. Soc. Change. https://doi.org/10.1016/j.techfore.2016.06.019.

Dutch Government, 2017. Regeerakkoord 2017: Vertrouwen in de toekomst. Dutch Government, The Hague.

Dutch Government, 2018. Voorstel voor hoofdlijnen van het klimaatakkoord. Dutch Government.

Dutch Government, 2019a. Klimaatakkoord. The Hague.

Dutch Government, 2019b. 2 Miljard Voor SDE+ Voorjaar 2020. https://www.rvo.nl/actueel/nieuws/2-miljard-voor-sde-voorjaar-2020.

Evans, G., Phelan, L., 2016. Transition to a post-carbon society: linking environmental justice and just transition discourses. Energy Policy 99, 329–339. https://doi.org/10.1016/j.enpol.2016.05.003.

Feenstra, C.F.J., Mikunda, T., Brunsting, S., 2010. What Happened in Barendrecht? Case Study on the Planned Onshore Carbon Dioxide Storage in Barendrecht, the Netherlands. ECN.

Forrester, J.W., 1961. Industrial Dynamics. The MIT Press, Cambridge.

Global CCS Institute, 2019a. Understanding CCS [WWW Document]. URL (accessed 3.15.19). https://www.globalccsinstitute.com/why-ccs/what-is-ccs/.

Global CCS Institute, 2019b. R&D Gaps for CO2 Capture From Industrial Sources [WWW Document]. URL. https://hub.globalccsinstitute.com/publications/strategic-analysis-global-status-carbon-capture-storage-report-4/46-rd-gaps-co2-capture.

Gough, C., Boucher, P., 2013. Ethical attitudes to underground CO2 storage: points of convergence and potential faultlines. Int. J. Greenh. Gas Control. https://doi.org/10.1016/j.ijggc.2012.12.005.

Greenpeace, 2008. False Hope - why Carbon Capture and Storage Won't Save the Climate. Amsterdam.

Ha-Duong, M., Loisel, R., 2009. Zero is the only acceptable leakage rate for geologically stored CO2: an editorial comment. Clim. Change 93, 311–317. https://doi.org/10.1007/s10584-009-9560-z.

Hansson, A., Bryngelsson, M., 2009. Expert opinions on carbon dioxide capture and storage-A framing of uncertainties and possibilities. Energy Policy. https://doi.org/10.1016/j.enpol.2009.02.018.

Havercroft, Ian, Consoli, Christopher, 2018. The Carbon Capture and Storage Index 2018: is the world ready for Carbon Capture and Storage? Global CCS Institute.

Heffron, R.J., McCauley, D., 2018. What is the 'just transition'? Geoforum 88, 74–77. https://doi.org/10.1016/j.geoforum.2017.11.016.

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. https://doi.org/10.1016/j.techfore.2006.03.002.

Heuberger, C.F., Staffell, I., Shah, N., Mac Dowell, N., 2017. What is the value of CCS in the future energy system? Energy Procedia 114, 7564–7572. https://doi.org/10.1016/j.egypro.2017.03.1888.

IEA, 2012. Energy Technology Perspectives 2012: Pathways to a Clean Energy System. Paris.

IEA, 2017. Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. Paris.

IEA, 2019. Carbon Capture, Utilisation and Storage. https://www.iea.org/topics/carbon-capture-and-storage/policiesandinvestment/.

IEA, OECD, 2004. Prospects for CO2 Capture and Storage. Paris.

IEA, UNIDO, 2011. Technology Roadmap - Carbon Capture and Storage in Industrial Applications. Paris.

ILO, 2015. Guidelines for a Just Transition Towards Environmentally Sustainable Economies and Societies for All. Geneva.

IPCC, 2005. IPCC Special report on carbon dioxide capture and storage. In: Metz, B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L.A. (Eds.), Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge and New York.

IPCC, 2014a. Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York.

IPCC, 2014b. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva.

IPCC, 2018. Global Warming of 1.5 °C: an IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Chang.

Janipour, Z., de Nooij, R., Scholten, P., Huijbregts, M., de Coninck, H., 2020. What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. Energy Res. Soc. Sci. 60 https://doi.org/10.1016/j.erss.2019.101320.

Jasanoff, S., 2018. Just transitions: a humble approach to global energy futures. Energy Res. Soc. Sci. 35, 11–14. https://doi.org/10.1016/j.erss.2017.11.025.

Kalavasta, 2018. Notitie CCS: Aanbevelingen succesvolle en kosteneffectieve implementatie CCS in nederland. Lochem, Netherlands and Paris, France.. Kalavasta.

Karimi, F., Toikka, A., Hukkinen, J.I., 2016. Comparative socio-cultural analysis of risk perception of Carbon Capture and Storage in the European Union. Energy Res. Soc. Sci. 21, 114–122. https://doi.org/10.1016/j.erss.2016.06.024.

Kim, H., Andersen, D.F., 2012. Building confidence in causal maps generated from purposive text data: mapping transcripts of the Federal Reserve. Syst. Dyn. Rev. https://doi.org/10.1002/sdr.1480.

Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy 31, 247–264. https://doi.org/10.1016/S0048-7333(01)00139-1.

Mazzochi, T., 1993. A Superfund for workers. Earth Isl. J. 9, 40–41.

Monastersky, R., 2013. Seabed Scars Raise Questions Over Carbon-storage Plan. https://www.nature.com/news/seabed-scars-raise-questions-over-carbon-storage-plan-1.14386.

Newell, P., Mulvaney, D., 2013. The political economy of the "just transition.". Geogr. J. https://doi.org/10.1111/geoj.12008.

Okereke, C., 2010. Climate justice and the international regime. Wiley Interdiscip. Rev. Clim. Chang. 1, 462–474. https://doi.org/10.1002/wcc.52.

Patrizio, P., Leduc, S., Kraxner, F., Fuss, S., Kindermann, G., Mesfun, S., Spokas, K., Mendoza, A., Mac Dowell, N., Wetterlund, E., 2018. Reducing US coal emissions can boost employment. Joule 2, 2633–2648. https://doi.org/10.1007/s10584-011-0071-3.

Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., Ürge-Vorsatz, D., 2016. Carbon lock-in: types, causes, and policy implications. Annu. Rev. Environ. Resour. 41, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

Shackley, S., Thompson, M., 2012. Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? Clim. Change 110, 101–121.

Simmons, G., Giraldo, J.E.D., Truong, Y., Palmer, M., 2018. Uncovering the link between governance as an innovation process and socio-economic regime transition in cities. Res. Policy. https://doi.org/10.1016/j.respol.2017.11.002.

Spreng, D., Marland, G., Weinberg, A.M., 2007. CO2 capture and storage: another faustian bargain? Energy Policy 35, 850–854. https://doi.org/10.1016/j.enpol.2006.10.009.

Stephens, J.C., 2015. Carbon capture and storage: a controversial climate mitigation approach. Int. Spect. 50, 74–84.

Stephens, J., Hansson, A., Liu, Y., de Coninck, H., Vajjhala, S., 2011. Characterizing the international carbon capture and storage community. Glob. Environ. Chang. 21, 379–390. https://doi.org/10.1016/j.gloenvcha.2011.01.008.

Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin McGraw-Hill, Boston.

Sunny, N., Mac Dowell, N., Shah, N., 2020. What is needed to deliver carbon-neutral heat using hydrogen and CCS? Energy Environ. Sci. https://doi.org/10.1039/d0ee02016h.

Swennenhuis, F., Mabon, L., Maver, M., de Coninck, H., 2020. What role for CCS in delivering just Transitions? An evaluation of the North Sea region. Int. J. Greenh. Gas Control 94, 102903. https://doi.org/10.1016/j.ijggc.2019.102903.

Swilling, M., Musango, J., Wakeford, J., 2016. Developmental states and sustainability transitions: prospects of a just transition in South Africa. J. Environ. Policy Plan. https://doi.org/10.1080/1523908X.2015.1107716.

Terwel, B.W., ter Mors, E., Daamen, D.D.L., 2012. It's not only about safety: beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. Int. J. Greenh. Gas Control 9, 41–51. https://doi.org/10.1016/j.ijggc.2012.02.017.

Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7.

van Alphen, K., Hekkert, M.P., Turkenburg, W.C., 2009. Comparing the development and deployment of carbon capture and storage technologies in Norway, the Netherlands, Australia, Canada and the United States-An innovation system perspective. Energy Procedia. https://doi.org/10.1016/j.egypro.2009.02.279.

Van de Graaf, T., Overland, I., Scholten, D., Westphal, K., 2020. The new oil? The geopolitics and international governance of hydrogen. Energy Res. Soc. Sci. https://doi.org/10.1016/j.erss.2020.101667.

van Egmond, S., Hekkert, M.P., 2015. Analysis of a prominent carbon storage project failure - the role of the national government as initiator and decision maker in the Barendrecht case. Int. J. Greenh. GAS Control 34, 1–11. https://doi.org/10.1016/j.ijggc.2014.12.014.

Vergragt, P.J., 2009. CCS: the next technological lock-in? A case study from the Netherlands. In: Paper to ISA Conference. New York, pp. 15–18.

Vergragt, P.J., 2012. Carbon capture and storage: sustainable solution or reinforced carbon lock-in. In: Verbong, G., Loorbach, D. (Eds.), Governing the Energy Transition: Reality, Illusion or Necessity? Routledge, pp. 112–135.

Vergragt, P.J., Markusson, N., Karlsson, H., 2011. Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. Glob. Environ. Chang. 21, 282–292. https://doi.org/10.1016/j.gloenvcha.2011.01.020.

Weller, S.A., 2019. Just transition? Strategic framing and the challenges facing coal dependent communities. Environ. Plan. C Polit. Sp. https://doi.org/10.1177/2399654418784304.

Wesseling, J.H., Van der Vooren, A., 2017. Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands. J. Clean. Prod. 155, 114–124. https://doi.org/10.1016/j.jclepro.2016.08.115.

Zachmann, G., Fredriksson, G., Claeys, G., 2018. The Distributional Effects of Climate Policies. Brussels.