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Published in:
Resources, Conservation & Recycling

DOI:
10.1016/j.resconrec.2021.106015

2022

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Bauer, F., Hansen, T., & Nilsson, L. J. (2022). Assessing the feasibility of archetypal transition pathways towards carbon neutrality: A comparative analysis of European industries. *Resources, Conservation & Recycling*, *177*, [106015]. https://doi.org/10.1016/j.resconrec.2021.106015

Total number of authors:
3

Resources, Conservation & Recycling 177 (2022) 106015

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Assessing the feasibility of archetypal transition pathways towards carbon neutrality – A comparative analysis of European industries

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ARTICLE INFO

Keywords:
Transition pathways
Sustainability transitions
Socio-technical analysis
Decarbonisation

ABSTRACT

Analyses of the future for manufacturing and heavy industries in a climate constrained world many times focus on technological innovations in the early stages of the value chain, assuming few significant changes are plausible, wanted, or necessary throughout the rest of the value chain. Complex questions about competing interests, different ways of organising resource management, production, consumption, and integrating value chains are thus closed down to ones about efficiencies, pay-back times, and primary processing technologies. In this analysis, we move beyond this to identify archetypal pathways that span across value chains in four emissions intensive industries: plastics, steel, pulp and paper, and meat and dairy. The pathways as presented in the present paper were inductively identified in a multi-stage process throughout a four-year European research project. The identified archetypal pathways are i) production and end-use optimisation, ii) electrification with CCU, iii) CCS, iv) circular material flows, and v) diversification of bio-feedstock use.

The pathways are at different stages of maturity and furthermore their maturity vary across sectors. The pathways show that decarbonisation is likely to force value chains to cross over traditional boundaries. This implies that an integrated industrial and climate policy must handle both sectoral specificities and commonalities for decarbonised industrial development.

1. Introduction

The literature on sustainability transitions has explored ways that more sustainable configurations of socio-technical systems can develop to mitigate the problematic effects of contemporary society on the local and global environment and climate (Grin et al., 2010; Markard et al., 2012). Although large parts of the research have focused on supporting and managing small and often local niches (Kemp et al., 1998; Schot and Geels, 2008) or shaping innovation systems around specific technologies for improved efficacy (Bergek et al., 2015; Jacobsson and Bergek, 2011), the concept of pathways has gained increasing interest recently (Rosenbloom et al., 2018; Turnheim and Nykvist, 2019). The concept of pathways is however used to describe different aspects of how futures may develop towards different aspects of sustainability in different research traditions. Rosenbloom (2017) identifies three distinctly different conceptions of pathways that specifically relate to the challenge of low-carbon transitions: i) biophysical pathways that describe long-term trajectories of anthropogenic green-house gas (GHG) emissions together with the effects of these on the climate using climate science; ii) techno-economic pathways that focus on connecting specific technological and economic processes to environmental indicators and outcomes using tools from technology assessment and economics; iii) socio-technical pathways that emphasise the evolutionary processes of social, technological, and institutional change in societal systems using tools from research on socio-technical transitions. The first two conceptions have become powerful tools for climate policy by becoming integrated in quantitative models such as integrated assessment models (IAMs) and energy systems scenarios, but these have also been criticised for lacking a credible understanding of how the change that is assumed in these models actually comes about, as well as the challenges and barriers needed to be overcome. Recent work has thus aimed to create bridges between some of these analytical traditions and integrate a more sensitive view of socio-technical dynamics into quantitative models and their resulting scenarios (Turnheim et al., 2015; van Sluisveld et al.,

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https://doi.org/10.1016/j.resconrec.2021.106015
Received 30 June 2021; Received in revised form 21 September 2021; Accepted 25 October 2021

2020). The understanding of the roles of institutions, politics, and actors in transition pathways can particularly be improved by complementary analyses of the socio-technical dynamics (De Cian et al., 2020).

The energy sector remains the domain of society associated with the largest use of fossil resources and associated greenhouse gas emissions. Considering its role in supplying all other domains with energy, it has a major responsibility in a low-carbon transition. The transition in the energy sector is also the one that has been most thoroughly researched. However, pathways to carbon neutrality require systemic transformations throughout the systems for production and consumption of other types of products than energy. Industrial processes account for about a third of global energy demand and a slightly higher share of GHG emissions, with the emissions intensive process industries being responsible for a majority of these (Wesseling et al., 2017). Although the industrial sector has been called “hard to abate” and to a large degree overlooked in climate policy (Åhman et al., 2017), the challenges and possibilities for this sector to decarbonise and be part of the transition to carbon neutrality deserve closer scrutiny (Bataille et al., 2018; Rissman et al., 2020). Key questions remain as to how the transition in these sectors can be accelerated to align with net zero pledges of key economies in the world, and what interventions are likely to be needed to do so (van Sluisveld et al., 2021).

Aiming to capture this complexity and approach the challenges with a more dynamic perspective than the hitherto applied techno-economic pathway scenarios have done, we identify and assess the feasibility of socio-technical transition pathways for emissions intensive industries towards decarbonisation. We focus on four key industries in Europe, in which decarbonisation has particular characteristics and challenges that remain largely unexplored: plastics, steel, pulp and paper, and meat and dairy. These sectors represent a large share of the European economy (in economic contribution, employment and greenhouse gas emissions), and produce products that to a large part are fundamental to the functioning of modern societies as well as culturally embedded. Further, we do not only consider the production stage, but include the whole value chain in the analysis. While consumption practices are often significantly influenced by culture and habits that may in some cases only change slowly, recent empirical studies highlight that e.g. meat consumption can be reduced quickly in some contexts (Dagevos and Voordouw, 2017; Neff et al., 2018), thus, highlighting the importance of considering opportunities and strategies for decarbonisation options in this part of the value chain as well (Harguess et al., 2020).

The analysis takes a grounded and bottom-up approach to identifying trends, visions, and strategies towards decarbonisation. The transition pathways presented here were inductively identified in a multistage process based on material produced in the European H2020 project REINVENT that ran from 2016 to2020. We assess the feasibility of these transition pathways through an operationalisation of the framework presented by Turnheim and Nykvist (2019), including both an analysis of the conditions and potential of pathways. This allows us to respond to the following research question: which are the possible transition pathways towards carbon neutrality in these emissions intensive industries and what conditions their feasibility? We thus respond to calls for research (De Cian et al., 2020; Turnheim et al., 2015; van Sluisveld et al., 2021) to provide more thorough and divserse analyses of how transition pathways are and can be shaped by different actors as well as how the co-evolution of social norms and practices shapes the development, adoption and diffusion of low-carbon technologies. The contribution of the paper is a deeper analysis of the social and political, path-dependent processes which will shape and determine the transition pathways beyond the techno-economically optimal solutions identified by IAMs and other models.

The paper is structured as follows. Section 2 presents transition pathways and key aspects for assessing the feasibility of these. Section 3 presents the research approach employed in this analysis and the empirical context. Section 4 brings together the observations from each of the sectors to a group of overarching archetypal pathways and analyses the feasibility of these. Section 5 presents conclusions and needs for future work.

2. Pathways and their feasibility

2.1. Roles of pathways

Thinking of transitions as potential developments along a multitude of potential pathways, instead of a development along a historically determined and well mapped road is a way of acknowledging uncertainty and opening up the discourse for a plurality voices and options (Stirling, 2011, 2008). A plurality of pathways thus allows us to consider not only the most feasible or desired (from some perspective) development, but also alternatives that could include transformations along other dimensions than the ones focused upon in narratives promoted by strong or dominant actors in contemporary discourses, e.g., industry itself, the European Commission, or integrated assessment modellers. Analyses of the future for manufacturing and heavy industries in a climate constrained world many times focus on technological innovations in the early stages of the value chain, assuming few significant changes are plausible, wanted, or necessary throughout the rest of the value chain. This tends to correlate well with maintaining the roles of strong, incumbent actors as these are also often responsible for creating roadmaps that present *the future*. Complex questions about competing interests, different ways of organising resource management, production, consumption, new sectoral couplings and integrating value chains are thus ignored or closed down. The roadmaps tend to focus on efficiencies and investment opportunities in techno-economic pathways rather than exploring more transformational socio-technical pathways, and tend to ignore institutional, political and socio-cultural implications (Rosenbloom, 2017).

Employing the notion of pathways can be a way of approaching governance for transitions through a lens that appreciates not only the dynamics of change, but also acknowledges that those dynamics themselves will change as transformations unfold. Assessing the feasibility of pathways thus requires paying attention not only to the promises of the different pathways, but to understand the conditions under which they are being or can be realised, as well as their potential for transformation (Turnheim and Nykvist, 2019), and it is to these aspects we now turn.

2.2. Conditions

Turnheim and Nykvist (2019) point to four types of conditions that influence the feasibility of pathways. Firstly, *maturity* refers to the extent to which pathways rely on options that are ready and currently available, or rather under development, testing, or even at the idea stage. This refers both to level of technical development, and to the availability of non-technical aspects, including required organisational forms, business models etc. The level of maturity also depends on whether options are transferrable across multiple geographical contexts, or, conversely, only functioning under very specific conditions.

Secondly, *integration* signifies that pathways may face significant divergence in terms of ease of integration with existing industries, systems and infrastructures. Pathways that can utilise existing infrastructures, and fit with established systems and industry processes require smaller investments and can be realised faster than pathways that necessitate substantial reorientation of complete value chains (Bataille, 2020; Hellsmark and Hansen, 2020). Some pathways involve organic growth and diffusion of modular or incremental solutions (e.g. deposit schemes for packaging or dietary changes) whereas others require planning and coordination of large investments in new infrastructure (e.g. pipelines for hydrogen or upgraded power grids).

Thirdly, *societal acceptability* highlights how pathways are associated with varying degrees of controversies and worries in society at large. While some options spark significant concerns among large groups in society, others do not or are driven by bottom-up initiatives.

Furthermore, in our understanding of societal acceptability we also include the extent to which options are acceptable to existing industries. Many options face limited support or resistance from industry, which significantly influence the feasibility of pathways (e.g. Hansen and Coenen, 2017; Smink et al., 2015). In addition, concerns and resistance also vary significantly between geographical contexts, stage of the emerging transition and further depend on the possibilities for addressing and countering concerns (Lee and Hess, 2019).

Finally, *political acceptability and delivery* points to differences in the expected political support or resistance that a given pathway may encounter. This is closely connected to the extent to which a pathway is considered to solve core societal problems, but also the pathway's fit with dominant political agendas (Normann, 2015). Political acceptability and delivery is also influenced by the capabilities of core actors promoting the pathway to mobilise and garner political support (Hess, 2014).

2.3. Potential and dynamics

The promises of pathways are not constant, but change over time as technologies, politics, and values move and transform. Assessing the feasibility of different pathways must thus include aspects that capture these dynamics. Two aspects are central to evaluate the dynamic potential of pathways: i) the development of new knowledge (learning) that may strengthen or weaken the promise of pathways; ii) the possible existence of branching points in which (groups of) actors make decisions or take actions that create lock-ins to pathways (convergence) or break with them (divergence) (Turnheim and Nykvist, 2019).

Learning may increase the feasibility of pathways, as it allows for overcoming central barriers to realisation of pathways (van Mierlo et al., 2020; van Mierlo and Beers, 2020). This can refer to rapid learning curves leading to decreasing production costs as well as learning leading to technological, social or organisational innovations that remove existing bottlenecks. However, learning may also decrease the feasibility of pathways. Rapid learning curves for competing pathways may decrease the chances of realisation of a specific pathway and it is thus important to consider the dynamic interaction effects between pathways. Understanding who learns as well as what is being learnt is thus foundational to assess if and how this contributes to accelerate or decelerate the emergence of specific pathways (Goyal and Howlett, 2020).

Branching points should be understood as "a key decision point on a pathway at which actors' choices, made in response to internal or external pressures, determine whether and in what ways the pathway is followed" (Foxon et al., 2013, p. 147). This underlines the non-linearity in the development of pathways and allows for identifying various critical events that are necessary for the realisation of pathways (Turnheim and Nykvist, 2019). In this way, attention to branching points also opens up for recognising where central choices between different pathways are being made. Branching points represent windows of opportunity where actors may converge around a pathway or, alternatively, abandon it in favour of alternative pathways or business as usual (Rosenbloom et al., 2018).

3. Research approach and empirical context

3.1. Identifying pathways

The pathways presented here were inductively identified in a multi-stage process from materials produced collectively in the project REINVENT– Realising Innovation in Transitions for Decarbonisation.[1] REINVENT was a collaborative Horizon 2020 project studying the decarbonisation of a group of emissions intensive industries in Europe: plastics, steel, pulp and paper, and meat and dairy. The project aimed to combine the use of both quantitative modelling approaches such as energy system models and IAMs with qualitative insights based on case-studies and stakeholder engagement to co-produce knowledge about the potentials, prospects, and pathways for decarbonising European industries. The present paper describes a meta-analysis based on several types of data collected, analysed, and published during the project. Most importantly, four sector-level analyses were prepared, which on a macro level analysed the structural characteristics of innovation and the potential for decarbonisation in the four industries. These allowed for understanding the most pertinent challenges for decarbonising the sectors and identification of possible industry-specific trajectories for decarbonisation (aan den Toorn et al., 2018; Bauer et al., 2018; Ericsson and Nilsson, 2018; Lechtenböhmer et al., 2018). The sector-level analyses were based on extensive desk research and the analysis of a large number of current innovation initiatives in each of the studied sectors, all collected in a database which describes and characterises the innovations with respect to key attributes such as drivers and decarbonisation mode (Hansen et al., 2018). Detailed analyses of drivers for decarbonisation and areas of contestation were conducted and compared across multiple case studies (Knoop et al., 2019; Tönjes et al., 2019). These materials were all used as the foundation for the analysis in the present paper.

Comparing decarbonisation trajectories in the four sectors, summarily described in the next sub-section, we identified shared trends and characteristics, which make up the pathways as presented in Section 4. These generic pathways partly evolved through, and were discussed and refined in, 10 expert workshops involving participants from government, industry, academia and think tanks. We thus take a grounded approach in identifying the pathways from empirical observations rather than starting from abstractions of technological promises. Pathways as outlined in the present paper are stylized abstractions and should not be considered to be fully excluding elements from each other, or other forms of parallel development, but following the extensive empirical research and stakeholder engagement presented above, we have identified these pathways to be the strongest contenders in contemporary industrial and political strategizing. We further connect the findings about the pathways from our material to the research literature. However, aiming to assess the *potential* of the pathways rather than only their limited *current* contribution to mitigating greenhouse gas emissions, we sketch pathways that stretch into the future. These pathways and the assessments of their potential are relevant for comparisons across industries and plausible also when considering other emissions intensive sectors.

3.2. Empirical context

The plastic industry is the largest subsector of the petrochemical industry (IEA, 2018) and the production of plastics and plastic products emits about 180 Mton CO_2-eq in Europe (Vanderreydt et al., 2021). The vast majority of emissions originate in the manufacture of primary plastics (Zheng and Suh, 2019). However, as about 99% of plastics are produced from fossil feedstocks, e.g. naphtha or ethane, they also embody large volumes of fossil carbon, which are released as CO_2 if plastic waste is incinerated at end-of-life – an increasingly common strategy as countries in the European Union (EU) move away from landfilling, but dont́ managed to establish effective recycling schemes for most types of plastics. A key challenge for the industry is thus to decarbonise[2] not only its energy use but also its feedstocks (Bauer et al., 2018).

We identify four main trajectories for decarbonising plastics: i)

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[1] https://www.reinvent-project.eu/

[2] Decarbonisation must for plastics be understood not as removing all carbon from the value chain, but as removing the fossil carbon which may at some point be emitted as CO_2.

optimising the production and use of plastics throughout the value-chain through efficient material use or substituting for other materials while ensuring that this does not cause unintentional increase of use of fossil resources for the production of the substitutes, ii) increasing collection, sorting and recycling of plastic waste to create circular material flows, which also relies on new requirements and standards for both material and product design, iii) producing biobased plastics, although this increases the competition for biomass resources which in the case of biofuels has caused significant contestation, and finally iv) making use of carbon capture and use (CCU) and power-to-X technologies to produce plastics through carbon capture and large scale hydrogen production from electrolysis.

Steel is key material in modern economies and value chains – construction and transportation without steel is difficult to imagine. The European steel industry emits more than 220 Mtons CO_2-eq annually (EUROFER, 2019), the majority of which come from the blast furnaces producing primary steel as these rely on coke (from metallurgical coal) for the process. Downstream processing is also energy intensive, resulting in another 17% of emissions (Lechtenböhmer et al., 2018). Recycling is well developed and significantly less emission intensive than primary production, but secondary production is still far from enough to supply European demand from growing infrastructure and cities. Important value chains such as vehicles may have specific and very high quality requirements on the materials used, still limiting the possibilities for recycled steel and leading to high expectations on low-carbon alternatives to primary production using blast furnaces (Vogl and Åhman, 2019).

The trajectories towards decarbonisation that we identify for the steel sector are i) efficiency improvements in both production processes and material use for reducing the need for energy inputs as well as use of steel in finished products and constructions, ii) increased focus on and improvements in recycling of steel to ensure that scrap-based production can deliver products of high qualities, i.e. without impurities that limit their applicability, iii) implementing new technologies in primary steel making that remove the need for fossil inputs, such as direct reduction with hydrogen from electrolysis or electrowinning – options that both require very large inputs of renewable electricity, and finally iv) managing the carbon emissions through CCU or carbon capture with storage (CCS).

The production of paper, board, and other pulp based fibres is based on biomass resources but still uses a significant volume of fossil energy, leading to GHG emissions of about 30 Mtons CO_2-eq in Europe (CEPI, 2019). While pulp production is concentrated to a few countries in northern Europe and uses almost exclusively renewable energy, mills for paper and board as well as recycled pulp throughout Europe use fossil energy to supply heat to the processes, e.g. for drying. Most of this energy use could reasonably easily be substituted and some of it eliminated through efficiency improvements (Ericsson and Nilsson, 2018). Recycling rates are high for most categories of products, but some value chains (e.g. hygiene products) are disconnected from recycling. Other value chains that could potentially benefit from a reorientation of the industry towards biorefineries producing a more diverse product portfolio are for example packaging, textiles, and chemicals, although the main focus for pulp mill biorefinery conversions thus far has been on biofuels (Bauer et al., 2017).

The trajectories towards decarbonisation that we identify for the pulp and paper sector are i) energy efficiency improvements and fuel changes to remove most of residual fossil fuel use in pulp and paper mills, ii) electrifying heating and drying processes with heat pumps and novel technologies such as microwave drying, iii) using the wood fibres and/or residues such as black liquor to produce new products, e.g. textiles or chemicals, iv) capturing and storing the biogenic carbon emissions from combustion processes to become a carbon sink for other industries.

The European meat and dairy industries are responsible for around 700 Mtons of Mt CO_2-eq, but what differentiates this sector from the others is that the majority of these emissions are non-CO_2 emissions. The main emission types and sources are CH4 from enteric fermentation and manure management together with N_2O from nitrogen volatilisation and manure management, which has implications for the decarbonisation possibilities. The nitrogen related GHG emissions are further related to managing nutrients in a manner that ensures that they are to the utmost degree utilised in crop production.

Analysis of the identified trajectories towards decarbonisation focus on i) more efficient management of the products to reduce waste throughout the value chain, which could potentially also lead cost reductions, ii) optimising processes for feed production, manure management, and husbandry to reduce emissions from nitrogen volatilisation, enteric fermentation, and manure management – although this may have adverse effects on productivity and animals, and iii) substituting consumption of meat and dairy for other alternative products such as plant based substitutes which have lower associated GHG emissions.

4. Assessment of pathways and their feasibility

Based on the above-described innovation trends and capacities in the studied value chains we identify five different pathways that span across the different sectors and can be thought of as archetypal transition pathways to carbon neutrality. These pathways are i) production and end-use optimisation, ii) electrification with CCU, iii) CCS, iv) circular material flows, and v) diversification of bio-feedstock use. As the majority of emissions arise in the early stages of the value chains, the main focus of these pathways is either on transforming these stages, or redefining the need for the production of virgin materials. To exemplify, in the case of plastics GHG emissions attributed to resin production are more than twice the amount of emissions attributed to the conversion stage, and scenarios suggest that electrification will also radically reduce emissions from conversion (Zheng and Suh, 2019) and in the case of steel GHG emissions are primarily attributed to the blast furnace and foundry processes for virgin steel production, whereas downstream casting and rolling are much less energy and emissions intensive (Wang et al., 2021). The pathways are described in more detail in the following sub-sections. We assess the conditions for them, as well as their potential using the framework described in Section 2. The findings are summarised in Tables 1 and 2.

4.1. Production and end-use optimisation

Optimising processes to reduce energy demand and emissions has been a prioritised activity on the innovation agenda of the process industries for the past decades, although with significant variation in how much has been achieved in terms of energy and emissions efficiency in different industries and regions (Cagno et al., 2015). This pathway spans across all the included industries, including continued process energy efficiency measures in plastics, steel, pulp and dairy manufacturing, minimising material use in applications of the materials such as construction and packaging, and reducing food waste through measures in the supply chain, i.e. extending shelf lives, although the technological options vary between the industries. However, whether this pathway can actually deliver a substantial decarbonisation of the industries or just a limited reduction of emissions is strongly questioned (Crijns-Graus et al., 2020).

The conditions for the production side of this pathway are generally well developed. The pathway follows a well-established pattern of focusing on incremental improvements of existing industrial processes, with only some innovations requiring more change to the processes. New more energy efficient operations or processes may also be developed that challenge some of the existing ones on a larger scale, e.g. new polymerisation processes in plastics manufacturing, but such changes are likely to take decades to be implemented throughout the industry if they follow historical patterns (e.g. the case of substituting the mercury

Table 1
Assessment of current conditions for pathways.

	Maturity of options	Integration with systems, industries and infrastructure	Societal (social and industrial) acceptability	Political acceptability and delivery
Production and end-use optimisation	Fragmented: The range from energy efficient equipment to renewable fuels/energy sources as well as integrated/shared use of products/utilities is well developed. End-use material efficiency options are undeveloped.	Fragmented: The long-term focus on energy and resource efficiency in process industries is well developed. Materials efficiency across value chains is undeveloped.	Fragmented: Developed, although with barriers, on the production side. Acceptability on the end-use side is likely to be relatively high but it is institutionally undeveloped.	Fragmented: Energy and emissions efficiency key to EU policies and developed but the potential to deliver complete decarbonisation is limited. End-use demand management and materials efficiency is undeveloped.
Electrification with CCU	Fragmented: Technological modules are mature, but not large-scale CCU systems. Electrification and hydrogen options vary in maturity across different applications	Limited: Electrical power systems not yet adapted for electrification, hydrogen and variable renewables production but grid expansion, flexibility measures and storage is prepared for and evolving.	Limited: Fear for limited access to green electricity and hydrogen at low cost; potential public resistance to wind power expansion; capturing carbon most likely acceptable	Limited: Growing attention to massive electrification and use of hydrogen but hesitancy towards CCU although chemical recycling of plastics is gaining more attention.
CCS	Limited: CCS mainly developed for power generation; sequestration not implemented in full scale for industry;	Undeveloped: CCS infrastructure is lacking and capture rates are limited when retrofitting existing plants.	Undeveloped: Long-term storage controversial; capturing carbon more likely acceptable.	Limited: Growing acceptance that CCS in industry is necessary for some emissions but so far no delivery except R&D.
Circular material flows	Limited: High recycling of some steel and fibre qualities but can be higher, very low mechanical recycling of plastics and chemical recycling is undeveloped	Fragmented: Recycling of some materials relatively well developed but further improvement requires changes in waste handling, recycling technologies and organization of value chains.	Limited: increasing acceptability for recycling, yet limited understanding for its effects in some sectors; differences in waste handling across geographical contexts.	Limited: Acceptability well developed, but delivery limited and situation across sectors is fragmented; EU push for circular economy provides directionality but not incentives.
Diversification of bio-feedstock use	Fragmented: Some diversification but yet limited to few product categories (fuels and some construction materials and textile fibres)	Limited: Several projects across industries but no aggressive push; reconfiguration of clusters and infrastructure is slow.	Fragmented: Generally positive view of the bioeconomy but serious concerns about competing land uses and biodiversity	Fragmented: Support for the bioeconomy, but conflicting with concerns for land use change, biodiversity, and other environmental impacts.

Table 2
Forward looking assessment of potential to realise pathways.

	Learning		Branching points	
	Increase feasibility	Decrease feasibility	Increase feasibility (convergence)	Decrease feasibility (divergence)
Production and end-use optimisation	Continued improved efficiency of processes and equipment. Develop solutions, metrics and knowledge for materials efficiency.	Rapid learning curves for renewables leading to decreasing energy costs.	Strong commitments to existing processes in business organisations (alternatives are unreliable). Policy attention to demand management.	Unclear policy directionality may limit investments to improve efficiency in existing value chains
Electrification with CCU	Innovations for efficient carbon capture or electrochemical synthesis; rapid learning curves for renewables and electrolysers leading to decreasing energy costs; increased ramping possibilities	Limited possibilities to adapt industrial production to intermittent renewable power.	Cross-industrial commitments to investments in renewable electricity and electrification; regions with renewable electricity resources taking the lead for electrification; market demand for green materials.	Political coalition building against CCU; restrictions on expanding renewable energy production
CCS	Adaptation of capture technologies to industrial processes; testing and establishing storage sites;	Rapid learning curves for renewables, electrification and hydrogen compete with CCS	Establishment of industrial CCS standards; strong business associations with political support commit to CCS globally	Strict regulations on sequestration; restrictions on trading CO_2 for CCS
Circular material flows	Efficient and effective material management and sorting systems; innovations in material recycling technologies (metals, fibres, plastics)	Increased diffusion of traditional waste incineration/sewage treatment systems; increased complexity of products and composites.	Regulations against virgin resource exploitation; industrial commitments and standards for recycled materials in products. New value chains and business models.	Restrictions on trading waste/recyclates; requirements and regulation on product quality making recycled flows unreachable
Diversification of bio-feedstock use	(Bio)technological innovations for food, feed, fibres, and energy; social acceptance for new foods and green protein.	Rapid learning curves for CCU competes with diversification of bio-feedstock use. Learning and innovation in agricultural reduces emissions from meat and dairy production	Establishment of new value chains through collaborations/mergers; reduced restrictions against GMO. Socio-cultural shifts in diets.	Restrictions on land/bio-feedstock use for new/specific purposes. Strengthening of meat culture.

based process in PVC manufacturing for the more efficient and less toxic membrane based one (Crook and Mousavi, 2016; Iles et al., 2017)). Examples of innovations for this pathway are energy efficiency measures for key energy intensive operations such as pumps, fans, evaporators, and dryers as well as technologies that allow for switching from fossil fuels in industrial processes to renewable energy such as biogas or solid biofuels. Heat integration within the industries and with surrounding clusters or communities provides further opportunities to create effects in the surrounding system and not only within the industries (Menrad et al., 2009). For dairies the options here are similar to the options within the other industries, although for meat production this pathway requires optimising animal husbandry in new ways, e.g. emissions minimising feed for cattle (Mazzetto et al., 2020). Along the value chain the pathway builds on optimising logistics and freights but requires little change of consumer behaviour.

The conditions for the end-use side are less developed in the case of materials. There are options to reduce materials demand through reduced use (e.g. removing excessive packaging), materials efficiency (e.

g. light-weighting long-lived construction) and reuse (e.g. steel beams) that are underutilised (Dunant et al., 2017; Hernandez et al., 2018). Although potentially highly feasible from a societal and political acceptability perspective these options seem immature with a lack of architecture and engineering knowledge, and the organisational forms and business models across value-chains that would be needed for realising them. For meat and dairy, on the other hand, veganism, vegetarianism or dietary changes towards less meet are spreading in some places and among some consumer segments although the tradition of eating meat is also strongly embedded in many cultures.

Societal acceptability for this pathway is generally high, although some different barriers do exist (Oikonomou et al., 2009). Progressive social movements argue that the pathway is a distraction as investments in incremental innovations limit the possibilities for investing in more radical change, e.g. opposing shifting from coal to natural gas which is by the proponents framed as a bridge to biogas but opposed as a further fossil lock-in. Opposition requiring radical action may thus create barriers for this pathway, e.g. current demands by movements such as Extinction Rebellion for declaring the climate crisis a state of emergency (Hulme, 2019). Industrial actors are also known to not prioritise investing in efficiency improvements as the return-on-investment for such technologies may be a few years and yield no benefits to the production output, which is then instead often prioritised (Energy Efficiency Financial Institutions Group, 2015). Thus, although not opposing efficiency possible improvements are anyways many times ignored. Political acceptability is generally high, e.g. EU commission arguing for energy efficiency as an enabler of a sustainable economy (European Commission, 2017), but delivery may be lagging behind regarding rapid and large public investments in new infrastructure for efficient freight – which could be increased railroad capacity or electric road systems – and heat networks.

The pathway has the potential to reduce the dependency on fossil resources for certain industrial processes and reduce emissions significantly, but most likely not to allow a complete decarbonisation of most value chains (Crijns-Graus et al., 2020), although the pulp and paper industry may come close. Learning that may further advance this pathway is continued investments in improved efficiency of existing processes, as well as possible substitute processes and products that fit within existing value chains. A threat to commitments to investing in efficiency is the promise of abundant and cheap renewable energy, which is assumed for the electrification pathway (Ollier et al., 2020). Trade organisations could be key actors here, if they consolidate their members around continued focus on efficiency of existing process and efficiently lobby for supporting such investments at the cost of supporting investments in alternatives that are less well known.

4.2. Electrification with CCU

Although the transition to a decarbonised power system is itself yet a promise of the future, this pathway relies completely on the presumption that electricity with no GHG emissions will be available at low costs. Electrification has the potential to substitute fossil energy use in many existing processes, e.g. to supply heat either directly, through microwave or infrared heating, or indirectly through producing hot water and steam with electric heat pumps and boilers. Further, electricity can also be used as an input for completely new processes, such as large scale production of hydrogen through electrolysis. Hydrogen produced using renewable electricity, instead of steam reforming of natural gas, is an option gathering interest in the steel industry, where it would allow for fossil-free direct reduction of iron (Kushnir et al., 2020), and also a cornerstone for CCU as the captured carbon is often planned to be processed with hydrogen to produce hydrocarbons and further chemical conversion. This implies massive investments not only in electricity generation but also in transmission capacity to make the produced power available for the industries that would use it. Hydrogen produced from electrolysis is however easier transported, e.g. in the form of ammonia, from distant regions, which could potentially reduce the need for massive expansion of power generation and transmission capacity in some industrial regions (Giddey et al., 2017). Similarly, iron may be produced and transported from regions endowed with renewable electricity resources where hydrogen can be used to reduce the iron ore. The technologies and solutions needed are mature, although many of them not previously implemented in the scale relevant for these industries. Integration possibilities are generally good but necessary expansion of generation and transmission may cause problems in dense industrial regions. Societal acceptability is generally assessed to be high, but local resistance to expansion of both electricity generation and transmission capacity as well as CCU installations is expected (Arning et al., 2020). This puts pressure on political acceptability and delivery, which is struggling to deliver renewable electricity to cover current demand, which would grow significantly if this pathway is followed.

Necessary learning and development to support this pathway are in scaling up several of the electricity based technologies, such as electrolysers and high temperature heating systems (Klöckner and Letmathe, 2020), as well as solutions able to cope with intermittency of power generation (Ren et al., 2017; Saba et al., 2018). This could be done through investments in solutions that maintain a buffer for the production, e.g. hydrogen or heat storage, or through retrofitting production processes, which are currently optimised for running at constant high loads to enable quicker ramping up or down. Both of these options are likely to incur increased specific production costs. Regions that have access to significant resources of renewable power, e.g. solar, wind or hydro, are likely to be able to exploit these to promote the development of the pathway, indicating the need for a geographically sensitive analysis.

4.3. CCS

Although technologies for carbon and capture and storage were initially identified primarily as a decarbonisation option for electricity generation it now seems more viable as a decarbonisation option for some industries which have a high dependency on fossil resources in their core processes or process related emissions that are difficult to abate in other ways (Bui et al., 2018). Thus there is significant activity on CCS related innovation in the steel industry, which would allow for the continued use of blast furnaces and CCS has been proposed as way to abate process emissions from plastics manufacturing as the steam cracking is the most emissions intensive part of the value chain, albeit that this would not reduce the dependency on fossil resource for the actual raw material, and to enable negative emissions from pulp mills, i.e. similar to bio-energy with CCS (Leeson et al., 2017).

The maturity of the options for this pathway is limited. Technologies for capturing CO_2 are developed but not tested in integrated solutions with the relevant industrial processes, as they have primarily been developed for petroleum processing or CCS from power generation (De Coninck and Benson, 2014). Infrastructure for CCS (transportation and storage) is also lacking and is a crucial component for the pathway as access to such infrastructure will determine the viability for industries or clusters to support and invest in CCS solution, otherwise risking to be stranded with their emissions (Middleton and Yaw, 2018). Although many scenarios and models rely heavily on negative emissions and CCS from emissions intensive industries (Mikunda et al., 2014; Schneider et al., 2017) to reach net zero emissions in time, it is clear that support for it is in many respects limited also amongst many segments of the industrial sector. Societal acceptability remains a key issue to resolve, even if it is found to vary geographically (L'Orange Seigo et al., 2014; Tcvetkov et al., 2019).

The potential for the CCS pathway relies on learning about the specific conditions that different industrial applications of CCS have (Leeson et al., 2017), and especially identifying where it can lead to a complete or close to complete decarbonisation of the process emissions which are the most difficult to abate. Thus increasing feasibility of the

CCS pathway is dependent on specific and tailored solutions, whereas it many times competes with the adoption of renewable energy which diffuses quickly at decreasing costs across contexts (Durmaz, 2018). This may lead to the pathway being developed mainly by industries and actors who identify few, if any, other options, leading to slow development and high costs for specific solutions. The cement industry, which was not part of our study, represent such an industry since the limestone feedstock contains carbon. Branching points leading to convergence around the CCS pathway can thus be created by focusing on the shared aspects, such as standards for transportation and trade, which would create a supportive context for specific solutions for capturing CO_2. Political commitments to develop the infrastructure in specific regions and corridors could similarly generate convergence around the issue, whereas continued uncertainty about international trade and shipping of captured CO_2 (Weber, 2021) will divert attention and investments away from the pathway.

4.4. *Circular material flows*

Changing from an economy that uses resources in a linear manner, from extraction through manufacture and use to waste management, into a more integrated use and reuse of resources that potentially eliminates or at least reduces the use for virgin resources is commonly described as a transition to a circular economy (Kirchherr and Reike, 2017). Reuse and recycling of resources are well established practices within some domains of the economy, but less so in others. Steel is recycled to a very high degree post-use, largely driven by the high value of metals (Björkman and Samuelsson, 2014), whereas plastics are recycled to a very low degree (Bucknall, 2020) – for most types of plastic products there are no recycling schemes and for packaging (where recycling is regulated) the implementation is limited, although increasing. For food recycling becomes another matter, but the matter of recycling of nutrients (primarily to capture nitrogen and phosphorus) is gaining increasing interest and options for making use of biogas digestate from anaerobic digestion of wastewater sludge or organic fractions of municipal solid waste are available, though not widely applied (Valve et al., 2020).

Although having been supported by social movements framing it as cradle-to-cradle or upcycling for some time, it has become adopted by and integrated in the mainstream policy discourse in recent years. The EU commission adopted its first action plan for the circular economy in 2015 and has since worked to operationalise it, e.g. through a strategy for plastics. Political acceptability for this pathway is thus well developed, but delivery is this far very limited (Hartley et al., 2020; Kirchherr et al., 2018). A new EU waste directive focusing on recycling has been difficult to implement, the plastics strategy is only a communication and the first directive to come out of it, the single-use plastics directive, does little to promote change in managing used plastics across the economy but focuses on marine littering (Elliott et al., 2020; Palm et al., 2021). Understanding of and acceptance for circular modes of production and consumption remain undeveloped and incongruent with the ambitious policy aims (Kirchherr et al., 2018; Repo et al., 2018).However, although many industrial actors support circular flows they are difficult to implement. Changing business models towards services instead of products is often claimed to be a key enabler for the circular economy, as it requires manufacturers to focus on making products with superior longevity, reparability, and recyclability but there is still considerable confusion as to what a circular business model really is and how to navigate the space of different possible models (Bocken and Ritala, 2021; Geissdoerfer et al., 2020). A focus on service based business models is however more likely to be a solution for goods close to end consumers and not the industries in focus here, e.g. steel is unlikely to be traded as a service for car manufacturing or construction. It also requires deep cultural change in social norms regarding ownership as important for creating identity and cultural significance in different contexts.

4.5. *Diversification of bio-feedstock use*

Extending the use of biobased materials to supply the economy with products and services that are currently supplied by fossil resources is commonly described as a transition to a bioeconomy (Bugge et al., 2016). The pathway includes using converting biobased resources for the production of materials and chemicals, increasing the use of biobased fibres for textiles, packaging, composites, construction etc., growing and valorising new crops for food, feed, and other industrial purposes such as fibres. Biobased plastics are being developed by several large and powerful actors, although the markets are still very limited and thus far only two biobased plastics are successfully marketed (biobased polyethylene (PE) and polylactic acid (PLA)). Steel and metallurgical industries are experimenting in a limited scale with biogas and wood-based coke substitutes. Downstream in the value chain the construction industry is experimenting with cross laminated timber as a structural material to replace steel and concrete. New foodstuffs and plant-based products that substitute meat and dairy products are becoming increasingly popular but still represent only a small share of European diets (Tziva et al., 2020).

Integrating bio-feedstock use into existing structures presents significant challenges for industries that would substitute fossil feedstocks for chemical conversion for biobased ones, whereas actors downstream in the value chains may have greater flexibility to substitute plastic products for new bio-fibre based ones, i.e. for packaging or textile products. As the knowledge base and capacities required for processing fossil resources may differ significantly from the ones required for bio-feedstock processing, integrating this feedstocks presents a great challenge for many industries. Societal acceptability for extensive use of biobased resources has been a complicated issue; although supported for its promise as a solution to the climate problem, social movements have campaigned against irresponsible exploitation of natural resources (Rosegrant and Msangi, 2014) and industrial actors accustomed to using fossil resources have been cautious towards biobased resources due to its low (carbon) density, seasonal availability and variable quality (Bauer et al., 2017). Political acceptability is generally seen as well developed, but delivery limited. Following the unforeseen complications around the development of markets for liquid biofuels and internal conflicts, the EU has been hesitant to expand policy support to new domains and niches which could build on each other (Lühmann, 2020; Wydra et al., 2021). Since biomass and land is a scarce resource there will always be issues around conflicting interests (e.g., biomass production versus nature preservation and biodiversity) and what is perceived to be the most beneficial uses of a limited biomass feedstock (e.g., for energy or materials).

5. Conclusions and policy implications

The sectoral analyses revealed a complexity and diversity of value chains and decarbonisation options as well as differences in innovation dynamics, governance, capacities, and uptake due the different structures of the sectors and inherent characters of the pathways. They also reveal the emergence of new sectoral couplings, thus obscuring traditional sector boundaries. Our comparative analysis across the sectors shows that despite considerable differences they align along five potential transition pathways (i.e., *Production and end-use optimisation, Electrification with CCU, CCS, Circular material flows*, and *Diversification of bio-feedstock use*). This implies that an integrated industrial and climate policy must handle both sectoral specificities and commonalities for decarbonised industrial development. Not all pathways lead to carbon neutrality on their own (e.g., optimisation or circularity) but must be combined with others (e.g., electrification and CCS). Correspondingly, electrification and CCU will be very challenging unless demand for virgin materials can be reduced through end-use optimisation and recycling.

The paper contributes by providing an analysis of not only the technological but also the social and political conditions for the five pathways. The paper also provides a forward-looking assessment of the developments and branching points that may increase or decrease the feasibility of the pathways. As such, the paper goes beyond traditional techno-economic analyses of potential pathways that are commonly presented in studies of decarbonisation options. Arguably, this provides an improved starting point for formulating coherent and comprehensive policies for decarbonisation (see below).

The pathways identified are at different stages of maturity and furthermore their maturity vary across sectors. *Production and end-use optimisation* and *circular material flows* are pathways, which are pursued already to some extent, although considerable potentials remain if these pathways are further supported and developed. In particular, end-use optimisation is an undeveloped option with a large potential for learning and development of policy to increase feasibility. Recycling rates are relatively high in the steel industry but very low in the plastics industry and the industry is unlikely to rapidly change this pattern due to existing lock-ins and business models. To accelerate change, policy and learning needs to develop across new value chains (involving product design and standards, waste management, recycling technologies, etc.). Circular economy has become a prominent term in the international policy discourse, but there is still a long way to go to make it a reality. *Diversification of bio-feedstock use* is thus far evolving slowly in line with bio-economy policies and aims. Bio-feedstock use is considerable and evolving in the paper industry, meat and dairy substitutes are developing, but bio-feedstock is still virtually non-existent in plastics where it could provide a source of carbon to replace fossil feedstock. This can partly be explained by the fact that many bio-economy policies have focused on biotech for agriculture or biofuels for transport rather than targeting plastics. *Electrification with CCU* is a new item on the policy agenda where recent initiatives are driven primarily by parts of industry, notably with CCU demonstration projects and hydrogen in steelmaking, but not yet the paper industry. There is also nascent interest in the chemicals industry to electrify processes, use green hydrogen and apply CCU through chemical recycling of plastics. Although *CCS* has largely been discarded as an option for European electricity generation it remains an option for some industries, although the limited commitment to this pathway in the industries studied implies it will most likely remain a peripheral solution unless others, e.g., the cement industry, step forward to push its development.

Governance for supporting any of the pathways would benefit from paying close attention to the possibilities of making use of branching points to enable new lock-ins that support and strengthen the commitment of different groups of actors to the pathways. Branching points that can lead to convergence will exist at different times in different sectors. At the same time, conflicts will arise between different groups of stakeholders and these conflicts will not always be easy to resolve but may require strong actions from policymakers acknowledging that not everyone will be winners. This implies sequential policy strategies based on more or less shared understandings of what decarbonised industrial development imply, e.g., to pursue several pathways simultaneously. For steel, such visions are forming with several key global players committing to investing in electrifying their processes and improving recycling, whereas for plastics similar visions for decarbonisation are still absent. Without direction for carbon neutrality, governance is difficult. The pathways show that decarbonisation is likely to force value chains to cross over traditional boundaries (for example by sourcing biogenic carbon for plastics instead of fossil feedstock), although this is commonly not reflected in industrial technology roadmaps. This highlights the need for more system-wide analyses and roadmaps with couplings between industrial sub-sectors as well as with electricity systems and other infrastructure. A shared political and industrial commitment to these key pathways is important for successful implementation.

Policy making for decarbonisation has hitherto focused on transport and energy, but supporting and developing these industrial decarbonisation pathways will require agencies, policy makers, and academia to develop capabilities that go beyond these traditional focal areas. Our analysis of the conditions and feasibility for archetypal decarbonisation pathways shows that they require much more than a carbon price to develop. A case in point is end-use optimisation where a carbon price signal is likely to have no or very limited effect, for example, on material efficiency and dietary shifts. Even CCS requires more than a carbon price, e.g., planning and permits for plants and infrastructure, land-use regulation, or monitoring and metrics for product labelling and green market demand. To reach carbon neutrality also requires policy coordination so that, for example, bio-feedstock is not only diverted to energy and transport fuels. All of this points to the important role of government in creating the enabling conditions for industrial carbon neutrality, and the need for complementary policies in different domains (Nilsson et al., 2021). Strong governance capabilities and expertise on industrial decarbonisation will also be important to avoid the risks of over-compensation and windfall profits, unfair protectionism, or carbon leakage.

CRediT authorship contribution statement

Fredric Bauer: Conceptualization, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Teis Hansen:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Lars J Nilsson:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Project administration.

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.

Acknowledgements

An earlier version of this paper was presented at the 14th Nordic Environmental Social Science Conference, June 2019, and at the Achieving Net Zero Conference, September 2019. The research reported in this paper was part of the project REINVENT – Realising Innovation in Transitions for Decarbonisation, funded by the EU through its framework programme Horizon 2020 (grant agreement ID: 730053).

References

aan den Toorn, S.I., Tziva, M., Negro, S.O., Hekkert, M.P., Worrell, E., 2018. Climate innovations in meat and dairy. REINVENT Deliverable 2.5.

Åhman, M., Nilsson, L.J., Johansson, B., 2017. Global climate policy and deep decarbonization of energy-intensive industries. Clim. Policy 17, 634–649. https://doi.org/10.1080/14693062.2016.1167009.

Arning, K., Offermann-van Heek, J., Sternberg, A., Bardow, A., Ziefle, M., 2020. Risk-benefit perceptions and public acceptance of Carbon Capture and Utilization. Environ. Innov. Soc. Transit. 35, 292–308. https://doi.org/10.1016/j.eist.2019.05.003.

Bataille, C., 2020. Physical and policy pathways to net-zero emissions industry. WIREs Clim. Change 11, e633. https://doi.org/10.1002/wcc.633.

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., Rahbar, S., 2018. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. J. Clean. Prod. 187, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107.

Bauer, F., Coenen, L., Hansen, T., McCormick, K., Voytenko Palgan, Y., 2017. Technological innovation systems for biorefineries: a review of the literature. Biofuels Bioprod. Biorefin. 11, 534–548. https://doi.org/10.1002/bbb.1767.

Bauer, F., Ericsson, K., Hasselbalch, J., Nielsen, T.D., Nilsson, L.J., 2018. Climate innovations in the plastics industry: prospects for decarbonisation. REINVENT Deliverable 2.3.

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. Transit. 16, 51–64. https://doi.org/10.1016/j.eist.2015.07.003.

Björkman, B., Samuelsson, C., 2014. Recycling of steel. In: Worrell, E., Reuter, M.A (Eds.), Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists. Elsevier, pp. 65–83. https://doi.org/10.1016/B978-0-12-396459-5.00006-4.

Bocken, N., Ritala, P., 2021. Six ways to build circular business models. J. Bus. Strateg. https://doi.org/10.1108/JBS-11-2020-0258.

Bucknall, D.G., 2020. Plastics as a materials system in a circular economy: plastics in the Circular Economy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. Royal Society Publishing. https://doi.org/10.1098/rsta.2019.0268.

Bugge, M., Hansen, T., Klitkou, A., 2016. What is the bioeconomy? A review of the literature. Sustainability 8, 691. https://doi.org/10.3390/su8070691.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11, 1062–1176. https://doi.org/10.1039/c7ee02342a.

Cagno, E., Trianni, A., Abeelen, C., Worrell, E., Miggiano, F., 2015. Barriers and drivers for energy efficiency: different perspectives from an exploratory study in the Netherlands. Energy Convers. Manag. 102, 26–38. https://doi.org/10.1016/j.enconman.2015.04.018.

CEPI, 2019. Key Statistics 2019: European Pulp & Paper Industry. Confederation of European Paper Industries, Brussels.

Crijns-Graus, W., Yue, H., Zhang, S., Kermeli, K., Worrell, E., 2020. Energy efficiency improvement opportunities in the global industrial sector. Encyclopedia of Renewable and Sustainable Materials. Elsevier, pp. 377–388. https://doi.org/10.1016/b978-0-12-803581-8.10906-3.

Crook, J., Mousavi, A., 2016. The chlor-alkali process: a review of history and pollution. Environmental Forensics. https://doi.org/10.1080/15275922.2016.1177755.

Dagevos, H., Voordouw, J., 2017. Sustainability and meat consumption: is reduction realistic? Sustainability: Sci. Pract. Policy 9, 60–69. https://doi.org/10.1080/15487733.2013.11908115.

De Cian, E., Dasgupta, S., Hof, A.F., van Sluisveld, M.A.E., Köhler, J., Pfluger, B., van Vuuren, D.P., 2020. Actors, decision-making, and institutions in quantitative system modelling. Technol. Forecast. Soc. Change 151, 119480. https://doi.org/10.1016/j.techfore.2018.10.004.

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.

Dunant, C.F., Drewniok, M.P., Sansom, M., Corbey, S., Allwood, J.M., Cullen, J.M., 2017. Real and perceived barriers to steel reuse across the UK construction value chain. Resour. Conserv. Recycl. 126, 118–131. https://doi.org/10.1016/j.resconrec.2017.07.036.

Durmaz, T., 2018. The economics of CCS: why have CCS technologies not had an international breakthrough? Renew. Sustain. Energy Rev. 95, 328–340. https://doi.org/10.1016/j.rser.2018.07.007.

Elliott, T., Gillie, H., Thomson, A., 2020. European Union's plastic strategy and an impact assessment of the proposed directive on tackling single-use plastics items. Plastic Waste and Recycling. Elsevier, pp. 601–633. https://doi.org/10.1016/b978-0-12-817880-5.00024-4.

Energy Efficiency Financial Institutions Group, 2015. Energy Efficiency – the First Fuel For the EU Economy: How to Drive New Finance For Energy Efficiency Investments. European Commission, Brussels.

Ericsson, K., Nilsson, L.J., 2018. Climate innovations in the paper industry: prospects for decarbonisation. REINVENT Deliverable 2.4.

EUROFER, 2019. Low Carbon Roadmap: Pathways to a CO2-Neutral European Steel Industry. The European Steel Association, Brussels.

European Commission, 2017. 2017 assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive as required by Article 24(3) of the Energy Efficiency Directive 2012/27/EU. COM(2017) 687 final. European Commission, Brussels.

Foxon, T.J., Pearson, P.J.G., Arapostathis, S., Carlsson-Hyslop, A., Thornton, J., 2013. Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future. Energy Policy 52, 146–158. https://doi.org/10.1016/j.enpol.2012.04.030.

Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A., Soufani, K., 2020. Circular business models: a review. J. Clean. Prod. 277, 123741 https://doi.org/10.1016/j.jclepro.2020.123741.

Giddey, S., Badwal, S.P.S., Munnings, C., Dolan, M., 2017. Ammonia as a renewable energy transportation media. ACS Sustain. Chem. Eng. 5, 10231–10239. https://doi.org/10.1021/acssuschemeng.7b02219.

Goyal, N., Howlett, M., 2020. Who learns what in sustainability transitions? Environ. Innov. Soc. Transit. 34, 311–321. https://doi.org/10.1016/j.eist.2019.09.002.

Grin, J., Rotmans, J., Schot, J, 2010. Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change. Routledge, New York.

Hansen, T., Coenen, L., 2017. Unpacking resource mobilisation by incumbents for biorefineries: the role of micro-level factors for technological innovation system weaknesses. Technol. Anal. Strateg. Manag. 29, 500–513. https://doi.org/10.1080/09537325.2016.1249838.

Hansen, T., Keaney, M., Bulkeley, H.A., Cooper, M., Mölter, H., Nielsen, H., Pietzner, K., Sonesson, L.B., Stripple, J., aan den Toorn, S.I., Tziva, M., Tönjes, A., Vallentin, D., Van-Veelen, B., 2018. REINVENT Decarbonisation Innovations Database [Data set]. Zenodo. https://doi.org/10.5281/zenodo.1284945.

Harguess, J.M., Crespo, N.C., Hong, M.Y., 2020. Strategies to reduce meat consumption: a systematic literature review of experimental studies. Appetite 144, 104478. https://doi.org/10.1016/J.APPET.2019.104478.

Hartley, K., van Santen, R., Kirchherr, J., 2020. Policies for transitioning towards a circular economy: expectations from the European Union (EU). Resour. Conserv. Recycl. 155, 104634 https://doi.org/10.1016/j.resconrec.2019.104634.

Hellsmark, H., Hansen, T., 2020. A new dawn for (oil) incumbents within the bioeconomy? Trade-offs and lessons for policy. Energy Policy 145, 111763. https://doi.org/10.1016/j.enpol.2020.111763.

Hernandez, A.G., Cooper-Searle, S., Skelton, A.C.H., Cullen, J.M., 2018. Leveraging material efficiency as an energy and climate instrument for heavy industries in the EU. Energy Policy 120, 533–549. https://doi.org/10.1016/j.enpol.2018.05.055.

Hess, D.J., 2014. Sustainability transitions: a political coalition perspective. Res. Policy 43, 278–283. https://doi.org/10.1016/j.respol.2013.10.008.

Hulme, M., 2019. Climate emergency politics is dangerous. Issues Sci. Technol. 36, 23–25.

IEA, 2018. The future of petrochemicals: towards more sustainable plastics and fertilisers. Int. Energy Agency. https://doi.org/10.1787/9789264307414-en. Paris.

Iles, A., Martin, A., Rosen, C.M., 2017. Undoing chemical industry lock-ins: polyvinyl chloride and green chemistry. Hyle 23, 29–60.

Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: contributions and suggestions for research. Environ. Innov. Soc. Transit. 1, 41–57. https://doi.org/10.1016/j.eist.2011.04.006.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol. Anal. Strateg. Manag. 10, 175–198. https://doi.org/10.1080/09537329808524310.

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the Circular Economy: evidence From the European Union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Klöckner, K., Letmathe, P., 2020. Is the coherence of coal phase-out and electrolytic hydrogen production the golden path to effective decarbonisation? Appl. Energy 279, 115779. https://doi.org/10.1016/j.apenergy.2020.115779.

Knoop, K., Lechtenböhmer, T., Mölter, H., Tönjes, A., Witte, K., 2019. Drivers of low-carbon innovation. REINVENT Deliverable 3.6.

Kushnir, D., Hansen, T., Vogl, V., Åhman, M., 2020. Adopting hydrogen direct reduction for the Swedish steel industry: a technological innovation system (TIS) study. J. Clean. Prod. 242, 118185 https://doi.org/10.1016/j.jclepro.2019.118185.

L'Orange Seigo, S, Dohle, S, Siegrist, M., 2014. Public perception of carbon capture and storage (CCS): a review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2014.07.017.

Lechtenböhmer, S., Schneider, C., Vogl, V., Pätz, C., 2018. Climate innovations in the steel industry. REINVENT Deliverable 2.2.

Lee, D., Hess, D.J., 2019. Incumbent resistance and the solar transition: changing opportunity structures and framing strategies. Environ. Innov. Soc. Transit. 33, 183–195. https://doi.org/10.1016/j.eist.2019.05.005.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., Fennell, P.S., 2017. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. Int. J. Greenhouse Gas Control 61, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020.

Lühmann, M., 2020. Whose European bioeconomy? Relations of forces in the shaping of an updated EU bioeconomy strategy. Environ. Dev. 35, 100547 https://doi.org/10.1016/j.envdev.2020.100547.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.

Mazzetto, A.M., Bishop, G., Styles, D., Arndt, C., Brook, R., Chadwick, D., 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems. J. Clean. Prod. 277, 124108 https://doi.org/10.1016/j.jclepro.2020.124108.

Menrad, K., Klein, A., Kurka, S., 2009. Interest of industrial actors in biorefinery concepts in Europe. Biofuels Bioprod. Biorefin. 3, 384–394. https://doi.org/10.1002/bbb.144.

Middleton, R.S., Yaw, S., 2018. The cost of getting CCS wrong: uncertainty, infrastructure design, and stranded CO2. Int. J. Greenhouse Gas Control 70, 1–11. https://doi.org/10.1016/j.ijggc.2017.12.011.

Mikunda, T., Kober, T., de Coninck, H., Bazilian, M., Rösler, H., van der Zwaan, B., 2014. Designing policy for deployment of CCS in industry. Clim. Policy 14, 665–676. https://doi.org/10.1080/14693062.2014.905441.

Neff, R.A., Edwards, D., Palmer, A., Ramsing, R., Righter, A., Wolfson, J., 2018. Reducing meat consumption in the USA: a nationally representative survey of attitudes and behaviours. Public Health Nutr. 21, 1835–1844. https://doi.org/10.1017/S1368980017004190.

Nilsson, L.J., Bauer, F., Åhman, M., Andersson, F.N.G., Bataille, C., de la Rue du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., van Sluisveld, M., Vogl, V., 2021. An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. Clim. Policy 21 (8), 1053–1065. https://doi.org/10.1080/14693062.2021.1957665.

Normann, H.E., 2015. The role of politics in sustainable transitions: the rise and decline of offshore wind in Norway. Environ. Innov. Soc. Transit. 15, 180–193. https://doi.org/10.1016/j.eist.2014.11.002.

Oikonomou, V., Becchis, F., Steg, L., Russolillo, D., 2009. Energy saving and energy efficiency concepts for policy making. Energy Policy 37, 4787–4796. https://doi.org/10.1016/j.enpol.2009.06.035.

Ollier, L., Melliger, M., Lilliestam, J., 2020. Friends or foes? Political synergy or competition between renewable energy and energy efficiency policy. Energies 13, 6339. https://doi.org/10.3390/en13236339.

Palm, E., Hasselbalch, J., Holmberg, K., Nielsen, T.D., 2021. Narrating plastics governance: policy narratives in the European plastics strategy. Environ. Polit. 1–21. https://doi.org/10.1080/09644016.2021.1915020. In press.

Ren, G., Liu, J., Wan, J., Guo, Y., Yu, D., 2017. Overview of wind power intermittency: impacts, measurements, and mitigation solutions. Appl. Energy 204, 47–65. https://doi.org/10.1016/j.apenergy.2017.06.098.

Repo, P., Anttonen, M., Mykkänen, J., Lammi, M., 2018. Lack of congruence between European citizen perspectives and policies on circular economy. Eur. J. Sustain. Dev. 7, 249–264. https://doi.org/10.14207/ejsd.2018.v7n1p249.

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S.A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E.D., de la Rue du Can, S., Sisson, B., Williams, M., Katzenberger, J., Burtraw, D., Sethi, G., Ping, H., Danielson, D., Lu, H., Lorber, T., Dinkel, J., Helseth, J., 2020. Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. Appl. Energy 266, 114848. https://doi.org/10.1016/j.apenergy.2020.114848.

Rosegrant, M.W., Msangi, S., 2014. Consensus and contention in the food-versus-fuel debate. Annu. Rev. Environ. Resour. 39, 271–294. https://doi.org/10.1146/annurev-environ-031813-132233.

Rosenbloom, D., 2017. Pathways: an emerging concept for the theory and governance of low-carbon transitions. Global Environ. Change 43, 37–50. https://doi.org/10.1016/j.gloenvcha.2016.12.011.

Rosenbloom, D., Haley, B., Meadowcroft, J., 2018. Critical choices and the politics of decarbonization pathways: exploring branching points surrounding low-carbon transitions in Canadian electricity systems. Energy Res. Soc. Sci. 37, 22–36. https://doi.org/10.1016/j.erss.2017.09.022.

Saba, S.M., Müller, M., Robinius, M., Stolten, D., 2018. The investment costs of electrolysis – a comparison of cost studies from the past 30 years. Int. J. Hydrogen Energy 43 (3), 1209–1223. https://doi.org/10.1016/j.ijhydene.2017.11.115.

Schneider, C., Friege, J., Samadi, S., Lechtenböhmer, S., van Sluisveld, M., Hof, A., van Vuuren, D., 2017. Existing visions and scenarios. REINVENT Deliverable 4.1.

Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Technol. Anal. Strateg. Manag. 20, 537–554. https://doi.org/10.1080/09537320802292651.

Smink, M.M., Hekkert, M.P., Negro, S.O., 2015. Keeping sustainable innovation on a leash? Exploring incumbents' institutional strategies. Bus. Strateg. Environ. 24, 86–101. https://doi.org/10.1002/bse.1808.

Stirling, A., 2011. Pluralising progress: from integrative transitions to transformative diversity. Environ. Innov. Soc. Transit. 1, 82–88. https://doi.org/10.1016/j.eist.2011.03.005.

Stirling, A., 2008. Opening up" and "closing down": power, participation, and pluralism in the social appraisal of technology. Sci. Technol. Hum. Values 33, 262–294. https://doi.org/10.1177/0162243907311265.

Tcvetkov, P., Cherepovitsyn, A., Fedoseev, S., 2019. Public perception of carbon capture and storage: a state-of-the-art overview. Heliyon 5 (12), e02845. https://doi.org/10.1016/j.heliyon.2019.e02845.

Tönjes, A., Mölter, H., Pastowski, A., Witte, K., 2019. Summary of decarbonisation case studies. REINVENT Deliverable 3.3.

Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., van Vuuren, D., 2015. Evaluating sustainability transitions pathways: bridging analytical approaches to address governance challenges. Glob. Environ. Change 35, 239–253. https://doi.org/10.1016/j.gloenvcha.2015.08.010.

Turnheim, B., Nykvist, B., 2019. Opening up the feasibility of sustainability transitions pathways (STPs): representations, potentials, and conditions. Res. Policy 48, 775–788 https://doi.org/S0048733318302968.

Tziva, M., Negro, S.O., Kalfagianni, A., Hekkert, M.P., 2020. Understanding the protein transition: the rise of plant-based meat substitutes. .mental Innov. Soc. Transit. 35, 217–231. https://doi.org/10.1016/j.eist.2019.09.004.

Valve, H., Ekholm, P., Luostarinen, S., 2020. The Circular Nutrient Economy: Needs and Potentials of Nutrient Recycling. In: Brandão, M., Lazarevic, D., Finnveden, G. (Eds.), Handbook of the Circular Economy. Edward Elgar Publishing, Cheltenham, pp. 358–368. https://doi.org/10.4337/9781788972727.00037.

van Mierlo, B., Beers, P.J., 2020. Understanding and governing learning in sustainability transitions: a review. Environ. Innov. Soc. Transit. 34, 255–269. https://doi.org/10.1016/j.eist.2018.08.002.

van Mierlo, B., Halbe, J., Beers, P.J., Scholz, G., Vinke-de Kruijf, J., 2020. Learning about learning in sustainability transitions. Environ. Innov. Soc. Transit. 34, 251–254. https://doi.org/10.1016/j.eist.2019.11.001.

van Sluisveld, M.A.E., de Boer, H.S., Daioglou, V., Hof, A.F., van Vuuren, D.P., 2021. A race to zero - assessing the position of heavy industry in a global net-zero CO2 emissions context. Energy Clim. Change 2, 100051. https://doi.org/10.1016/j.egycc.2021.100051.

van Sluisveld, M.A.E., Hof, A.F., Carrara, S., Geels, F.W., Nilsson, M., Rogge, K., Turnheim, B., van Vuuren, D.P., 2020. Aligning integrated assessment modelling with socio-technical transition insights: an application to low-carbon energy scenario analysis in Europe. Technol. Forecast. Soc. Change 151, 119177. https://doi.org/10.1016/j.techfore.2017.10.024.

Vanderreydt, I., Rommens, T., Tenhunen, A., Mortensen, L.F., Tange, I., 2021. Greenhouse Gas Emissions and Natural Capital Implications of Plastics (including biobased Plastics). Greenhouse Gas Emissions and Natural Capital Implications of Plastics (including biobased Plastics). European Topic Centre on Waste and Materials in a Green Economy Mol.

Vogl, V., Åhman, M., 2019. What is green steel? Towards a strategic decision tool for decarbonising EU steel. 4th ESTAD proceedings, P532.

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., Chen, .W..-Q., 2021. Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. Nat. Commun. 12, 2066. https://doi.org/10.1038/s41467-021-22245-6.

Weber, V., 2021. Are we ready for the ship transport of CO 2 for CCS? Crude solutions from international and European law. In: Review of European, Comparative & International Environmental Law, p. 12399. https://doi.org/10.1111/reel.12399.

Wesseling, J.H., Lechtenböhmer, S., Åhman, M., Nilsson, L.J., Worrell, E., Coenen, L., 2017. The transition of energy intensive processing industries towards deep decarbonization: characteristics and implications for future research. Renew. Sustain. Energy Rev. 79, 1303–1313. https://doi.org/10.1016/j.rser.2017.05.156.

Wydra, S., Hüsing, B., Köhler, J., Schwarz, A., Schirrmeister, E., Voglhuber-Slavinsky, A., 2021. Transition to the bioeconomy – analysis and scenarios for selected niches. J. Clean. Prod. 294, 126092 https://doi.org/10.1016/j.jclepro.2021.126092.

Zheng, J., Suh, S., 2019. Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Change 9, 374–378. https://doi.org/10.1038/s41558-019-0459-z.