Climate Innovations and New Pathways for Decarbonisation

Deliverable 2.8

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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 and investment opportunities. In this analysis we move beyond that to identify pathways that span across value chains in the sectors focused upon in the REINVENT project. Employing the notion of pathways can be a way of approaching governance for transitions in a way that appreciates not only the dynamics of change, but also acknowledges that those dynamics themselves will change as transformations unfold. The pathways as presented in the present paper were inductively identified in a multi-stage process from materials produced collectively in the REINVENT project. The identified pathways are i) production and use optimisation, ii) electrification with CCU, iii) circular material flows, and iv) 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. Such a policy agenda must cover coordination across a broad spectrum of instruments in its implementation, e.g. planning, permitting, land-use regulation, investments in renewable electricity generation and transmission, and new infrastructures for hydrogen and CCU. A key policy challenge will be how to de-risk investment and create market demand in ways that do not lead to industry windfall profits, unfair protectionism, or carbon leakage.

1 Introduction

Industrial processes account for about a third of global energy demand and a slightly higher share of GHG emissions, and energy-intensive processing industries are responsible for the majority (Wesseling *et al.* 2017). Although these sectors have been called “hard to abate” and to a large degree overlooked in climate policy (Åhman *et al.* 2017) their challenges, potentials, and possibilities to be part of the low-carbon transitions deserves closer scrutiny, especially to enable the implementation of policies for innovation and transition (Bataille *et al.* 2018).

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 transition pathways for these sectors towards low-carbon configurations. We assess their feasibility through an operationalisation and empirical analysis of transition pathways that largely builds on the framework presented by Turnheim and Nykvist (2019). We focus on four key economic natural resource-based economic sectors in Europe. These are sectors where decarbonisation is particularly challenging, and where low carbon transitions are relatively unexplored: pulp and paper, meat and dairy, steel, and plastics. While these sectors represent a large share of the European economy (in economic contribution, employment and greenhouse gas emissions), they are also central to almost all parts of society. Further, we do not only consider the production stage but include the whole value chain in the analysis, and we do it from within, i.e. taking a bottom-up approach to identifying trends, visions, and strategies towards decarbonisation through innovation. Visions and strategies from within the sectors and among value chain stakeholders are important to understand and combine with technology and economy-driven models for low-carbon transition pathways. The analysis draws on previous work within the REINVENT project that has mapped innovations throughout these value chains.

2 Identifying pathways and assessing their feasibility

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 2008, 2011). 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. 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 as a singularity. 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 and investment opportunities, i.e. transforming socio-technical pathways into techno-economic ones (Rosenbloom 2017).

Employing the notion of pathways can be a way of approaching governance for transitions in a way 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 according to the framework developed by Turnheim & Nykvist (2019) which will be used. The framework differentiates between analysing i) the conditions for pathways, in terms of the maturity of the options included, the possibilities for integration with existing industries and infrastructures, the societal acceptability, as well as the political acceptability and delivery, and ii) the decarbonisation potential of the pathway in terms of future learning that can increase or decrease the feasibility of the pathway, and branching points that can strengthen or weaken the feasibility of the pathway.

Through this assessment we capture what types of interventions are needed to facilitate decarbonisation along the different pathways for the stages identified in the REINVENT analytical framework (Bulkeley and Stripple 2018). The maturity and learning for each pathway capture the *innovation dynamics*; political acceptability and delivery capture the necessary *governance initiatives*; integration and societal acceptability capture the *intervention capacities* in terms of social and material practices needed; and branching points are essential to identify the potential for support and *uptake* (or lack thereof).

The pathways as presented in the present paper were inductively identified in a multi-stage process from materials produced collectively in the REINVENT project. Sector-level analyses that on a macro level analyse the structural characteristics of innovation and the potential for decarbonisation were used to understand the most pertinent challenges for decarbonising the sectors (aan den Toorn *et al.* 2018, Bauer *et al.* 2018, Ericsson and Nilsson 2018, Lechtenböhmer *et al.* 2018). A database of current innovation initiatives in each of the studied sectors described and characterised the innovations with respect to key attributes such as drivers and decarbonisation mode was used to provide in-depth examples of how and where decarbonisation initiatives are undertaken (Hansen *et al.* 2018). Combining the macro- and micro-level data we identified trajectories for low-carbon innovations in each sector. Comparing the trajectories and opportunities in each sector we identified shared patterns. These shared patterns are the pathways described in chapter 5 and assessed using the framework described above.

3 Sector Trajectories

3.1 Plastics

Plastics are not only associated with large carbon emissions from the energy intensive primary production, estimated to around 860 Mtons CO2-eq globally (Hamilton *et al.* 2019) which correspond to around 120 Mtons CO2-eq from the European production with the main share of the missions originating from the steam cracking process. However, the plastics themselves also embody large volumes of fossil carbon which are released if plastic waste is finally incinerated. Plastic value chains often span across many industries as plastic components are often only a part of a finished product, such as vehicles, buildings, and electronics, or constitute its packaging. However, as almost all plastics (~99 % of the 360 million tonnes used annually) are produced from fossil resources such as petroleum naphtha or natural gas liquids, the decarbonisation challenge is similar. The large, global primary producer of polymers, e.g. SABIC, Sinopec, and ExxonMobil, are often closely connected to, or even part of, petroleum and energy conglomerates which presents a structural barrier for decarbonising the production. At the same time some of these global petrochemical actors are also the ones developing biobased plastics, e.g. Braskem (with Petrobras as large owner) and NatureWorks (partially owned by PTT). Leveraging resources of the strong global actors is likely to be necessary for decarbonisation to gain momentum. Downstream actors, compounders and converters, that process polymers into plastic products are commonly SMEs with less resources.

From the macro-level analysis and the database four main trajectories have been identified for decarbonising plastics: i) 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 requires new requirements and standards for 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 CCU and power-to-X technologies to produce plastics through carbon capture and large scale electrified hydrogen production.

3.2 Pulp and Paper

Value chains for paper and board are primarily connected to packaging, the use of graphic papers, sanitary products and a diminishing use of newsprint. Recycling rates for both paper and board are significantly higher than those for plastics, but can still be increased. The production of pulp and paper is based on biomass resources (wood) and recycled paper, but uses a significant share of fossil energy – the sector is associated with around 32 Mtons CO2-eq of GHG emissions. The majority of fossil fuels is used to supply heat at moderate temperatures, e.g. for drying of paper, which could be decarbonised with significant but reasonable efforts through investments in improved energy efficiency, biofuels, or electrified heating processes. Barriers exist in terms of inertia due to the several decades long investment cycles and large scale of investments in the industry. Beyond decarbonising internal fuel use the industry has the potential to contribute to decarbonising other sector by converting traditional pulp (and paper) mills to so called biorefineries, diversifying from traditional markets for paper and board.

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. In a carbon constrained world non-fossil carbon resources become crucial, which would also put pressure on implementing carbon capture and use (CCU) and chemical synthesis technologies at pulp mills, which have large emissions of biogenic CO2 from its boilers, or converting these boilers to gasifiers that could directly produce syngas. CCU options are however not yet really part of the discourse within the pulp and paper industry. They would also require large investments in renewable electricity to provide the hydrogen necessary for chemical synthesis through electrolysis, or imports of hydrogen.

3.3 Steel

Steel is a crucial material in many value chains, of which the most prominent are construction, metalware, and transportation. The European steel industry is responsible for emissions amounting to around 235 Mtons CO2-eq in total. The majority of the emissions (~75%) originate from the blast furnaces used for primary steel making, which uses large volumes of coke to reduce the iron ore. This is also the process that has the greatest potential radical changes for decarbonising the industry. Downstream processing (hot and cold rolling) also requires significant energy inputs, both thermal and mechanical, which corresponds to another 17% of the GHG emissions. Similar to the other energy-intensive process industries investments in new process technologies are very large and the investment-cycles are long.

The trajectories towards decarbonisation that were identified for the steel sector are i) efficiency improvements in both production processes and downstream material use to reduce the need for energy inputs and 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, or finally iv) managing the carbon emissions through carbon capture and use or storage (CCU or CCS).

3.4 Meat and dairy

The European meat and dairy industries are responsible for around 700 Mtons of Mt CO2-eq, but what differentiates this sector from the others is that the majority of these emissions are other emissions than CO2 from fossil energy. The main emission types and sources are CH4 from enteric fermentation and manure management together with N2O 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.

The trajectories towards decarbonisation identified in the sector 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 Cross-Sectoral Pathways

Based on the above described sectoral trajectories and capacities in the studied value chains we identify four different pathways that span across the different and can be thought of as archetypal pathways for industrial decarbonisation. These four pathways are i) production and use optimisation, ii) electrification with CCU, iii) circular material flows, and iv) diversification of bio-feedstock use and 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.

Table 1. Assessment of current **conditions** for pathways

	Maturity of options	Integration with clusters, industries and infrastructure	Societal (social and industrial) acceptability	Political acceptability and delivery
Production and use optimisation	Developed: range from energy efficient equipment to renewable fuels/energy sources as well as integrated/shared use of products/utilities	Developed: long-term focus on energy efficiency in process industries	Developed, although with barriers	Fragmented: energy and emissions efficiency key to EU policies; delivery limited as the potential for complete decarbonisation is questioned
Electrification with CCU	Fragmented: technological modules are mature, but not complete CCU systems	Undeveloped: electrical power system not adapted for electrification, CCU infrastructure lacking.	Fragmented: fear for high electricity prices but capturing carbon most likely acceptable	Limited: little attention to large expansion of power generation and hesitancy towards CCU
Circular material flows	Fragmented: high recycling of some steel and fibre qualities, but not other materials	Fragmented: recycling of some materials well developed	Fragmented: increasing acceptability for recycling, yet limited understanding for its effects in some sectors	Acceptability developed, but delivery limited; 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, construction materials, textile fibres)	Limited: several projects across industries but no aggressive push; reconfiguring of clusters and infrastructure slow.	Fragmented: positive view of renewables but concerns about land use change and biodiversity	Fragmented: support for using bio-feedstocks, but conflicting with (i)LUC, biodiversity, and other environmental concerns

Assessment terms: undeveloped; limited; developed; fragmented

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 use optimisation	Continued improved efficiency of processes and equipment	Rapid learning curves for renewables leading to decreasing energy costs; limited possibilities to reach complete decarbonisation	Strong commitments to existing processes in business organisations (alternatives are unreliable)	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 leading to decreasing energy costs	Rapid learning curves for renewables competes with CC;	Establishment of CC standards; industrial commitments to investments in renewable electricity	Political coalition building against CCU and electrification
Circular material flows	Efficient and effective material management and sorting systems; innovations in metal recycling	Increased diffusion of traditional waste incineration/sewage treatment systems	Regulations against virgin resource exploitation; industrial commitments and standards for recycled materials	Restrictions on trading waste/recyclates; requirements 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;	Rapid learning curves for CCU competes with diversification of bio-feedstock use;	Establishment of new value chains through collaborations/merger; reduced restrictions against GMO	Restrictions on land/bio-feedstock use for new/specific purposes

4.1 Production and use optimisation

Optimising processes to reduce energy demand and emissions has been a prioritised activity on the innovation agenda of the energy-intensive 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. The options do however vary significantly between the energy intensive process industries and the meat and dairy industries. 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. However, whether this pathway can actually deliver a complete decarbonisation of the industries is strongly questioned, although it promises to reduce emissions significantly in the short term.

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, 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. 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 fact that electricity with no GHG emissions will be available throughout Europe at low costs. It further assumes a significant expansion of generation capacity that will allow for industries to implement processes that use electricity for completely new purposes, such as large scale production of hydrogen through electrolysis, heating and drying in many different stages of the value chains of the studied industries. CCU is thus far mainly envisioned as an add-on to existing industries using fossil resources such as steel-works and in this way has a limited decarbonisation potential.

Abundant electricity available at low cost is however also a key enabler for CCU from biogenic origin, e.g. from combustion of forest residues at pulp mills, for the production of plastics and chemicals as these processes will require energy for the capture processes and also hydrogen for downstream conversion of the captured carbon. 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 locally.

4.3 Circular materials 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. 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, whereas plastics are recycled to a very low degree – 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.

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 (European Commission 2015) and has since worked to operationalise it, e.g. through the recent strategy for plastics (European Commission 2018). Political acceptability for this pathway is thus well developed, but delivery is this far very limited. 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. Societal acceptance for circular modes of production is seemingly rather well developed among consumers, although food is likely to be a more sensitive issue regarding recycling of nutrients, feeding waste to animals and other solutions. Recent voluntary recycling schemes for textiles initiated by large brand-owners also show a willingness to consider recycling for other types of products than those that have hitherto been strictly regulated, such as packaging. However, although many industrial actors support circular flows it is difficult to implement. Changing business models towards services instead of products is often claimed to be and key enabler for the circular economy, as it would require manufacturers to focus on making products with superior longevity and reparability. This is however more likely to be the case 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.

4.4 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. 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 (bio-PE and PLA). Steel and metallurgical industries are experimenting in a limited scale with biogas and wood-base coke substitutes. 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.

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 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. Political acceptability is generally seen as well developed, but delivery limited. Following the unforeseen complications around the development for liquid biofuels, extending policy support to new domains has been hesitant.

5 Conclusions and implications

The sectoral mappings reveal the complexity and diversity of value chains, their decarbonisation options and potentials, as well as differences in innovation dynamics, governance, capacities, and uptake due the different structures of the sectors. 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 also align along four transition pathways (i.e., Production and use optimisation, Electrification with CCU, 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.

The pathways are at different stages of maturity and furthermore their maturity vary across sectors. Production and use optimisation and circular material flows are largely pursued already, although considerable potentials remain. For example, recycling rates are very high in the steel industry but very low in the plastics industry. Bio-feedstock use is thus far changing slowly but it is also subject to emerging bio-economy policies. Bio-feedstock use is considerable and evolving in the paper industry, meat and dairy substitutes are developing, but bio-feedstock is virtually non-existent in steel and plastics. Electrification with CCU is a new item on the policy agenda where recent initiatives are driven primarily by parts of industry (notably steel, but not the paper industry).

Governance for supporting any of the four pathways must pay close attention to the possibilities of making use of branching points to enable new lock-ins that support and strengthen the commitment to the pathways. Branching points that can lead to convergence will exist at different times in different sectors. This implies sequential policy strategies based on more or less shared understandings of what decarbonised industrial development imply. For steel, such visions are forming. For plastics there are no such visions and without direction, governance is difficult. The pathways show that decarbonisation is likely to force value chains to cross over traditional boundaries, although this is commonly not reflected in industrial technology roadmaps which highlights the need for this type of cross-sectoral analyses. 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 pathways will require agencies, policy makers, and academia to develop capabilities that go beyond these current focal areas. Realising the pathways will require much more than a carbon price. It requires planning, permitting, land-use regulation, investments in renewable electricity generation and transmission, and new infrastructures for hydrogen and CCU. It also requires policy coordination so that, for example, bio-feedstock is not only diverted to transport fuels.

The identified pathways can be pursued and co-evolved in parallel and partly sequentially. A key policy challenge will be how to de-risk investment and create market demand in ways that do not lead to industry windfall profits, unfair protectionism, or carbon leakage.

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