Assessment of the Broader Impacts of Decarbonisation

Deliverable 3.7

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Summary

Deliverable 3.7 focuses on the environmental, economic and social impacts and implications of the innovations under investigation within REINVENT. It aims to qualitatively assess these through the development of a set of four archetypal innovation pathways for each of the sectors under study. These innovation pathways integrate the findings and prior analyses from WP1, 2 & 3 with WP4 & 5 modelling and scenarios. This deliverable maps innovations investigated by REINVENT along two axes, resulting in a quadrant diagram highlighting archetypal innovation pathways for sector development out to 2050. These pathways enable the identification of future potential environmental, economic and social impacts of each pathway and map out expected implications relating to the decarbonisation potential, maturation of identified innovations, and developments of social norms and expectations.

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1. Introduction

Sectoral stakeholders, from both private industry and public policy frequently refer to the necessity of a variety of measures that will need to be undertaken to achieve net zero emissions by 2050. While decarbonisation will need to be tackled utilising a variety of tools, technologies and approaches, there are three broad problems with this assumption when we are interested in assessing the economic, environmental and social impacts and implications associated with multiple innovation types. First, this simple additive approach is frequently deployed as rhetorical cover for a hands-off regulatory environment combined with broad spectrum public support for innovations. This is built upon a problematic economic reductivism that assumes a strict state/market dichotomy, where the former solely regulates while the latter innovates (Mazzucato, 2015).

Second, it often proceeds from a technological reductivism that fails to recognise that the innovations and measures themselves do not develop independently of the broader institutional, social and cultural (infra)structures within which they are embedded. The technological reductivism involved here means this approach is often blind to how innovations interact positively or negatively and the ways in which choices determine the lock-in of certain paths and trajectories.

Third, it tends to fetishise the process of innovation itself. This again means the importance of the broader institutional, social and cultural matrices within which specific innovations are embedded is missed. Here, this results in a narrow focus on direct innovations within the sector, and a failure to consider innovations and changes that work indirectly on a sector's value chain. An example here is the effect of urban transportation regulations and mass transit planning in order to increase air quality, reducing GHG emissions in the steel sector through an overall reduction in the demand for steel for cars.

Within the REINVENT project, the sectors under discussion are considered as socio-technical systems operating through complex value networks and where low carbon transitions are fundamentally shaped by the interplay of inertia and innovation (Bulkeley and Stripple, 2018). This basic framework informs this report, which develops a series of archetypal innovation pathways in order to assess the future environmental, economic and social impacts and implications of the innovations under investigation within REINVENT. This approach highlights points of tension between pathways, anticipating points of future systemic lock-in (Wesseling and Van der Vooren, 2017) that would slow or prevent sectoral decarbonisation by 2050.

2. Archetypal innovation pathways

In the wake of the Paris agreement foresight processes have become an increasingly important and explicitly recognised means to imagine and govern climate futures (Hajer and Pelzer, 2018; Vervoort and Gupta 2018). In order to assess the economic, environmental and social impacts and implications of the innovations under investigation within REINVENT this report undertakes a socio-technical foresight exercise, in order to develop a set of four archetypal innovation pathways for each of the sectors under study. The futuring process couples 'techno-scientific potentials and prospects with envisioned societal change and new social arrangements' (Konrad and Böhle, 2019) in order to develop future scenarios. These processes seek to make futures visible, and thereby governable.

In broad outline, two forms of futuring process can be discerned, descriptive and normative (McDowell and Eames, 2006). Descriptive approaches include forecasts which undertake formal quantitative and modelling activities to extrapolate from current trends; exploratory scenarios emphasising drivers and barriers; and technical scenarios which focus on technical feasibility. Normative approaches include visioning techniques of desirable futures; backcasts and pathways which begin from predetermined end-points and then develop possible pathways capable of reaching these; and roadmaps which describe the requirements for desirable futures.

The approach undertaken here is a qualitative normative pathway process. One that takes inspiration from the 2018 Material Economics report 'Industrial Transformation 2050'[1]. Here, three pathways are identified for industries in Europe: A New Processes pathway – focuses on the development of new core industrial processes; a Circular Economy pathway – emphasising increased materials recirculation and efficiency; and a Carbon capture pathway – which relies on the scale-up and roll-out of CCS. Each of these pathways draw from four different strategies for emissions reductions: Increased materials efficiency; high-quality materials recirculation; new production processes; carbon capture and storage/use. The pathways deploy these strategies with a variety if emphases.

The pathways developed in this report are similar to the initial strategies identified by Material Economics. The overall approach differs in three respects however:

[1] As REINVENT is focused on the plastic, steel, meat & dairy and pulp & paper industries, aggregating across innovations requires a certain amount of abstraction in order to classify particular pathways appropriate to all four sectors. In this case, a quadrant diagram approach was chosen to classify innovations into specific archetypal categories.

[2] These individual archetypal categories were then taken as the sole basis for archetypal pathways. They were not combined to produce composite pathways as was undertaken by Material Economics in developing their New Process, Circular Economy and Carbon Capture pathways.

[3] This means that each innovation pathway identified here is not to be considered as a full roadmap. The purpose of this report is not to provide complete qualitative pathways, but rather to develop a series of pathway development grids that (1) feed into ongoing modelling and scenario work within the REINVENT project and (2) to highlight points of tension and anticipate future systemic lock-ins related to broader economic, environmental and social issues.

A 2x2 grid (quadrant diagram) is a commonly used tool within the futures literature (e.g. Raven 2014; Raven and Elahi 2015) to enable a broader, strategic forecasting process by extrapolating macrosocial and macroeconomic trends and using these as a frame to develop very specific future pathways within each quadrant. REINVENT innovates on this process in two ways. By basing a quadrant diagram on innovation typologies along two linked axes, we can develop a futuring framework that:

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[1] Indeed, the steel and plastics pathway development grids themselves draw heavily on this report.

- Is not reliant on extrapolated macrosocial and macroeconomic trends, but rather highlights potential future environmental, social and economic impacts as part of the innovation pathway development.
- Can be translated into the Integrated Assessment Models utilised within REINVENT to investigate potential decarbonisation and macroeconomic trends that result from the adoption of particular pathways.

This approach draws from: classical science fiction prototyping, the Science & Technology Studies infrastructural analysis of Keller Easterling (2014) and the REINVENT analytical framework (Bulkeley and Stripple, 2018) in order to define an innovation-decarbonisation typological space (the quadrant map). This is then used to identify possibility spaces opened up by certain archetypal innovation trajectories – through the production of normative narrative scenarios. This enables innovations for decarbonisation to be approached in a way that avoids simply a bottom-up technological determinism, as well as the top-down imposition of reified macro-social and macro-economic categories. It therefore establishes a framework for thinking about archetypal innovation pathways as innovation infrastructures rather than as discrete innovation technologies, and crucially identifies their environmental, economic and social impacts and implications as part of this broader innovation infrastructure.

3. Typological innovation mapping

REINVENT makes use of a quadrant diagram approach in order to develop qualitative scenarios that aggregate and extrapolate information on innovations from WP2 and WP3 data in order to feed into WP4 modelling work and WP5 analyses. This report develops a quadrant diagram of archetypal innovation pathways according to decarbonisation point and decarbonisation type.

This process develops the IPCC AR5 decarbonisation typology within the REINVENT analytical framework. First, it takes the decarbonisation points identified by Fischedick et al. 2014 (numbered circles 1-5 in fig. 1 below) and overlays a binary distinction between process and product/service. First, process decarbonisation points refer to those innovations to manufacturing processes. Product/service focused decarbonisation points are generated through innovations developing new products, or that are focused on the services provided by or demand for existing products. Second, an additional binary distinction is made between emissions reduction types that seek to either reduce emissions from existing manufacturing processes or embedded within existing commodities, and emissions reductions resulting from avoidance through e.g. substituting processes and products or avoiding elements of these altogether.

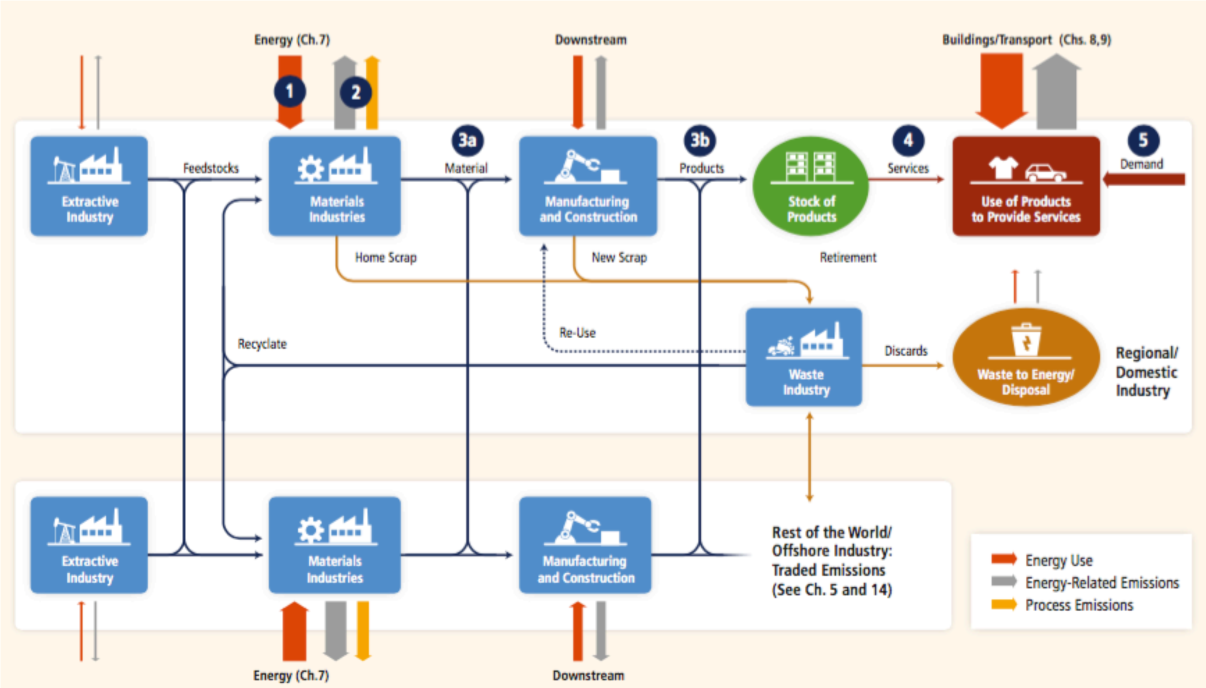

Figure 1: Industrial activity over the supply chain (Fischedick et al. 2014)

Treating these as the axes of a two-dimensional grid produces the quadrant diagram in fig. 2. Where each quadrant identifies innovations according to decarbonisation points and types that they undertake. This draws directly on the REINVENT Decarbonisation Innovations Database (D2.1), sectoral reports (D2.2-D2.6) and Innovation biographies (D2.7) undertaken within WP2, as well as the in-depth case studies (D3.3) undertaken within WP3 and further desk-based research.

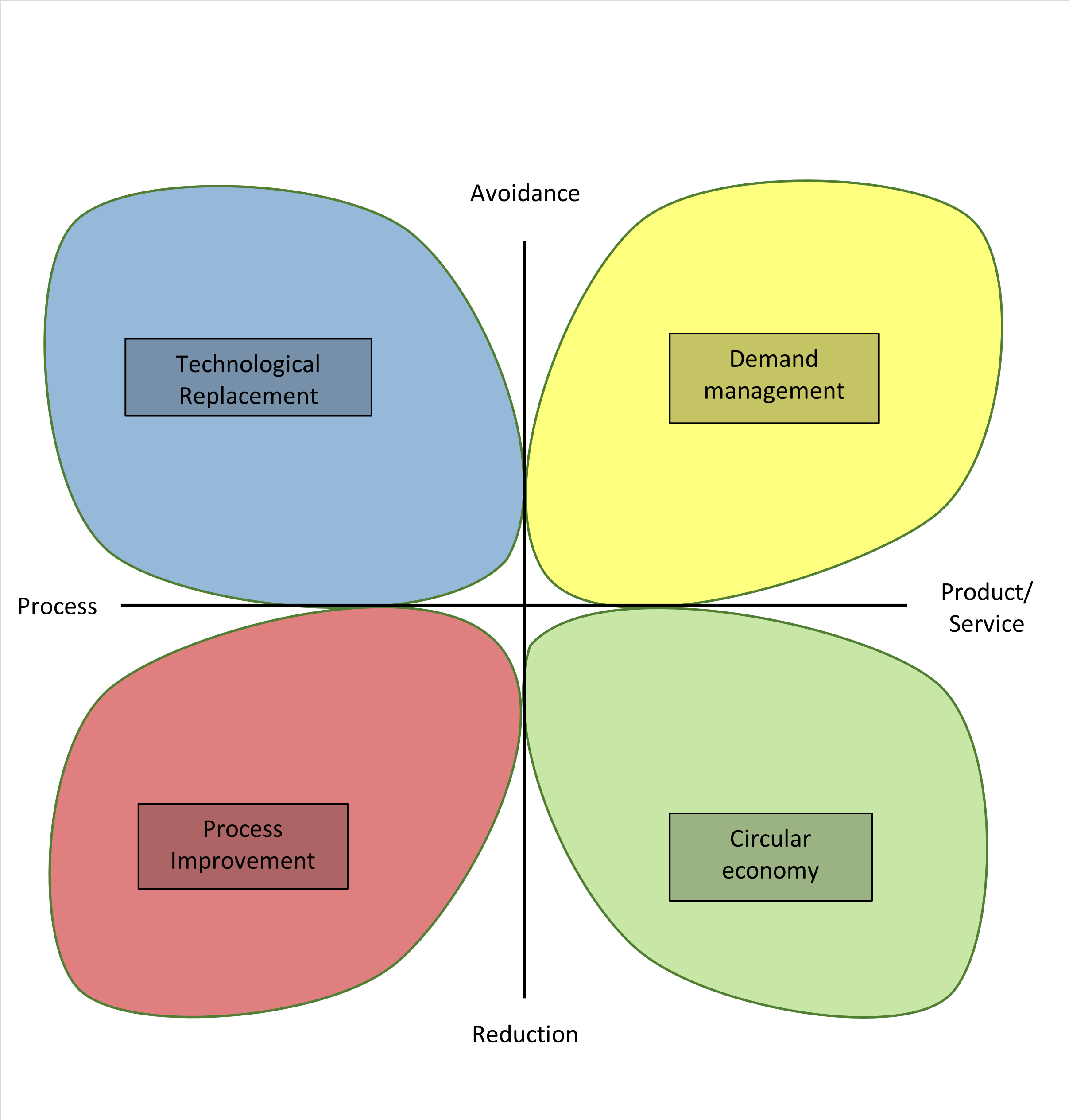

Figure 2: Quadrant diagram showing archetypal innovation pathways

1. **Technological replacement** (process - avoidance)
   Example innovations within each sector:

   - **Steel:** Electrowinning, Hydrogen direct reduction
   - **Plastics:** Synvina, bioplastics, use of CCU e.g. Aircarbon, plastic foam from waste CO2, Ingeo
   - **Pulp & paper:** REEP, alternative materials
   - **Meat & dairy:** Cell meat, Plant Meat products, Oatly, Protix

   Meat & dairy example: Innovations in this quadrant focus on reducing the climate 'inefficiency' of existing meat and dairy production through the replacement of current systems of meat and dairy production by alternative systems. This follows the logic of the very popular, very consistently restated Churchill quote about the inefficiency of growing whole chickens for meat. This partly works through the development of novel products and analogues (insect proteins, oat 'milk', plant-based meat alternatives) and partly through the development of meat through cellular agriculture instead of traditional agriculture. Distinguishing this from dietary change is important here – as there is little attempt to explicitly shift tastes, consumption habits, cultural framings of meat etc. but rather to simply replace current products and methods with more efficient analogue products and industrial or laboratory based processes.

2. **Demand management** (product/service - avoidance)
   Example innovations within each sector:

   - **Steel:** modular construction, urban planning/design, material substitution, reduced steel designs
   - **Plastics:** Banning, toy library, zero waste packaging
   - **Pulp & paper:** Paperless offices/homes
   - **Meat & dairy:** Meat Free Mondays, OFN, community fridge, GPA

   Meat & dairy example: Innovations clustered here incorporate a variety of cultural factors oriented around a repositioning of social relationships to and through food production and consumption and thereby managing demand. This may involve a focus on changing current dietary patterns through the simple removal/reduction of meat in diets and increasing the availability/prevalence of vegetarian and vegan options. Innovations clustered here also explicitly look to move away from current retail consumption patterns to food sharing and sociality, community growing in urban and rural settings, challenging the existing institutional power structures of large retailers/producers and reintroducing smaller scale food production through organic, agro-ecological and Community Supported Agricultural methods.

3. **Circular economy** (product/service - reduction)
   Example innovations within each sector:

   - **Steel:** Secondary Steel production, recycling, CCU
   - **Plastics:** recycling, plastic mining, CCU
   - **Pulp & paper:** re-use of fibres, lower quality materials
   - **Meat & dairy:** Sistema BioBolsa, biodigestors

   Meat & dairy example: Innovations here work largely within the existing patterns and institutions of food production and consumption. However, they seek to produce circular production and value chains by reintroducing prior waste streams back into production chains. In the case of meat & dairy, this involves the use of biodigestors to make use of waste food items for both energy (via biogas) production and fertilisers.

4. **Process Improvement** (process - reduction)
   Example innovations within each sector:

   - **Steel:** Insulation, gas recycling, emissions reduction to existing production methods, reduction of yield losses, CCS
   - **Plastics:** CCS, Covestro
   - **Pulp & paper:** energy improvements, Ligno boost, dewatering technologies
   - **Meat & dairy**: Clean Cow, Mootral, Farmtool

Meat & dairy example: Innovations here are embedded within and focused on existing processes and methods, but seek to reduce climate impacts/GHG emissions though a combination of technological innovations, new metrological systems enabling more explicit and efficient management of production processes and reducing waste throughout the production/value chain – again increasing the efficiency of existing processes.

4. Archetypal pathway grid development

The quadrant mapping produced here forms the basis for the development of the archetypal pathway grids. These are normative in form rather than exploratory. That is, rather than trace the potential impacts of innovation developments in order to assess their breadth and depth of decarbonisation, we begin by assuming that each pathway can lead to net zero emissions by 2050, and then ask what forms the broader innovation context would have to take to enable this scenario.

At the March 2019 REINVENT meeting hosted by PBL in The Hague, an indicative list of key nodes/points where contestation and tension are likely to arise within the sectors going forward to 2050 was presented. These nodes are taken as key points in the innovation infrastructure. Combining these with the theory of change as established within the analytical framework (Bulkeley and Stripple 2018), as shown in fig.3 below highlights how the dynamics of inertia/innovation play a role in the forms and potential impacts of tensions for each pathway node.

Identified pathway nodes:

1. **Technology:** Particular technological types, the availability of these (readiness and implementation timescales), the kinds of protections and support required (e.g. intellectual property rights), size and scale.
2. **Policies:** Regulations, market provision and making, basic financial support, basic science/knowledge provision.
3. **Markets:** Size, scope (local, national, regional, global) market-relationships and structure (e.g. oligopoly and market concentration, vertical and horizontal integration), bans and boycotts or products and companies.
4. **Finance:** Sources, types, investor pressure (directly via boards and shareholder activism, indirectly via risk metrics and exposure mechanisms).
5. **Public pressure:** Direct forms of public pressure and activism that don't work through appeals to the state (covered in policies), consumer activism (covered in Markets), or investment pressure (covered in finance), so things like awareness raising, direct action, sabotage as well as cultural shifts and changes in taste.

The incorporation of further desk research and stakeholder input gained during and following from a REINVENT workshop held in Düsseldorf on September 16, 2019 allowed issues around agency, materiality, power and geography that impact on each of the pathway nodes to be highlighted. These nodes are then used to structure pathway development grids for each of the four innovation quadrants for each sector[2] which can be found in appendices 1-4.

[2] Note that given the difficulties with establishing Demand Management innovations from within the existing pulp and paper sector literature, this pathway development grid has not been developed.

This process enables the novel assessment of decarbonisation potential to be deduced from the broader environmental, economic and social impacts that are brought to light through the pathway development grids. That is, we do not begin by an initial assessment of the decarbonisation potential of an innovation and then seek to determine its costs, other economic impacts, social and environmental implications. Instead, through the elucidation of the broader innovation infrastructure within the pathway grids, we seek to determine the overall implications of this innovation scenario in order to understand its potential viability and therefore decarbonisation potential. Simply put, any innovation e.g. current steel production methods with CCS, could in absentia of additional technologies, policies, markets, finance and public pressure enable deep decarbonisation. However, when these economic and social implications are considered as a fundamental part of an innovation's development, its capacity for decarbonisation may appear much more limited. On the other hand, innovations that are as yet marginal, such as new wood-based textile fibres, may have a large impact if public pressure on reducing the use of plastics for textiles grows.

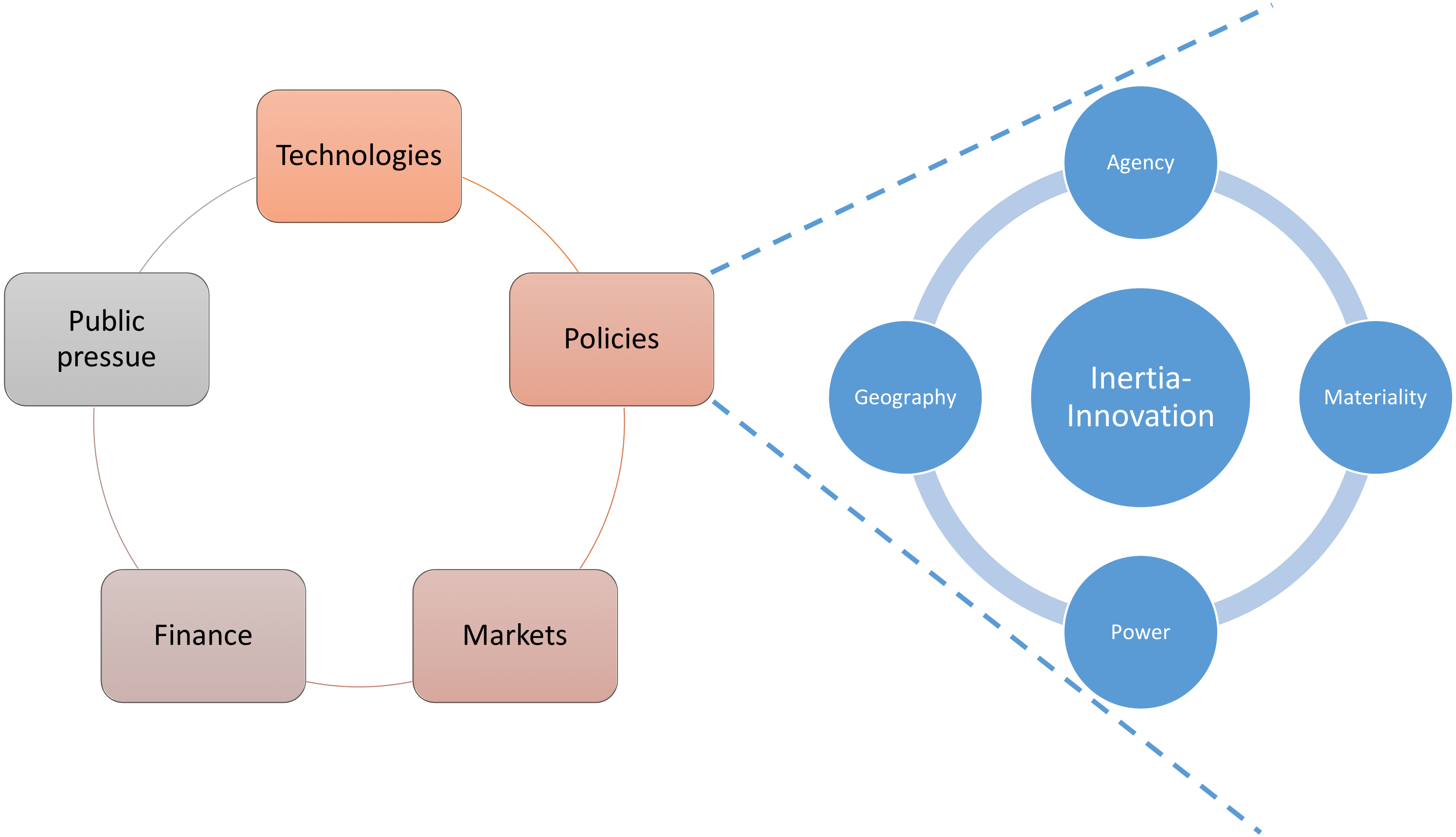

Figure 3: Inertia/innovation dynamics at play within each nodal point

5. Future economic, environmental and social implications

Through the typological mapping it becomes evident that the innovations identified in the previous work packages have the potential to contribute to decarbonising the sectors in focus in very different ways. Each of the pathways is developed as an archetype, focusing solely on that form of innovation development. By undertaking a normative scenario process and asking what changes are required within the broader innovation infrastructure for sectors to approach net zero emissions by 2050, we highlight the provisional nature of decarbonisation pathways. This indicates how decarbonisation is dependent not simply upon technological development, but also financial markets and their willingness to provide investment capital to cover the costs for the necessary investments, the support and development of markets and regulatory capacities, as well as changes in social norms and expectations surrounding the functional characteristics of the value chains. While real world decarbonisation can be expected to involve some mixture of these archetypal scenarios, the development and comparison of the pathway development grids further explicates the tensions and choices that will likely arise in the future. This enables us to establish a non-exhaustive list of the potential influence these will have on the environmental, economic and social impacts of the innovations in the four REINVENT sectors.

Economic impacts and implications

ETS reform and scale, establishing sector covering carbon price:

- In the plastics sector, the removal of the carbon leakage status of plastics producers is expected to be undertaken in phase 4 (TR and PI) or phase 5 (DM). The PI pathway also envisages expansion of the ETS to include offsetting of captured CO_2 from plastics production. The CE pathway is expected to progress through more specifically targeted regulation and is therefore ETS agnostic.
- Similarly to plastics, in the steel sector the CE pathway is expected to progress through regulation focused on urban air quality, planning and transport and is therefore ETS agnostic. The DM pathway is also expected to proceed through policies and programs not dependent on carbon pricing. The TR and PI pathways likely have inverted relations to ETS development and the establishment of an increasing carbon price. A high, early price and the removal of free allocations, combined with low or stable electricity prices would support the spread of breakthrough technologies such as H-DR, whereas a slower implementation of ETS reform would foster the maintenance of existing primary steel production progressively retrofitted with CCS/U.
- In the meat and dairy sector, the establishment of a broader carbon pricing regime is fostered by the CE and PI pathways, both of which generate bioenergy via biodigestion, and in the case of PI, significant bioenergy from crops grown on otherwise spared land. Both the TR and DM pathways could benefit from the extension of carbon pricing to meat and dairy production. The former due to this making meat and dairy substitutes more price comparable, while the latter could foster dietary change.

- This work does not support any strong inferences regarding ETS reform and scale in regards the pulp and paper sector.

Speed of phaseout of fossil fuel subsidies:

- In the plastics sector the TR, CE and DM pathways all support the rapid reduction of fossil fuel subsidies as feedstocks shift to non-fossil sources and quota replacements (TR); overall demand is reduced for plastics particularly with respect to packaging and virgin plastics from fossil sources banned in the 2040s (DM); or increased recycling with the steady reduction of downcycling (CE). Continued use of fossil feedstocks in the PI pathway however supports continued fossil resource production as an increasing proportion of these are diverted into virgin plastics even while electrification and energy efficiency requirements reduce the use of fossil fuels as an energy source.
- In the steel sector the CE pathway supports rapid fossil fuel subsidy phaseout due to the switch from BF/BOF primary to electrified secondary steel production. The DM pathway also supports rapid phaseout in spite of maintaining BF/BOF by an overall reduction in steel use and demand due to shifting urban planning, mobility patterns and increased mass transit. The TR pathway supports later phaseout due to the immaturity of breakthrough technologies such as hydrogen direct reduction, although limited early replacement of BF/BOF by natural gas supports reduction in coal subsidies. The PI pathway does not support subsidy phaseout as deployment of CCS/U to steel production maintains levels of fossil fuel use.
- In the meat and dairy sector, in the TR pathway, shifts from producing meat and dairy products from livestock animals to plant-based and lab-grown products will likely increase electricity requirements, this will have an uncertain impact on fossil fuel subsidy phaseout, depending on the speed and scale of non-fossil and renewable energy rollout. Both the PI and CE pathways are expected to generate increasing amounts of bioenergy due to opportunities presented by land-sparing and through biodigestion, supporting subsidy phaseout. The DM pathway involves a broad shift from large scale sustainable intensification to smaller-scale organic and agroecological methods, reducing requirements for fossil fuel inputs for large scale machinery and buildings, again supporting subsidy phaseout.
- In the pulp and paper sector, again, strong inferences regarding the speed of fossil fuel phaseout are difficult to gauge, although fuel switching within the TR and PI pathways are expected to remove the main fossil use early on, while strict requirements on phasing out remaining fossil fuel use are expected to be implemented in the CE pathway by the 2040s.

Trade composition and scale:

- In the plastics sector, trade composition and scale will be influenced by the speed with which linear value chains are converted into circular ones and whether these value chains comprise short or long loops. In the TR pathway bio-based inputs are sourced initially from intra-EU sources and markets, particularly if land-sparing and sharing agricultural practices enable increased production. As bio-based plastics come to dominate the plastics market, there will be increased pressure to source biomass globally. In the CE pathway initial diversion of trade in plastic waste develops shorter trade loops within the EU, as global markets and recycling capacity develops these may well extend outwards again resulting in globe spanning circular plastics trade. In the PI pathway progression to circular value chains is slowed and petro-chemical feedstocks continue to be sourced globally. However, customs are introduced on the importation of petro-plastics in order to hinder carbon leakage. In the DM pathway, there is a reduction in demand for virgin plastics, with the expansion of eco-design directives increasing longevity and reuse alongside mandatory deposit schemes and zero waste programmes in the retail sector. These all reduce plastics trade and reduce the size of circular loops.

- In the steel sector, the CE pathway would see significant shifts in external trade patterns with net exports of scrap steel reducing, until no significant scrap exports are undertaken after the 2030s. At this point scrap steel predominantly used to satisfy European demand. Likely declining primary steel production continues to be exported globally. Initially European and then global markets in premium-priced low carbon steel are expected to develop under DM, TR and PI pathways, alongside specialty lightweight steels under DM. European market for steel expected to shrink given demand reduction shifts impacting on construction and transportation in the DM pathway.
- In the meat and dairy sector, the TR pathway could continue to see expanding global trade in feedstocks for lab-grown products as well as other essential crops such as soy. Expanding global trade for animal meat and dairy products given European dietary shifts could also be expected in the TR, DM and PI pathways (for the latter explicitly marketed as low carbon products. Expanding trade in analogue products as well as circularly farmed products could be expected in the TR and CE pathways. The CE pathway would also support increasing trade in bioplastics feedstocks and bioenergy.
- In the pulp and paper sector trade in high grade papers is likely to diminish in all pathways as information transmission becomes increasingly digital. (Although unexamined here) a DM pathway focusing on reduced e-trade and general consumerism could also see reductions in paper products for trade generated by retail (particularly online). Trade in paper products for hygiene products is likely to follow historical trends.

Circularity, increasing information requirements and coordination

Increasing circularity and complexity have implications with respect to information and coordination requirements, which can impact upon the structure of the industry through the development of new intermediary data services and providers, or through increasing collaboration, control and concentration within the sectors.

- In the plastics sector, the CE pathway results in rapidly increasing information requirements. The early expansion of intermediaries involved in collecting and sorting recycling will result in a requirement for increasing alignment of firms along the value chain given requirements for smart sorting and tracing. This could result in an expanded role for dedicated data providers or through closer interlinkages and control between plastics manufacturers, compounders and converters and recyclers, likely increasing concentration within the sector and the market power of the large manufacturers. In the TR pathway increasing information requirements derive from the development of biodegradable plastics which adds complexity to the process of recycling bio-based plastics. Information requirements also increase as plastics manufacturers develop bio-based plastics that are not drop-in analogues. Again, this is likely to increase the concentration and power of large (increasingly bio-based) manufacturers. Within the DM pathway, complexity is likely to be constrained due to reduced plastics use via single use banning, mandatory deposit schemes increasing reuse and shift towards low and zero waste retail. This would limit information requirements and the development of data providers. However, the potential development and spread of home-based plastic smelting and 3D printing would increase tracking requirements without fostering increased centralisation. Within the PI pathway complexity and information requirements will likely track current trends.

- In the steel sector, the CE pathway is also likely to see increasing collaboration and coordination along the value chain to improve circularity through tracking and tracing steel components prior to recycling, improvements in the handling and sorting of scrap and improved product designs. Coordination requirements will be less important in the DM pathway but will still be present given requirements for developing and producing flexible, multiple purpose and modular steel design components. The TR and PI pathways are not expected to face additional information and data tracking requirements of this sort.
- Similarly to the plastics and steel sectors, in the pulp and paper sector increased recycling combined with the introduction of new products such as cellulose based textile fibres and new processes utilising sidestreams can be expected to increase information requirements and coordination along the value chain. Additional information and coordination requirements were not noted for the TR, PI and DM pathways.
- The meat & dairy sector does not follow the pattern established by the other sectors. Here, information requirements are increased in the TR pathway due to the necessity to track novel ingredients and processes in accordance with developing novel food and labelling directives. This information burden would likely foster the increased concentration and power of large food producers. The PI pathway involves a variety of smart and precision agriculture developments, management information systems for livestock control, data analytics and field robotics. The early cost of these would make them cost efficient only for large producers and so foster increased concentration and industrial scale farming, although these systems would be expected to become cheaper and available to smaller production operations over time. Information requirements would also increase under the DM pathway given shifts to short-chain agriculture, waste avoidance and food sharing. The economic impact of these is uncertain however. It is unclear what the data and information requirements of the CE pathway would be in the meat and dairy sector.

Economic growth:

Increasingly questions are being raised within Europe as to whether economic growth as measured by gross domestic product (GDP) should remain the basic measure of our economy. While some suggestions have focused on expanding on GDP as a measure (e.g. OECD 2011; World Bank 2012) others - informed by the ecological economics literature - focus on ideas of sufficiency and degrowth, such as those informing the first post-growth conference hosted by the EU Parliament in September 2018.

- The four pathways impact on and relate to economic growth and post-growth in similar ways across all four sectors. Innovations for decarbonisation within PI and TR pathways support increasing economic growth through efficiency and productivity increases (PI) and through the substitution of GHG emitting processes enabling new European and global markets for low carbon and green products (TR). The CE pathways similarly provides the basis for alternative growth processes (Lazarevic and Valve, 2017) through the economic valuation of former waste and sidestreams, supporting new industries or shifting profit sources within current incumbent actors. Depending on the extent to which demand focused innovations and regulations prioritise use reduction, increasing product life-times and re-use over product recycling however the CE pathways are also compatible and supportive of broader shifts to post-growth economies. The DM pathways, due to their focus on demand reduction through socio-cultural shifts, as well as through product-design emphasising re-usability and longevity present a challenge to current growth-based economies and foster a shift to post-growth paradigms.

Social impacts and implications

Employment & regional development:

- In all sectors, the general demand reductions involved in the DM pathway may be expected to have negative impacts on employment throughout the value chain. Job losses will have to be accompanied by retraining and other (green) employment opportunities if not ameliorated by the implementation of broader societal working reductions and/or UBI programmes.
- In the plastics sector, the shift to bio-based plastics will likely have the greatest implications for the dispersed and compounding and converting sector in the TR pathway. As bioplastics increasingly diverge from drop-in alternatives, these smaller employers which make up the largest segment of the plastics sector will likely need significant public support in order to implement costly new processes, new skills development and avoid job losses or facilitate retraining. As biomass requirements increase there may be increased opportunity for employment in biomass production in existing forestry and agricultural sectors, although the quality of this employment is unlikely to be high. In the CE pathway, while the increase in recycling will present the opportunity for expanding employment in recycling collection, sorting and processing, an expected shift from mechanical to chemical recycling processes will likely negatively impact the mechanical recycling industry (particularly in post-consumer recycling). Increasing complexity and information requirements within the CE pathway generally will also likely require significant financial input. As circular value chains expand to become global with the spread of advanced recycling processes, job losses may be expected in the recycling and reprocessing segment. The PI pathway may expect increasing employment in the plastics pollution removal segment. However the minimisation of material use in products may require support for converters and compounders, in order to ameliorate reduced diversity in plastic products. Costly CCS/U infrastructure is likely to result in increasing concentration within the sector, having the largest impact on distributed compounders and converters.
- In the steel sector, the CE pathway will likely result in reduced employment in regions involved in primary steel production and from public and private divestment from laggard companies, with concomitant increases in employment in upstream segments involved in the production of new and more complex product designs. Employment implications within TR and PI pathways are more difficult to discern.
- In the meat and dairy sector the process substitution in the TR pathway is expected to result in the increasing concentration of power in large food producers as well as large meat and dairy prodcuers in the medium term. This will likely result in decreasing and lower quality employment in farming. Increasing community supported and short chain agriculture along with small scale and urban farming in the DM pathway may be expected to result in increasing work within the farming sector, however full-time employment may decrease. The increasing focus on sustainable intensification within the PI pathway may also be expected to have negative impacts on rural employment. In the CE pathway prospects for employment and rural development are uncertain, however the costs associated with biogestion and CCS/U may result in increasing farm sizes and employment reductions.
- This work does not support any strong inferences regarding employment and regional development in regards the pulp and paper sector.

Changing sociocultural norms:

- In the plastics sector, the potential simplification of plastic types may help reorient relationships with plastic away from ubiquity and more towards one of essential products within the PI pathway. The TR is expected to elicit few shifts if biobased plastics largely replace fossil-based plastics on a like-for-like basis. The CE pathway will likely involve the development of ubiquitous reuse and recycling norms within increasingly closed loop value chains, with mandatory deposit schemes and consumer involvement in recycling emphasising the importance of waste avoidance. The DM pathway could see large scale sociocultural changes around shopping habits with the banning of plastics and the development of zero waste retailing re-emphasising locally produced goods given long-haul packaging restraints.
- In the steel sector, few sociocultural shifts are anticipated within the TR, CE and PI pathways. The DM pathway however would involve large scale shift in urban living to accommodate and enable reductions in steel use within the construction sector, and particularly with respect to urban mobility with a reduction in car use, increased mass transit and travel by bicycle.
- In the meat and dairy sector, changing social relationships to food production and consumption as a whole are important here. In the TR, PI and CE pathways, innovations here are expected to help maintain the centralisation of meat within European diets. In the TR and PI pathways food production will become ever more remote from daily life given its increasingly industrially processed nature. In the case of CE, the reduction of waste, particularly the highly visible post-consumer waste is expected to become increasingly central to relationships to food. In the DM pathways, large scale shifts in relationship to food production may be expected as this is reinserted into the daily lives of people through urban and community farming practices made possible by reduced working time commitments. Food consumption may take on an increasingly functional element due to the protein transition and repositioning of food in terms of the provision of balanced macronutrients, but it will likely also become increasingly central once again to social wellbeing and existence.
- In the pulp and paper sector, few sociocultural changes are expected within the PI and TR pathways. The CE pathway will again reinforce an emphasis on waste reduction and commitments oriented around reuse and recycling. The DM pathway, reductions in paper demand are expected to be undertaken through broader commitments to less explicitly consumerist lifestyles and a concomitant reduction in shopping, particularly online.

Environmental impacts and implications

Biodiversity:

- In the plastics sector, impacts in all pathways will expected to be positive with respect to marine biodiversity due to reducing levels of overall pollution, particularly so in the DM pathway due to demand reductions and widespread banning of certain plastic types. In the TR pathway, the replacement of fossil plastics with biobased plastics may have negative biodiversity impacts according to the scale of primary plastic production and the management of biomass production.
- In the steel sector, biodiversity implications of the different pathways are not easy to gauge. Reduced mining in the DM and CE pathways may have positive biodiversity implications while

the shifts in urban planning, construction and transportation involved in the DM pathway may also have positive biodiversity impacts.

- In the meat and dairy sector all pathways can expect positive biodiversity impacts due to land-sparing and sharing practices, hedgerow management, peatland and wetland restoration and rewilding. Agroecology, multi-purpose land use and organic practices will also provide additional positive biodiversity impacts in the DM pathway.
- In the pulp and paper sector, biodiversity implications will largely depend on forestry management practices although demand reductions in the DM pathway may also be expected to have positive impacts.

Decoupling natural resource use:

- Given current evidence on the historical trajectories and future possibilities of absolute material decoupling (Hickel and Kallis 2019), in general, natural resource decoupling will follow shifts from growth based economies to postgrowth economies.
- For all sectors, increasing information requirements within circular chains required to track material components in recycling and reuse of plastics and steel, smart agriculture and forestry management in meat and dairy and pulp and paper sectors will likely increase material requirements for computing and ICT infrastructure.
- In the plastics sector, the TR pathway may experience increasing environmental implications from the substitution of fossil-based plastics by bio-based. As scale up of bio-based progresses from the 2030s onwards this could have biodiversity implications depending on the management of biomass growth. However, there will be concomitant reductions in fossil resources. The CE and DM pathways would be expected to require far fewer virgin materials due to increased recycling, reduction and reuse. The PI pathway would be expected to continue historic trends in fossil resource requirements without concomitant demand reduction or recycling requirements, becoming an increasingly important segment of fossil resource use.
- In the steel sector, mineral requirements for primary steel are expected to decrease for CE and DM pathways as scrap steel saturates European markets and lightweight designs, modular reuse and urban construction and transportation shifts reduce demand. TR and PI pathways may see mineral requirements remain static or decrease more slowly depending on global markets for low carbon primary steel produced by e.g. hydrogen direct reduction or through BF/BOF with CCS.
- In the meat and dairy sector, overall environmental resource use in the form of agriculturally productive land may increase under the extensive production methods fostered in the DM pathway, but these are expected to be multi-use and developed alongside rewilding schemes, forest and peatland regeneration, as well as the expansion of agricultural production within cities. The efficiency of resource use afforded within the TR pathway would be expected to reduce land use but the extent of this may depend on accompanying dietary shifts. Both CE and PI pathways are expected to reduce land use. In the PI pathway land-sparing will be countered however by increasing bioenergy production.
- In the pulp and paper sector, decreased use of forest resources would generally be expected in DM and CE pathways, but may not experience declines under PI and TR pathways.

Pollutants:

- For all sectors, similarly to natural resource use, increasing information requirements within circular chains will likely increase energy requirements in terms of electricity use, resulting in increased pollution from energy production.
- In the plastics sector, plastic pollution is likely to decrease in pathways through increased recycling and landfill bans (CE); demand reduction and reuse (DM); shift to more environmentally friendly and biodegradable plastics (TR), however issues around information and component tracking with respect to biodegradable plastics may slow pollution reduction. The PI pathway is likely to focus more heavily on pollution clean-up given the slow closure of its linear value chain.
- In the steel sector, decreasing mineral requirements in the CE and DM pathways will reduce pollution from mining residues. TR and PI pathways may see pollution from mining practices reduce more slowly.
- In the meat and dairy sector all pathways are expected to reduce pollution with manure runoffs decreasing due to better manure management and fertiliser practices in the CE and PI pathways, dietary changes and smaller scale agricultural practices in the DM pathway and through substituting livestock for bioreactors and plant-based food processing.
- In the pulp and paper sector the TR, CE and PI pathways are expected to reduce pollution through reintegrating waste and sidestreams into economic value creating processes. Again, pollution reductions could be expected in the DM pathway through generalised demand reduction and concomitant reductions in pulp and paper processing.

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Appendix 1: Plastics sector pathway development grids

Table 1: Plastics - Technological Replacement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Biobased plastics is increasingly becoming popular although very much a niche.	Sensitive debate of land-use has brought a political standstill, insecurity over bioplastics benefits and problems.	Immature markets for biobased plastics; only a few new production process technologies offered for licensing	Massive investments in petro-plastics but growing concern in 2019 over the future and growth of inefficient conventional petro-plastics. "Will investments lead to the returns previously taken for granted as demand might slow down?" asks leading financial new outlets	Plastics increasingly gaining a bad name.
2020-2030	New biobased plastics (PHA, PEF) introduced in small scale; PLA takes off globally; pilot scale testing of bio-naphtha in steam crackers and petrochemical clusters. Biobased PE and PP production emerges in Europe, steam cracker conversions from fossil to biobased material in several locations, not least biomass regions such as Scandinavia petrochemical facilities (Stenungsund etc.).	Quota requirements for biobased replacement of all traditional plastics; mass balance for green atoms allowed in new regulations; petrochemical industries losses its "carbon leakage" status after mounting political and public pressure, the result is that alternatives are able to compete with the conventional petro-plastics	"green plastic" market labels established – first applied to cosmetics and food packaging;	VC interest in biotech startups focusing on biobased plastics; financial actors shy away from oil extraction and refining;	Sports teams cancel sponsorship deals with petroleum and petrochemical firms; Petrochemical businesses are increasingly linked to the oil and gas industry.

2030-2040	European bio-PE production takes over bio-ethanol demand; CCU from waste and biomass gasification (converted waste incinerators and pulp mills); first runs on 100 % bio-naphtha in a European steam cracker;	Policies prioritising material use over energy use for biomass resources; increasing quota requirements on renewable content in plastics and chemicals reaching 50%; CCU production are increasingly becoming feasible and subsidised as a way to live up to Co2 target reductions	European farming association first to claim to use only home-grown plastics;	EIB launches big new programme on investments for renewables;	Revived debate on food vs fibres/textiles/plastics due to land and water use changes in agriculture and horticulture; high public support for the emerging CCU technology
2040-2050	Alternative plastics have taken over from traditional ones that could not be made from biomass (e.g. PET);	A combination of policies effectively put an end to fossil feedstocks in the chemical industry; biobased and CCU-based plastics has taken over the market as political forces has skewed the market towards renewables	Plastics in Europe are largely biobased/CO2-based and circulated.	Investing into petro-plastics are widely regarded as a very risky investment as tendency and incentives turn the financial market towards renewables.	Continued controversies on land use for different purposes; delegitimisation of fossil resource use Increasing vegetarian and vegan norms (-50% meat consumption in the EU since 2020) offsets new potential for land use for material production in Europe.

Table 2: Plastics - Demand Management

Decadal period	**Nodal points**				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	The waste management systems start to improve, recycling rates in Europe are going up. The demand of plastics to packaging are flatting out as the need for virgin plastics are reduced. Better tech solutions for reusable plastics start to emerge; e.g. Loop industries.	The first single-use plastics ban in the EU gets implemented. Eco-design directive gets extended and start to have impacts of resource efficiency and energy demand. The first legislations which puts a fee on the weight on your garbage and its collection are getting into force.	Zero waste stores start to challenge conventional practises, however still a niche. Plastic free aisles emerge in some stores., while alternatives start to pop up.	Integrating ESG criteria into financial operations. Some financiers are growing ware of the increasingly bad image of plastics. Will the plastic boom really continue?	Protests against the excess of packaging in Europe. Worldwide worries and increasing concern over marine pollution issues. Backlashes against single use plastics, plastics are increasingly gaining a bad name. Zero waste movements start to develop.

2020-2030	The waste management structure is improved all over Europe which results in better fractions and high-end value - higher quality plastics in loop structures. Consequently, recycled plastics are able to compete with virgin plastics to a higher degree than previously. Block chain technology is developed, largely because of consumer pressure due lack of traceability of products.	Increasing pressure, more and more items are being banned and taxed. EU renegotiates several trade agreements to include provisions on CO2 intensive production. EU single-use plastic ban is extended to certain food containers and films. Increasing quotas, the eco-design directive gets expanded, textiles falls under the design directive. The common fishing policy (CFP) start to address fishing gear – push towards biobased and biodegradable options. Paying for the garbage amount becomes norm across the EU/waste quotas are implemented. Simultaneously mandatory deposit schemes are set up across the EU The global framework of plastic issues are set up	Closed loops of packaging in retail start to emerge. Minimum waste principles win grounds. Large retail actors start to collaborate on standardised packages and principles.	Aligning of plastic finance with SDGs, biobased production and recycling facilities are increasingly challenging fossil-based production. The expected increase of plastic demand is not fulfilled, several petrochemical actors are forced to sell off its assets while many production facilities around the world are forced to run on half of its capacities.	Zero waste movements accelerate in numbers and get increasingly influential in various sectors; retail etc. Waste benchmarking/waste shaming – the issues of waste generation becomes a public concern. Norm creation: Plastic is wrong, "are there any health impacts?" Avoid usage. Artificial, Anthropocene marker Consumer pressure builds regarding working conditions and fair wages in production which accelerates development of traceability technology which in turn makes material tracing easier.
2030-2040	Home-based plastic smelters to 3D printing allows individuals to use plastics to compose and repair whatever items they wish out of plastics. Demand for virgin plastics drops heavily as collection/mining of wasted plastics increases with NIR-technology.	In phase 5 of EU ETS, the 'carbon leakage' principle are removed. Customs are instead set up to offset the inclusion of CO2 costs in production in the EU. Total ban in the EU of single-use products of up to 100 single use items – single-use gains a bad reputation and norms pushes for reusable options. A tax on non-looped fossil-based textiles are set up. Tires and other synthetic rubber application are addressed through a new directive	Mainstreaming of zero-waste retail: Bringing your own packages becomes norm. In other stores standardised single use packages are still in use but mainly falls under the deposit scheme which now are extended to also include many PP, PE and cartons packages.	The carbon bubble bursts! The future of the petro-plastics starts to look gloomy; investments flows out of conventional petrochemical production. Credit ratings for petrochemical companies' plummets – becomes risky investments. Demand of virgin fossil plastics falls rapidly.	Increasingly clear that plastics might lead to health impacts as it becomes clear that the death of thousands of species can be directly and indirectly linked to plastic exposure. Large quantities of plastics cannot any longer be branded as safe as health concerns related to plastics increases.

		The mandatory deposit schemes are unified in an EU wide scheme. The scheme now also includes many PE and PP packages – plastics are increasingly being looped.			
2040-2050	Plastics meets competition from superior bio-based materials, demand decreases further as plastics are losing popularity.	A global ban of single-use plastics is agreed on after years of negotiations through the global framework of plastic issues. Virgin plastic from fossil sources are banned in the EU, plastics are now either out-phased, biobased or recycled. The material is however not particularly popular due to health concerns.	Internalization of zero waste principles across sectors. "waste" belongs to the past – An empty bottle, package or used film is a resource – there is either a reuse value in it or a deposit attached to the item. Few items in metal, carton or plastics goes to the bin. Bins in the society is massively reduced and replaced with deposit stations and reuse workshops where you can sell or remake your resources.	Increasing use of renewable energy and electrification of transport together with a lowering demand of fossil-based plastics undermines the whole fossil-based industry. Fossil fuels drops in value as the uses for it disappears. It is difficult for fossil-based plastic to compete with 'safe health approved' recycled and biobased plastic due to regulation and lack of demand.	Increasing amount of health scandals: Plastics are related to the overall drop of fertility rates. Hazardous plastic particles are commonly found in human organs such as brain and heart tissues. Suing of DuPont and ExxonMobil in the US as several deaths are proved to be linked directly to plastics. Lack of demand and thousands of lawsuits contributes to the bankruptcy of the once business giant ExxonMobil. Example: Time magazine frontpage 8 of May 2046: Plastics – the DDT of the 21st century

Table 3: Plastics - Circular Economy

Decadal period	**Nodal points**				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Increasing recycling rates and waste collection necessitates expansion and improvements to collection and sorting technology and infrastructure. Investments in new sorting and mechanical recycling by both public (sorting) and private actors.	Policy attention to plastics starts increasing in order to address growing public pressure. Bans on specific products (single use, microbeads …) especially with a view to reducing marine litter. Large scale changes to the dynamics of global trade in waste (China's National Sword policy and the extended Basel	Numerous examples of horizontal and vertical integration in the plastics supply chain. Examples include: the Circular Plastics Alliance; CEFLEX (for flexible packaging); the Ellen MacArthur Foundation's New Plastics Economy Global Commitment; the Plastics Leak Project; and the Polyolefin Circular Economy	First steps being taken towards securing the financial backing for circular economy initiatives/transitions. One example is the EU's Circular Economy Finance Support Platform.	Around the mid-2010s, public awareness of plastic pollution expanded dramatically. Attention mainly devoted to marine littering and driven by viral photos/videos of animal suffering due to plastics in the ocean; in connection to this, growing contestation of plastic bottles and bags; a zero waste movement of activists and lifestyle personalities

		convention); new waste collection targets agreed on in order to secure a steady and growing waste stream as input to the circular economy.	Platform (linking PlasticsEurope, European Plastics Converters, and European Plastics Recyclers)		advocate and campaign for ways to eliminate household waste
2020-2030	Some of the more difficult recycling challenges begin to be addressed by chemical recycling at smaller scale – use is limited to specific polymers and product groups; to chart the increasing amount of products and integrate them better into reusable/recyclable supply chains, blockchain technology is adapted and deployed at scale; increased sorting of complicated waste fractions (e.g. automotive, healthcare); recycling schemes developed for key bioplastics	Policies to monitor and enforce quota requirements on recyclability and recycled content in plastics, including labelling schemes to guide consumer purchasing; extended refund (deposit-return) schemes for standardized packaging; green plastic public procurement (construction, healthcare, schools, offices etc.); extended producer responsibility fees for a growing class of products (differentiated or increased); tax schemes supporting recycled content; extending Ecodesign requirements to ensure recyclability of an increasing amount of plastic products including automotive and construction plastics; restrictions on additives.	Integration and alignment of firms in pursuit of circular economy initiatives leads to pilot schemes in reusable, closed-loop branded packaging (see the Loop Packaging System); this also happens to a great extent in the business-to-business segment (e.g. Svenska retursystem); non-recyclable products are boycotted and banned by activist consumer groups; consumers show increasing preference for products with recycled content or high recyclability as well as alternative packaging (e.g. paper); market for recycled plastics increases in volume, quality and competitiveness with virgin fossil plastic.	The financial sector begins to increasingly respond to public and investor pressure to divest from fossil-heavy positions, including chemicals/plastics; ESG investment criteria start incorporating fossil-based products in risk and sustainability considerations.	As recycling and reuse rates increase, public pressure turns towards the issue of toxic/hazardous additives in plastics and in the waste stream; large-scale campaigns in support of clean, healthy, recyclable/recycled packaging; zero-waste movement gains strength and recognition, resulting in mainstreaming of zero-waste sections in supermarkets and city-scale zero-waste initiatives; increasing pressure to use biofeedstocks as virgin source to fill up markets not met by recycling
2030-2040	General chemical recycling achieves cost-efficiency and makes a large-scale market breakthrough. Works alongside mechanical recycling, which is still the better option for less complex plastic products such as packaging; pilot scale deployment of CCU to plastics and other chemicals; bio-plastics cover some supply of virgin	In response to large-scale climate change protests the world over, governments are forced to resign/reconvene and introduce drastic policy packages to address the bursting of the carbon bubble and inaction on climate change. Ambitious policies are then introduced, including: general fossil resource/carbon taxes on products and services; heavy fees on	Industries in all sectors suffer from general financial panic as the carbon bubble bursts (see Finance column). This forces large-scale restructuring to align with emergency policy packages, consumer concerns, and new sustainability criteria in the financial sector. Circular economy initiatives move from pilot schemes and greenwashing into core business operations.	The carbon bubble bursts! Financial crisis erupts following mass sell-off of shares in fossil fuel companies as investors respond to overblown valuations and stranded assets (in part caused by over-optimistic projects of future demand for plastics, oil, and gas). Economic downturn provides an opportunity to mainstream	Following disappointing action in the previous decade on achieving the 2030 Sustainable Development Goals and in response to scientific and political reports documenting serious shortfalls in cuts to GHG emission rates, citizens mobilize globally in largest ever climate change protests. As the carbon bubble bursts, the protests only grow in strength and scale. Many governments are forced to resign

	material for simple plastics and develop for more advanced plastics	unsustainable businesses, rationing and quotas to curb overconsumption.		sustainability considerations in the financial sector, channelling funds towards circular economy initiatives with proven sustainability benefits.	and a few years of political instability ensue.
2040-2050	Biological carbon capture and utilization working in harmony with chemical recycling and mechanical recycling; virgin bio-plastics for key advanced applications (e.g. healthcare)	Landfilling is banned as material and waste loops completely close for all product categories.	Responding to policy, investor, and consumer pressure in the previous decade, the plastic sector achieves full circularity along the supply chain and severely limits the input of virgin fossil plastic as feedstock demand is almost entirely met by recycling and bioplastic.	A decade of slower, but sustainable growth in the financial sector as it is forced to re-link to the real economy and take much greater heed of sustainability.	Consumer pressure remains on laggard countries and companies, forcing them to swiftly catch up to the new emerging paradigm of full circularity in industry operations and waste management.

Table 4: Plastics - Process Improvement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	CCS technology is once again up in the air, several locations are testing out CCS possibilities, e.g. in Norway and Switzerland. Norwegian actors are frontrunners.	CCS is mentioned and included in various scientific models as a key solution to meet the increasing challenges of climate change. Political pressure for supporting and public financing of the technology is mounting.	CCS is still seen as economically unfeasible but with future potential.	Massive investments in petro-plastics but growing concern in 2019 over the future and growth of inefficient conventional petro-plastics. "Will investments lead to the returns previously taken for granted as demand might slow down?"	The concern of the issues around plastics are mounting around the world. Production has in the last few years 2018, 2019 gained increasing attention.

2020-2030	Electrified steam cracker pilot projects; CCS pilots in waste incineration and industrial applications; improved converting technologies minimising material use in products	First regulations for CCS; EU ETS removes free allocation of emission rights to industries, halfway through phase 4; expansion of ETS to include offsetting of captured CO2; Ban on landfill of waste in EU, waste is increasingly seen as a resource; Customs are introduced on the import of petro-plastics to hinder a "carbon leakage" of European petrochemical industry	Labels for "Low CO2" and "no CO2" plastics are launched in Europe; volatility in electricity markets and industrial electrification speeds up; increasing prices of carbon credits; decreasing markets for fossil vehicle fuels	Finance seeing decreasing petroleum demand due to efficiency and electrification – shying away from investments in exploration and new wells; approval of new certificate system to include CCS in green bonds	Large protests against carbon footprint of plastics; improved waste management practices with focus on incineration; Increasing political and public concern over GHG impacts leading to revises of the EU ETS phase 4 plan to dismiss the free allocation of emission rights (to petrochemical producers).
2030-2040	Major retrofitting of steam crackers and petrochemical clusters (electrification and efficiency measures); full-scale implementation of CCS. With CCS facilities production in Europe are increasingly able to outcompete the petro-plastic imports which experience very high duties	Increasingly strict energy efficiency requirements on industrial production (benchmark vs state-of-the-art); bans against new oil well exploration	Electricity prices stabilize as load shedding practices are established; EPR schemes include responsibility for waste incineration emissions; overcapacity in oil refining;	Plastic manufacturers invest in waste incineration and CCS; rush in the financial sector to invest in new CCS projects leading to decreasing costs	Calls for plastic manufacturers to take responsibility for emissions in whole value chain, including waste incineration; Reuse principles wins ground, items are more efficiently used across European societies
2040-2050	Electrification of most production processes; remaining large point emission sources covered with CCS;	Policies setting strict requirements on phasing out using fossil resources for all energy purposes	spot market for captured CO2 established; natural gas grids/markets converted to grids/markets for hydrogen from electrolysis	Captured CO2 now the largest commodity traded internationally	

Appendix 2: Steel sector pathway development grids

Table 5: Steel - Technological Replacement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Mostly incremental, technical process innovations which are integrated into existing structures due to high investment costs and high market entry barriers; low innovation rates also due to limited testing; radical innovations stuck in pilot or demonstration phase Many current innovation projects focusing on carbon-free primary steelmaking technologies: hydrogen direct reduction (H-DR) (SALCOS, HYBRIT: pilot plant by 2020), electrowinning (upscaling by SIDERWIN) and hydrogen plasma reduction (SuSteel, demo scale by 2019); development of electrolysis	Under the influence of strong EUROFER lobbying and the threat of carbon leakage, free allocation of EU ETS allowances remains until 2026. Government support for the industry's competitiveness in international context (e.g. free ETS allowances); regulation focused on safety, local pollutants and incremental actions (e.g. energy efficiency measures) Public institutions influencing the focus of R&D by offering public funding and the willingness to balance risks (e.g. via the EU's Horizon2020 or the Innovation Fund)	Industry characterised by oligopolistic structures, most of the companies operating integrated steel plants in Europe are part of innovation projects; R&D cooperation of market competitors at a pre-competitive stage resulting in co-development of innovations (e.g. ULCOS) Free steel industry allocations within the EU ETS result in continued low carbon costs. No market yet for a price-premium attracting low-CO_2 steel. No common or overall target for decarbonisation agreed on by the European steel industry Little pressure from end consumers due to operation in business-to-business markets	Low innovation rates also due to high risk and cost, little capital availability, long investment cycles; radical innovations require financial savings to deal with setbacks and failure; reason for many radical innovations to remain on experimental scale Large investment costs impose high entry barriers to new market entrants Funding for innovation projects provided by European programmes (H2020, SPIRE, RFCS and FCH2-JU) but also from national sources in Sweden, France, Austria and Germany as well as the companies involved.	Public and NGO pressure on steel companies using coal has not been witnessed yet, although it appears to be increasing in the coal power sector; little public attention also due to operation in business-to-business markets

	for use in steel plants by H2FUTURE project				
2020-2030	Many steel production technologies still under development, not yet clear which will make it to commercialisation and when Replacement of some blast furnace and basic oxygen furnace (BF/ BOF) sites by natural gas based DRI and scrap-based steelmaking; as there are strong synergies with electrification of primary steelmaking, this is a first step towards later electrification of primary production (or purchasing of 'green' iron) CCS added to existing integrated sites to reduce emissions until breakthrough technologies are scaled up Material and energy efficiency as well as demand management measures implemented to later complement breakthrough technologies to create a sustainable steel value chain	Policy development focusing on ETS reform to move towards full auctioning within the 2030s Continued innovation funding within ETS reform largely oriented towards efficiency measures; EU's Horizon Europe (budget of 100 billion € for 8 years until 2029) succeeding Horizon2020; support for further cooperation with research institutes all along the value chain Sectoral emission reduction targets set also for industry, but not legally binding	Constant electricity demand (economic growth compensated for by efficiency and small sufficiency gains) and electricity prices (lower production cost of renewable electricity sources increasingly noticeable) Carbon costs remain low due to EU policy on ETS free allocations to the steel industry. Public focus on GHG emission reductions brings steel industry to agree on an overall decarbonisation target, but it leaves room for interpretation New market emerging for premium priced low carbon steel	Market introduction of breakthrough technologies requires large investments in scale-up and demonstration; private financial institutions still hesitant to bear risk of uncertain future development; funding for innovation projects continues to be supported by European programmes and national governments	Increasing public pressure to reduce industry emissions combined with concerns over steel sector jobs in both primary and secondary steel production. This helps foster a focus on efficiency measures and public awareness of the difficulty of emission reductions in the steel value chain. Debates about infrastructure required for operation of breakthrough steel production facilities (electricity, hydrogen)
2030-2040	Step-by-step replacement of integrated sites with arc furnaces and H-DR plants; more DRI helps balance renewable power loads but needs very much electricity for hydrogen production or hydrogen imports Further substitution of blast furnaces by electrowinning	Continued R&D funding by EU programmes, focus shifts to upscaling commercial operation of low carbon breakthrough technologies Electrification of steel production (as well as CCS) depends on high carbon price and a solution for the carbon leakage problem	Rise in carbon costs due to full auctioning of ETS allowances. Production costs of H-DR slightly higher than those of integrated steel plants, but decreasing electricity prices and a high carbon price improve the competitiveness of H-DR	Better economic feasibility and also funding opportunities of specialised small-scale production Continued funding from institutional investors for technologies improving materials, energy and emissions efficiency of	Continued concerns and disruptions regarding impacts of breakthrough steelmaking plants and necessary infrastructure

	in ironmaking, upgrading of existing mini-mills (secondary steelmaking) with electrowinning plants to increase the share of virgin iron in the process		Technological progress in low-temperature steelmaking (electrowinning) and better economic feasibility of specialised small-scale production offer potential for new market entrants Growing internal market for higher priced low carbon steel and emerging global market, thus increasing EU exports	primary and secondary steel production.	
2040-2050	Fossil-free value chain of H-DR by 2045 Fundamental changes to existing production facilities entail large potentials for industrial symbiosis, e.g. through excess hydrogen and heat	European regulation to withdraw from steel production at BF/ BOF sites	H-DR as competitive as integrated steel plants due to decreasing electricity prices and a high carbon price New market entrants Further development of global market for low carbon steel.	Broader variety of funding opportunities from private sector as risk linked to breakthrough technologies better to assess; decrease of public funding as some breakthrough technologies are successfully operating on commercial scale	Public acceptance of breakthrough technologies largely assured as facilities in operation prove rather secure and previous alternatives also contained severe disadvantages

Table 6: Steel - Demand Management

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Comparatively low growth in steel production and use in the EU; one third of EU steel produced from recycling steel scrap: Steel used in automotive mainly from primary, steel for buildings and infrastructure from secondary steelmaking Constant spread and improvement of digital technologies that enable higher product-service efficiency (car sharing etc.)	Government support for the industry's competitiveness in international context, regulation focused on safety, local pollutants and incremental actions (e.g. energy efficiency measures) Demand-side and consumption-focussed policies (e.g. public procurement or quota-certificate schemes) have been discussed to reform the	Mass market for bulk basic materials, strong price competition and low profit margins; small markets for specialised materials, quality competition and higher margins Shares of finished steel use according to sectors: 33% in construction, 25% metalware/tubes, 22% cars/transport, 20% machines, other	Funding for innovative projects provided by EU and state governments; little interest from private institutions Some private companies invest in business models basing on increasing product-service efficiency (mainly car sharing)	Public and NGO pressure on steel companies using coal has not been witnessed yet, although it appears to be increasing in the coal power sector; little public attention also due to operation in business-to-business markets

	and service-demand reduction (e.g. switch from private to public transport)	ETS and alleviate problem of potential carbon leakage	Little pressure from end consumers for decarbonisation measures due to operation in business-to-business markets		
2020-2030	Extension of steel product lifecycles through production of more flexible, multi-purpose use and modular design components (e.g. for buildings) In some cases substitution of steel with aluminium, plastics, carbon fibre or wood if respective pros outweigh the cons (product durability, functionality, environmental impact…) Lightweighting through improved product design (e.g. automotive) and co-development of high-strength speciality steels Implementation of CCU from off-gases at blast furnace and basic oxygen furnace (BF/ BOF) sites, some other BF/ BOF sites are replaced by natural gas based DRI and scrap-based steelmaking	Policies and governmental support for higher material efficiency in product design to achieve extended product life and lower steel input (dematerialised products), e.g. policies for using material-efficient shaped steel structures, extending the lifetime of buildings from on average 60 to 80 years (effect on steel demand visible in 2080) or reduction of steel use in buildings by building in fewer components (due to general overuse of steel in buildings by a factor of two) Governmental incentives for increase in product-service efficiency (e.g. car sharing, higher building occupancy) and service-demand reduction (e.g. less individual mobility, switch from private to public transport, sustainable consumption) to decrease steel demand Demand-side policies and changes in public procurement to create markets for higher-priced low carbon steel	Public focus on GHG emission reductions brings steel industry and downstream manufacturers to agree on an overall decarbonisation target, but it leaves room for interpretation Lower sales of conventional steel resulting from slowly decreasing steel demand in Europe are compensated for by export as global demand keeps on rising Political support for product-service efficiency leads to market entrance of further suppliers of sharing systems for cars etc. (stock turnover of cars takes around 10 years) New market begins to emerge for premium priced low carbon steel. Increased demand for speciality steels for lightweighting.	Continued funding by public institutions Governmental investment in public transport to decrease need for individual mobility	Increasing public pressure to reduce industry emissions combined with concerns over steel sector jobs in both primary and secondary steel production. This helps foster a focus on efficiency, circular economy and demand management measures and public awareness of the difficulty of emission reductions in the steel value chain.

2030-2040	Continued improvement of product design aiming at lower material demand and extended steel product lifeycycles Step-by-step replacement of integrated sites with arc furnaces and H-DR plants; CCU at remaining BF/ BOF sites	Expansion of demand-side policies to grow niche market for low carbon steel, e.g. establishment of criteria and labels for ‘green steel’ to increase the impact of customer choice and public procurement, policies to favour low carbon steel in public procurements, emission quotas for steel in products such as cars Big cities start introducing self-driving car schemes, which de-incentivises car ownership as sharing models become increasingly convenient.	Lower steel demand in Europe, also due to policy incentives for higher per capita occupancy rates in houses and lower car ownership as public transport systems satisfy mobility needs More intensive use of fewer products to be complemented by new business strategies by steelmakers to avoid being perceived as harmful to their business Further development of internal market for higher priced low carbon steel; product design using less steel could help compensate for higher material costs; also global market developing for EU exports of low carbon steel. Lower sales of conventional steel in Europe are compensated for by global exports	Public as well as private institutions divest from steel companies not engaging in decarbonisation measures Focus of public investment now on provision of public transport rather than infrastructure for individual mobility (motorway widening etc.)	Continued concerns and disruptions regarding impacts of breakthrough steelmaking plants and necessary infrastructure; thus strong support for circular economy, efficiency and demand management measures to minimise new technology implementation
2040-2050	Continued replacement of remaining BF/ BOF sites by alternative CO_2-free steel production processes	Continuation of demand-side policies supporting the low carbon steel market	Further decrease of steel demand in Europe, but increased domestic sales of higher-profit low carbon steel Further development of global market for low carbon steel, continuing global steel exports from Europe	Private investment in businesses offering demand management solutions now lucrative due to high public demand	Still high public pressure to implement circular economy, efficiency and demand management measures rather than technological replacement; but at the same time public acceptance of (former) breakthrough technologies largely assured as facilities in operation prove rather secure and previous alternatives also contained severe disadvantages

Table 7: Steel - Circular economy

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	High steel recycling rates in Europe but downcycling due to copper and other alloys represents a problem; also steel losses from remelting/ slagging, low scrap collection rates for some products, abandoned obsolete stock Low incentives to develop better sorting and recycling technologies; chemical separation of steel products under research Comparatively low growth in steel production and use in the EU; one third of EU steel produced from recycling steel scrap mostly in Italy, Germany and Spain R&D efforts to enable CCU for production of fuels and chemicals from BF off-gases.	Political regulation focused on safety, local pollutants and incremental actions (e.g. energy efficiency measures) due to government support for the industry's competitiveness in international context Trade tariffs, e.g. in the US, result in lower steel (scrap) exports, thus higher remaining stocks Few policies to support increase in steel recycling as recycling rates are already high compared to other materials	Net scrap exports from the EU, where end-of-life-scrap is dominant over fabrication scrap (already large steel stock in the EU) Industry characterised by oligopolistic structures, transition has to involve today's incumbents Position of European steel industry towards decarbonisation has changed since roadmap in 2013, few forerunners have announced clear step-by-step transition plans for decarbonisation until 2050 Little pressure from end consumers for circular economy measures due to operation in business-to-business markets	Financial support for innovation processes from governmental rather than private institutions to preserve competitiveness in a global market where competitors tend not to engage in circular economy measures	Public and NGO pressure on steel companies using coal has not been witnessed yet, although it appears to be increasing in the coal power sector; little public attention also due to operation in business-to-business markets
2020-2030	Technology innovations towards tracing steel components (before recycling) and handling and sorting of scrap Availability of scrap steel in Europe rises, also slow quality increases due to better sorting. Higher share of scrap-based strip steel production due to increased	Prevention of downcycling and steel losses: Policies and governmental support for better scrap sorting and product design (modular design, single material design) enable easier disassembling, remanufacturing and refurbishment of products. Reutilisation cycles should preferably dominate over	Fewer net scrap exports occur (still export of downcycled construction steel, some import of higher quality scrap) Replacement of BF/ BOF sites by scrap-based steelmaking allows for preservation of locations and jobs Public focus on GHG emission reductions brings steel industry	Public as well as private institutions divest from steel companies not engaging in circular economy and other decarbonisation measures Development of innovative circular economy technologies financed by private institutions as a global market for such equipment evolves	Increasing public pressure to reduce industry emissions combined with concerns over steel sector jobs in both primary and secondary steel production. This helps foster also a focus on circular economy, efficiency and demand management measures and public awareness of the difficulty of emission reductions in the steel value chain.

	use of technologies like Direct Strip Casting (DSC) which tolerate a higher content of tramp elements without quality losses. Implementation of CCU from off-gases at blast furnace and basic oxygen furnace (BF/ BOF) sites BF/ BOF sites are replaced by scrap-based steelmaking (electric arc furnace), especially in areas with limited renewable energy sources/ hydrogen infrastructure. More energy-intensive primary steelmaking takes place in places with comparatively better renewables/hydrogen supply.	recycling and demand for new products Government support for replacement of BF/ BOF sites by scrap-based steelmaking to preserve locations and jobs Public procurement involves circular economy criteria for steel products	to agree on an overall decarbonisation target, but it leaves room for interpretation; European steelmakers broadly engage in circular economy measures and decarbonisation activities in general to ensure future economic competitiveness (e.g. in anticipation of increasing carbon prices) and for public relations reasons Increased collaboration along the steel value chain to improve circularity, e.g. through better product design.		Pressure building on steel recycling – through building and urban planning at municipal and regional levels.
2030-2040	Availability and quality of scrap steel in Europe rises further, albeit slowly; Copper-contaminated steel scrap is diluted by iron from electrowinning or hydrogen direct reduction (H-DR); increased use of scrap in the further processing of direct reduced iron. Secondary surpasses primary steel production, CCU at remaining BF/ BOF sites	Continuing government support for better scrap sorting and product design preventing downcycling of scrap	Decreasing European steel demand is met with scrap-based steel by 2040 No significant net scrap exports occur (still export of downcycled construction steel, some import of higher quality scrap) Primary steel produced in Europe is exported globally	EU funding programmes only support companies complying with certain circular economy standards	Continued concerns and disruptions regarding impacts of breakthrough steelmaking plants and necessary infrastructure; thus strong support for circular economy, efficiency and demand management measures to minimise new technology implementation

2040-2050	Amount of scrap steel in Europe stabilised. No more use of CCU for production of fuels and chemicals due to whole-economy net zero target		Decreasing European steel demand continues to be met with scrap-based steel; due to better sorting and recycling technologies fewer imports of higher quality scrap necessary		Still high public pressure to implement circular economy, efficiency and demand management measures rather than technological replacement; but also public acceptance of breakthrough technologies (as defined around 2020) largely assured as facilities in operation prove rather secure and previous alternatives also contained severe disadvantages

Table 8: Steel - Process Improvement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Ongoing, albeit patchily supported trials with CCS. Relative emissions reductions driven by reduction of yield losses, and therefore efficiency gains.	Under the influence of strong EUROFER lobbying and the threat of carbon leakage free allocation of EU ETS allowances remains until 2026 – maintaining low carbon costs for the steel industry. Regulations focus on safety, local pollutants and incremental energy efficiency (e.g. energy audits) Companies' innovation strategies aim at productivity gains	Free steel industry allocations within the EU ETS result in continued low carbon costs. No market yet exists for a price-premium attracting low-co2 steel. Industry characterised by oligopolistic structures, transition has to involve incumbents No decarbonisation target agreed on by the EU steel industry Little pressure from end consumers due to operation in business-to-business markets	EIB investment in Aperam finances efficiency measures in European stainless steel production (Belgium and France). Similar finance arrangements throughout the industry focus on process efficiency gains. Funds and investors supporting efficiency-improving projects with a focus on emission reduction: EIB 25% Commitment, Institutional investors group on climate change IOGCC	Public and NGO pressure on steel companies using coal has not been witnessed yet, although it appears to be increasing in the coal power sector; little public attention also due to operation in business-to-business markets

2020-2030	First generation CCS technologies continue to be deployed and ongoing trials with second generation CCS technologies First full size trial system (IGAR project by ArcelorMittal, targeted for 2022) utilising plasma torch technology in blast furnace production begins, replacing coke by electricity. High electricity prices slow scaling of this technology. Rapid scale up of material, energy, and emissions efficiency technologies.	Policy focus on ETS reform to move towards full auctioning within the 2030s. Continued innovation funding within ETS reform largely oriented towards efficiency measures. French and German based primary steel producers lobby at EU level for policy focus on efficiency measures and support for current primary steel production processes over fostering secondary steel production. This delays recycling regulations ensuring separation of copper and steel. Policies and regulations designed to assuage public concerns regarding CCS Policies for reuse of fully functional steel components (to stop losses from re-melting and contamination), systematic efforts to recover steel to avoid losses. CCS (as well as electrification) depends strongly on high carbon price and a solution for the carbon leakage problem	Carbon costs remain low due to EU policy on ETS free allocations to the steel industry. Increasing electricity use due to recovering economic growth and domestic & business sector heating/cooling in light of more extreme weather events. This results in higher electricity prices and maintenance of fossil fuel electricity sources (gas/coal) with electricity from renewables being largely additional. New market begins to emerge for premium priced low carbon steel. Set-up of a structure for steel reuse, thus avoidance of redundant melting Continuous information programmes for efficiency gains Public pressure makes steel industry agree on decarbonisation target, but it leaves room for interpretation	IIGCC and other institutional investors remain focused on financing efficiency measures to existing production processes. National level financing provides support for ongoing and novel CCS projects Finance shifting away from electrowinning and direct hydrogen reduction given continued low carbon prices and continued high electricity prices.	Increasing public pressure to reduce industry emissions combined with concerns over steel sector jobs in both primary and secondary steel production. This helps foster a focus on efficiency, circular economy and demand management measures as well as public awareness of CCS trials/usage. Critical public debate on the safety, security and long-term sequestration capacity of CCS, resolved largely in favour of the technology.
2030-2040	CCS scaling begins with roll out of first and second generation technologies on existing plants Sector-wide deployment of energy efficiency measures	Continued increase in electricity use and high prices mitigates against policy support for broad electrification of steel sector Significant EU policy orientation therefore around CCS scale up, more limited support for plasma torch technology. Strong industry lobbying for CCS support in	Carbon costs increasing due to full auctioning of steel industry allowances. However, continued increases in electricity use and prices mitigates against policy support for electrification of steel sector. Further development of internal market for low carbon steel	Significant EU and national level funding made available for CCS Continued funding from institutional investors for technologies improving materials, energy and emissions efficiency of primary and secondary steel production.	Continued concerns and disruptions regarding impacts of breakthrough steelmaking plants and necessary infrastructure as well as impacts of CCS (democratic accountability, siting, security and longevity etc); thus strong support for circular economy, efficiency and demand management measures to minimise new technology implementation

		light of increasing carbon price resulting in significant public funding for CCS R&D and project support. At state level, proliferating legal measures made available and deployed against CCS protests.			Drive for municipal and regional level planning accountability for infrastructure and buildings lessens with industry and policy assurances around emissions efficiency and intensity of current steel production methods. Similarly, demand reduction concerns lessened by building requirements to forced internal migration and into the EU due to flooding, heat events, agricultural disruption and instability.
2040-2050	Sector-wide application of CCS at scale, alongside now well established efficiency measures.	EU policy formulated around poles of CCS saturation alongside wide raft of efficiency measures and technologies and aggressive support for global low carbon market development through trade and tax support, alongside international development programmes focusing on low carbon infrastructure projects.	Carbon costs increase further. Focus on expansion of global low carbon steel market	CCS funding shifts to predominantly private finance heavily supported by national and EU level policies and project underwriting.	Still high public pressure to implement circular economy, efficiency and demand management measures rather than technological replacement; but at the same time public acceptance of CCS largely assured.

Appendix 3: Meat & Dairy sector pathway development grids

Table 9: Meat & Dairy - Technological Replacement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Plant-based meat and dairy production technologies fairly well established. Use of GMO ingredients in some products (e.g. genetically modified heme in the impossible Burger). Lab-cultured meat trials developing beef, chicken, egg and fish products. Not yet commercially viable at scale. Insect proteins available in the form of protein meal for animal and pet foods, insect oil, wet food ingredients for pets and fertilisers.	2018 revisions to Novel food directive reduce timeline to approval, protect proprietary data collected in support of application for 5 years, enabling retention of IP rights. Innovation for meat analogues supported by: 2012 Innovating for Sustainable growth: A Bioeconomy for Europe; 2017 Plant protein regulation; 2018 EU Protein Plan; 2018 expert report DG research and innovation; Food 2030 Initiative Product labelling clarity determined under 2011 Food Information to Consumers regulation. Current CAP support for ongoing meat and dairy production.	Plant-based meat and dairy analogues penetrating retail markets. Plant-based meat becoming available within the foodservice industry. Insect products commercially available for animal and pet feed (such as Protix chicken and fish feeds, wet pet food products etc.). Establishment of meat analogue stakeholder groups: The Modern Agriculture Foundation (2014, Israel), The Good Food Institute (2016, US), Next Nature Network (2014, NL). New harvest (US) work to establish new markets, provide market analytics and consumer research and acceptance.	Financing provided in the cellular agriculture sector along a biotech start-up model by mission-oriented VC funds such as the FAIRR Foundation New Crop Capital, Fifty Years, Stray Dog Capital. These focused on funding the new ecosystem of meat analogue start-ups. Public provision of financial support via Universities for basic science provision, H2020 etc.	Increased awareness of health impacts of high levels of meat consumption, alongside animal welfare, climate and environmental concerns with animal meat and dairy production. Mainstreaming vegetarian/vegan diets developing also in relation to health, animal welfare and broader ethical concerns e.g. class and race-based focus on food production.

2020-2030	Early trials focusing on the development of lab-cultured structured meat products, alongside cost reductions in serum free growth media, and advances in scaffolding and bioreactor technology at proof of concept and small-scale trials that reduce production costs of lab-cultured processed meat products. Scaling innovations to food production processes enabling plant-based foods to be produced at industrial scale. Innovation around GMO ingredients and processing technologies to increase likeness to animal meat. Insect proteins largely limited to pet foods. Agricultural land-sparing by the less resource intensive meat and dairy analogues enables early peatland/wetland restoration and re/afforestation	Ongoing uncertainty over naming and labelling of plant-based meat and dairy analogues. Differential patterns of national regulatory practices without overall EU level coordination Meat analogue stakeholder groups increase lobbying activities in contestation with Farmers, dairy and livestock groups. Tensions over novel food directives and retention of IP rights. CAP reform supporting land-sparing and land-sharing initiatives.	First commercially available lab-cultured processed meat products trialled in the foodservice sector. Developing market penetration of plant-based products increasingly impacting on livestock and dairy farmers. Further farmer profit squeeze from large food producers shifting to support for processed plant-based meat and dairy products lab. Increasing concentration of meat alternative producers. Meat and dairy analogue stakeholders emphasise addressing consumer acceptability, focus on rejecting dietary change (e.g. veganism) in favour of consuming meat and dairy produced from plants/lab-cultured. Focus on overcoming 'yuk factor' of novel foods through awareness raising. Increasing concentration of meat and dairy producers in response to threat to market share from meat and dairy analogues. Expansion of global trade for both animal meat and dairy products (due to falling EU consumption) and for meat and dairy analogues.	Continuation of VC financing dependent upon IP provision and support. Large food producer financial support for lab-cultured meat and buy-outs/partnering with plant-based meat and dairy producers CAP providing financial support through land-sparing/sharing to farmers.	Potential backlash against 'Frankenstein foods', targeting restaurants and production sites. Concerns over ownership and control of food production. Meat remains central (and increasingly so to European diets). This increasingly shifts to processed products and foodstuffs, rather than wholefoods/cuts, and is increasingly composed of plant-based meat.

2030-2040	Continued advances in plant-based analogues, improving taste, texture and mouthfeel. Reducing unit costs of production and use of novel ingredients. Processed lab-cultured meat products available as premium retail. Early commercialisation of 'lab-cultured' structured meats Uptake of insect protein and fats for animal feed products Improvements in cellular agriculture techniques enable trials for exotic and novel meat products (previously non-food animal meats, wholly synthetic meats) Expanding land restoration and afforestation	Naming and labelling policies increasingly harmonised at EU level, reduction in protection for animal meat-based terms as plant-based and lab-cultured products increasingly subsumed under the category of 'meat'. Policies supporting and developing EU trade, maximising economic growth or focused on localised food provision. Support for food provision by small number of producers or drive for antitrust regulation, increased competition and local/cooperative food production	Plant-based meat and dairy products continue to increase market share displacing processed animal meat products which they closely resemble. Processed lab-cultured meat products available as premium retail. Early commercialisation of 'lab-cultured' structured meats available in foodservice outlets. Traditional meat production focusing increasingly away from processed foods and on whole cuts as premium product in EU markets. Continued concentration of both traditional and plant-based/lab-cultured meat and dairy production.	Continuation of previous funding trends maintaining and furthering market concentration and power of large food producers.	Increasing concerns over food security and concentration within the meat and dairy sector.
2040-2050	Continued advances in plant-based ingredient modification. Reducing unit costs for lab-cultured meat enable production at industrial scale. Insects continue to be used for animal feed products. Commercialisation of exotic and novel meat products.	Continued support for meat and dairy analogue innovation in both novel ingredients and production processes in naming/labelling, market regulation and IP provision. CAP increasingly focused on supporting multi-use agriculture given continued land-sparing. Some shift towards support for open/public knowledge for older technologies.	Widespread adoption of plant-based meat and dairy products. Continued advances in ingredient modification. Lab-cultured processed meat products still premium retail, increasing drive for product differentiation. Structured meat products also available in premium retail sector. Exotic and novel meat products available in limited foodservice outlets. Start shift here to smaller bioreactors, community-owned and controlled due to price reductions	Developing shift towards provision of public funding for not-for profit and community owned/controlled meat and dairy analogue production at smaller scale. Resistance by private finance.	Food production seen increasingly as less of a technical production issue and increasingly as one of ownership and control. But food not considered as culturally or socially central, but rather one of basic rights.

Table 10: Meat & Dairy - Demand Management

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Community-based food sharing schemes at small-scale (Community Fridge projects). Early development of online food system disintermediation platforms directly connecting producers and consumers (e.g. Open Food Network; FarmDrop)	Product labelling clarity determined under 2011 Food Information to Consumers regulation. Increased focus on climate/environment/health benefits of reduced meat diets Ongoing CAP reform process and support for organic/regenerative/multi-use agriculture.	Expansion of non-meat food products driving and responding to dietary shift.	Disruptive supply chain disintermediation – short chain agriculture via online platforms both privately owned (funded largely by venture capital) and on an open platform (shared) basis.	Increased awareness of health impacts of high levels of meat consumption, alongside animal welfare, climate and environmental concerns with animal meat and dairy production, driving dietary shifts towards reduced meat diets, vegetarianism and veganism
2020-2030	Spread of short chain agriculture, particularly along community ownership models, Adoption of enhanced soil carbon storage techniques, hedgerow management, peatland and wetland restoration, woodland farming.	CAP reform process and support for organic, regenerative and multi-use agriculture as opposed to sustainable intensification. Support for public knowledge of novel food production. Reduced IP protection, including around smart agriculture. Dietary regulations focusing on health big driver of dietary change Continuing trials with reducing working hours and Universal Basic Income trials supporting increased time availability to engage with food production/consumption as socially valuable practice. Regulation of soy imports	Limited disruption of large retail sector from disintermediating platforms/community and local food projects, food sharing programmes. Commercial emphasis on the protein transition – dietary protein from non-animal sources through multistakeholder projects/groups such as the Green Protein Alliance	Increasing public finance for not-for-profit and community owned projects focused on waste-reduction; short chain agriculture; nutrition and cooking projects. Increasing shift to reduced working week/Universal Basic Income/Services supporting small scale production especially in urban environments	Continued public concern with high profile Amazon destruction, resulting in awareness raising and direct action around both soy in animal feed (imported as soymeal) and also soy-based food products. Increasing mainstreaming of both reduced animal product and vegetarian/vegan diets developing also in relation to health, animal welfare and broader ethical concerns e.g. class and race-based focus on food production – cheap, racialised, and insecure labour in large-scale food production. Increasing centrality of awareness of food wastage, including through overconsumption.

2030-2040	Spread of now economically sustainable short chain agricultural practices with a focus on quality products incorporating peatland and wetland restoration, reforestation and afforestation. Smart agricultural technologies become viable at small scale on an open source basis.	Urban planning shifts emphasising multi-use green corridors for food growing, and green spaces suitable for agricultural projects and biodiversity support. CAP reform also emphasising and supporting urban and peri-urban agriculture. 4-day working weeks become the norm.	Short chain markets and food production (supported by previous CAP shift in focus to sustainable extensification) Bottleneck around slaughtering and processing small batches.	Increased public financing via CAP reform supporting the development of urban community agriculture projects.	Large scale acceptance of the necessity of dietary change towards reduced meats alongside desire for change driven by animal welfare and health concerns. Developing food-system cultures combining previously limited slow-food movement with concerns over food security: focus on provenance, Redeveloping relationship with food production, short-supply chains, urban food production. Food wastage increasingly negatively perceived as part of cultural shift in relation to food production and consumption. Concerns around zoonotic transmission given increasing proximity of animals (largely monogastrics) in small-scale community and urban farming.
2040-2050		Completed UBI/UBS rollout supporting reduced working time and enabling further community involvement in collectively owned local and urban food growing projects Regulation and provision for small scale animal husbandry, regulation and provision of animal slaughter and processing facilities and infrastructure. Continuation CAP reform trends.	Food reincorporated into central social role with shared production and consumption, large number of short-chain, disintermediated networks Small-scale extensive meat and dairy production producing reduced quantities of high-quality meat		Further repositioning of livestock animals culturally away from solely meat production, but e.g. for Cows towards active management of biodiverse grasslands. Increasing awareness of the social role and importance of food production and consumption. Food wastage largely taboo.

Table 11: Meat & Dairy - Circular economy

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Early uptake of biodigestors such as Sistema Biobolsa to enable production of bioenergy from manure, crops and crop by-products Limited application of bio-based materials in construction (e.g. wool insulation).	2018 update of European Bioeconomy strategy focused on three broad areas: strengthen/scale-up bio-based sectors; deploy local bioeconomies; understanding ecological boundaries CAP reform elements focusing on supporting European bioeconomy strategy. Increasing focus on circular production chains via circular economy action plan	New intermediary markets involved in recycling food waste. Increasing focus on multi-purpose agriculture, carbon farming and bioenergy production.	FAIRR style risk indexes and metrics gaining in prominence and importance for finance. Public financing initiatives via CAP reform, bioeconomy and circular economy supporting initial trials and demo projects.	Growth of public awareness of negative climate and environmental effects of current linear meat and dairy production methods. Increasing awareness of use and importance of circular production and value chains
2020-2030	Expanding trials/scale-up of bioenergy production with CCS/CCU by biodigestion utilising land freed up from agricultural/livestock intensification. Expanded use of digestate as fertiliser Continued trials and early commercialisation of engineered biofilters enabling the production of bioplastics from CH4 by methanotrophs (CH4 oxidising bacteria) from livestock effluent; increasing phosphate recycling Increasing use and commercialisation of bio-based materials in construction (e.g. wool insulation)	Early development of carbon price (for bioenergy). Bioenergy trade associations pushing for higher GHG emission reduction targets. Bioeconomy Strategy continues CAP reform structured around bioeconomy strategy and the green architecture. EU wide regulations for digestate transportation. Developing support for increased phosporous use regulation in light of increasing concerns over availability.	Development of European markets for bioplastics, alongside further development and integration of markets for biofuels. labeling/voluntary standards developed for products that have been produced on farms adopting a circular approach.	Establishment of €100m Circular Economy Bioinvestment Platform within EIB, funding pilot to demo and demo and demo to industrial scale projects. FAIRR style risk indexes and metrics continue gaining in importance. Increasing shareholder agitation and divestment drives focus on circular production and the conversion of current waste streams into upstream and cross-sector inputs.	Public awareness around phosphate limits growing, combined with awareness of reliance in Europe of phosphate imported from countries without democratic oversight of phosphate production and trade i.e Morocco. Increasing public awareness and concern with total system of food production, predominant concern is with climate and environmental impacts. Limited dietary shifts towards reduced meat consumption, vegetarianism and veganism, also emphasising importance of reducing and recycling post-consumer waste.

2030-2040	Engineered biofilters for bioplastics production mature technology deployed at scale. Manure management practices including phosphate recirculation widespread. Biodigestors and bioenergy production with CCU enter widespread use.	Established carbon price. Developing regulation and labelling to ensure circular products meet minimum standards around soil and manure management, biodiversity maintenance and multiple use.	Further development of European markets for bioplastics addressing infrastructural concerns around recycling. Further expansion of market for circularly farmed products	Public financing initiatives via CAP reform, bioeconomy and circular economy increasingly focus on supporting scale-up of potentially viable technologies	Public concern over phosphate limits receding with increased recycling and recirculation. Public pressure around meat and dairy production, focusing protests on non-circular, non-sustainable producers.
2040-2050	Technology in place for widespread digestate transport and use.	Increasing carbon price. EU policy formulated around Maintenance and expansion of bioenergy production with CCS/CCU including through increasing carbon price, continued support for development of bioplastics and use/deployment of other bio-based materials. Aggressive support for global low carbon, low resource intensity meat and dairy products through trade and tax support. CAP reform continues previous trends.	Global bioplastics market develops. Relatively large fertilizer market share for digestate. All manure digested and co-digested products produced.		

Table 12: Meat & Dairy - Process Improvement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Ongoing trials and early commercialization of feed supplements and gut defaunation technologies to reduce methane emissions from enteric fermentation and optimise ruminant digestion in ruminants, including genetic selection techniques. Small scale trials of Smart/precision agriculture combining field robotics, big data, AI and management information systems focused on increased productivity of feed production.	CAP reform focuses on sustainable intensification	Current meat and dairy production in the EU, variable levels of concentration. High market power of retailers and large food producers	FAIRR style risk indexes and metrics gaining in prominence and importance. Venture capital financing for precision/smart agriculture as well as for biotech innovations focused on reducing methane emissions from enteric fermentation.	Increased awareness of health impacts of high levels of meat consumption, alongside animal welfare, climate and environmental concerns with animal meat and dairy production.
2020-2030	Expanding trials of bioenergy production with CCS utilising land freed up from agricultural/livestock intensification. Expanding EU soy crops using spared land. Fertilizer developments (controlled release) – more efficient use of nitrogen, and nitrification inhibitors Commercialization and uptake of enteric fermentation reducers such as DSMs Project Clean Cow and Mootral. Early Use of ionophore antibiotics (used for efficiency but also	Early development of carbon price (for bioenergy). Bioenergy trade associations pushing for higher GHG emission reduction targets. Ongoing uncertainty over naming and labelling of plant-based meat and dairy analogues. Differential patterns of national regulatory practices without overall EU level coordination, continued strong lobbying from meat and dairy incumbents, farmers groups. CAP reform continues to focus on sustainable intensification- emphasising	Early establishment of carbon price supporting emerging markets for bioenergy. Increasing livestock stocking densities, smaller numbers of bigger producers, resulting in increasing concentration in the food production system, driven in part by efficiency and productivity focus/scale required for cost effective precision agriculture/methane reduction technologies. Development of voluntary health information and food labelling schemes designed to counter health concerns regarding high levels of meat consumption	FAIRR style risk indexes and metrics continue gaining in importance. Increasing shareholder agitation and divestment drives focus on increasing productivity and efficiency of processes and reducing resource use under sustainable intensification Continued venture capital for precision agriculture/methane reduction, including for biodigestion and biofiltering. CAP support focused on financing efficient resource use.	Public pressure and reform processes focused on dealing with externalities from sustainable intensification with respect to jobs and biodiversity. Continued public concern with high profile Amazon destruction, resulting in awareness raising and direct action around both soy in animal feed (imported as soymeal) and also soy-based food products. Meat remains central to European diets, but as part of overall balanced diets focused on reduced consumption, particularly of processed products.

	depress CH4 production). Continued trials with vaccination and antibiotic defaunation technologies. Commercialization and uptake of precision agriculture and management information systems for livestock (e.g. Farmtool) Early commercialization of manure management using engineered biofilters for Methane removal from manure and biodigestors for bioenergy production. Adoption of enhanced soil carbon storage techniques, hedgerow management, peatland and wetland restoration, woodland farming.	efficiency and productivity of existing meat and dairy production methods. Regulatory changes enabling use of ionophore antibiotics.			Increasing public pressure to phase out/ reduce/modify antibiotics use alongside general animal welfare and ethics concerns.
2030-2040	Broad commercialization of bioenergy production and infrastructure with CCS/CCU utilising land freed up from agricultural/livestock intensification. Spread and standardised use of genetic selection, vaccination, ionophore antibiotics and feed supplements to reduce methane emissions from enteric fermentation. Standardized use of precision agriculture techniques and data management, increasing spread of field robotics.	Established carbon price. Further support for phosphorous regulation and recycling. CAP reform continues to focus on sustainable intensification- emphasising efficiency and productivity of existing meat and dairy production methods, alongside further support for land-sparing/land-sharing measures increasing soil carbon sequestration and storage.	Carbon price enables development of markets for bioenergy in energy markets and heating, including potential export markets for biogas. Market concentration trends continue.	FAIRR style risk indexes and metrics established as standard investment tool. Precision/smart agriculture, methane reduction technologies increasingly supported and financed by large agro-chemical and agricultural equipment and logistics organisations. CAP support continues to focus on efficient resource use.	Continued concerns and disruptions regarding biodiversity impacts of bioenergy production and necessary infrastructure as well as impacts of CCS (democratic accountability, siting, security and longevity etc) Increasing concern regarding animal welfare and treatment issues in sustainable intensification, particularly around genetic selection and technologies to optimise digestion/reduce methane emissions.

	Data analytics increasingly used for hedgerow management and increasing soil carbon storage. Broad commercialization of manure management using biofilters and biodigestors.				
2040-2050	H2 as input for NH3 production from electrolysis instead of steam reformed natural gas. Intensification of above processes resulting in marginal efficiency and productivity gains through enteric fermentation reduction, precision agriculture, manure management and enhanced soil carbon storage. Further expansion of bioenergy production and infrastructure with CCS/CCU due to increased land-use efficiency, alongside peatland and wetland restoration, reforestation and afforestation.	Increasing carbon price. EU policy formulated around Maintenance and expansion of bioenergy production with CCS/CCU including through increasing carbon price, continued support for development efficiency measures and technologies and aggressive support for global low carbon, low resource intensity meat and dairy products through trade and tax support. CAP reform continues previous trends.	Increasing carbon price resulting in further market developments for bioenergy including limited expansion of export markets. Increasing production of low carbon, low resource intensity meat and dairy products for export markets.	NH3 manufacturing undertaken by mix of existing nitrogen manufactures and new H2 focused producers backed by venture capital	Still high public pressure around biodiversity concerns but at the same time public acceptance of CCS largely assured.

Appendix 4: Pulp & Paper sector pathway development grids

Table 13: Pulp and Paper - Technological Replacement

Decadal period	Nodal points				
	Technology	Policies	Markets	Finance	Public pressure
Present – 2020	Increasing energy efficiency in production processes; experimenting with biocomposites and cellulose fibres; lignin from pulp mill black liquor to new biofuels (experimentation)	Focused on energy efficiency of existing processes; continued producer responsibility for packaging and newspaper	Increasing demand for paper packaging; decreasing demand for printing paper	Little interest	FSC increasing demands on forest biodiversity; critical plastic debate continues and paper is positioned against plastic as more sustainable
2020-2030	Fuel switching in paper mills to solid biomass and biogas removes remaining fossil energy use within the industry; new processes for products developed from sidestreams (lignin and hemicellulose derivatives) launched	Quota requirements supporting using biobased materials in different domains, e.g. packaging and construction	Premium prices for biobased content emerge in niche sectors such as outdoor clothing and equipment and cosmetics	Increasing VC interest in biotech startups; green bonds for investments in fuel switching	
2030-2040	Forest and paper companies launch new biotech platforms; new biobased (chemicals) production starts: specialty chemicals and modified cellulose fibres for waterproof fabrics and packaging of liquids etc	Policies prioritising material use over energy use for biomass resources; increasing quota requirements on renewable content in plastics and chemicals reaching 50%		EIB launches big new programme on investments for renewables in all industries – speeds up conversion of pulp mills to biorefineries	Protests against bioenergy as conflicts around renewable feedstocks for different demands grow “materials should remain materials”; pressure from countries in southern Europe to enforce very strict criteria on forest management

2040-2050	Paper is no longer paper – fibres can be modified in many ways for packaging, insulation material etc; all sidestreams from pulp mills chemically converted to valuable products	Policies setting strict requirements on phasing out using fossil resources for materials	Biobased products the norm across all categories		wasteful use of paper (use to read things once and then throw away) no longer acceptable

Table 14: Pulp and Paper – Circular Economy

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Increasing energy efficiency in production processes; recyclable envelopes	Focused on energy efficiency of existing processes; continued producer responsibility for packaging and newspaper	Increasing demand for paper packaging; decreasing demand for printing paper	Little interest	FSC increasing demands on forest biodiversity; critical plastic debate continues and paper is positioned against plastic as more sustainable
2020-2030	reusable paper packaging for e-trade; recycled cellulose based textile fibres are introduced as niche products	Stricter recycling targets for all packaging materials	continued decreasing demand for printing paper; increasing demand for paper packaging substituting for plastic	Interest among VC finance for new tech firms in recycling	Critical debate about forest management; printing paper in everyday use (newsprint, magazines) becomes less common; printed ad flyers no longer seen as acceptable

2030-2040	recycled premium quality carton and graphic paper introduced; gasification and CCU pilots; cellulose fiber based shoes and other non-traditional textile products	Regulations on recyclability of textiles and fibres	Agreement between brand owners on standardized carton packaging for many foods; decreasing demand for virgin packaging due to increasing use of reusable and recycled packaging materials; increasing international trade in recyclates	Green bonds for new large investments in cellulose fibres and their recycling	
2040-2050	Full scale gasification and chemical synthesis facilities installed in most retrofits of existing pulp mills	Policies setting strict requirements on phasing out using fossil resources for materials; high and strict recycling policies for all materials			Complete delegitimisation of virgin fossil resource use

Table 15: Pulp and Paper - Process Improvement

Decadal period	Nodal points				
	Technology	**Policies**	**Markets**	**Finance**	**Public pressure**
Present – 2020	Increasing energy efficiency in production processes; experimenting with biocomposites and cellulose fibres; lignin from pulp mill black liquor to new biofuels (experimentation)	Focused on energy efficiency of existing processes	Increasing demand for paper packaging; decreasing demand for printing paper	Little interest	FSC increasing demands on forest biodiversity; critical plastic debate continues and paper is positioned against plastic as more sustainable
2020-2030	Fuel switching: gas, oil and coal for biomass an electricity; energy efficiency improvements; CCS pilots; developing sidestream products available through efficiency improvements	First regulations for CCS; EU ETS removes free allocation of emission rights to industries; expansion of ETS to include captured CO2	volatility in electricity markets as industrial electrification speeds up; increasing prices of carbon credits; Increasing gas prices and decreasing availability of coal	EIB prioritizes investments in efficiency improvements through interest rate discounts; approval of new certificate system to include CCS in green bonds	Critical debate about forest management; NGOs demand more protection of forests and increased biodiversity in managed forests

2030-2040	Full electrification of industrial drying and heating: IR/microwave/high temperature heat pump technologies diffuse; BECCS pilots at pulp mills; full-scale implementation of CCS	Increasingly strict energy efficiency requirements on industrial production (benchmark vs state-of-the-art)	Electricity prices stabilize as load shedding practices are established	rush in the financial sector to invest in new CCS projects leading to decreasing costs	Increasing political and public concern over GHG impacts leading to revises of the EU ETS phase 4 plan
2040-2050	All fossil fuel use in the pulp and paper industry removed.	Policies setting strict requirements on phasing out using fossil resources for all energy purposes	European spot market for captured CO2 established	Captured CO2 now the largest commodity traded internationally	