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How to decarbonise energy-intensive processing industries?
Survey and conceptualisation of their specific innovation systems

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Abstract
Energy-intensive processing industries (EPIs) such as iron and steel, aluminum, chemicals, cement, glass, and paper and pulp are responsible for a large share of global greenhouse gas emissions. To meet 2050 emission targets, a transition to low carbon, often radical innovations is required, but this process is going slow. Insights from sociotechnical and innovation systems perspectives are therefore needed to facilitate and steer this transition process. The transitions literature has so far however, neglected EPIs.

This paper characterises the sociotechnical and innovation systems of EPIs in terms of stylized facts, identifying similarities and differences between the individual industries. These stylized facts are recognized through an iterative process that builds on the authors' expertise on EPIs and a review of available literature and documentation. Building on the limited body of available literature, it subsequently explores how these stylized facts may influence low carbon transition processes and identifies literature gaps from which a first agenda to further transitions research on EPIs is sketched. Insights obtained through such research would not only benefit policy recommendations, but may also lead to theoretical enrichment, as the unique EPI characteristics are likely to result in for example new transition dynamics or lock-in mechanisms. The paper is concluded with some implications for policy.

Introduction

Energy-intensive processing industries (EPIs) are industries that convert natural resources into basic materials through processes that require high energy inputs. The EPIs included in this paper convert natural resources such as iron ore, bauxite, petroleum, lime stone and biomass into iron and steel, aluminum, chemicals, cement, glass and paper; essential material building blocks on which society relies (Allwood and Cullen 2012). The need for sustainability transitions in these industries is significant; globally, industry is responsible for over 30% of all greenhouse gas emissions, of which the majority is emitted by EPIs (Fischedick et al., 2014a). In the EU28, EPIs emitted in 2010 13% of all energy-related greenhouse gasses and are responsible a large share of local air pollutants (Lechtenböhmer et al. 2015). Although significant resources and energy efficiency improvements have been made over the past decades (Worrell et al., 2009; Fischedick et al., 2014a), meeting the EU 2050 emission reduction target of 80 to 95% compared to 1990 (EC, 2011), requires extensive low carbon innovation. The recently in Paris adopted “well below 2C” target even requires EPIs to decrease emissions to zero before 2070 (Åhman et al 2016). The transitions to low carbon EPIs are however going slow (Saygin et al., 2011; Cagno et al., 2013) and more insight into the socio-technical barriers that inhibit these transitions is necessary to formulate adequate policy support.

Studies employing sociotechnical systems and innovation systems (ST&I systems) perspectives have provided valuable insights into the drivers and barriers to the development, diffusion and adoption of new, sustainable technologies and practices, as well as into the lock-in of existing regimes with established and less sustainable technologies. These insights have shaped public policy to more effectively facilitate and steer sustainability transitions (Alkemade et al., 2011; Kivimaa and Kern, 2015; Smith and Kern, 2009). Empirical analyzes of sustainability transitions have so far, however, focused on the energy, buildings and transport sectors and has insufficiently studied other sectors, like EPIs, where insights into sustainability transitions and associated policy recommendations are also needed.

There is however also a theoretical contribution to studying EPIs from an ST&I systems perspective. Examples of such studies conducted so far have focused on the tile (Gabaldón-Estevan et al., 2014), paper and pulp (Karltorp and Sandén, 2012), steel (Rynikiewicz, 2008) and cement and concrete industries (Dewald and Achternbosch, 2015; Wesseling and Van der Vooren, 2016), and indicate that many barriers to low carbon innovation result from unique EPI characteristics. The lack of demand for example, relates to EPIs being far removed from the end-consumer, while the lack of regulatory pressure results from a fear of disadvantaging domestic industries in a highly global and price competitive commodity market. This paper argues that these unique ST&I system characteristics provide opportunities for theoretical enrichment of the transitions literature, for example by identifying new transition dynamics or lock-in mechanisms.

This paper positions EPIs in the transitions literature, to enable broader empirical application of the literature and to enrich its theoretical foundations. For this purpose, it first systematically discusses the characteristics of ST&I systems in EPIs, using stylized facts. Subsequently it explores, based on the limited data available, how these stylized facts may affect low carbon transitions in EPIs and specify an agenda on how to further the field of sustainability transitions research focusing on EPIs. It is referred to low carbon transition here instead of sustainability transition, because the paper is primarily interested in climate related sustainability; other sustainability issues relevant to EPIs, like resource exhaustion, are outside the focus of this paper. The paper is concluded by reflecting on the emerging field of low carbon transitions in EPIs and by providing policy implications based on existing knowledge.

Methods

ST&I systems perspective

Different approaches have been developed to study sustainability transitions, including the multi-level perspective, strategic niche management, transitions management, and sectoral and technological innovation systems perspectives. What these perspectives have in common is that they study the emergence, functioning or transformation of an ST&I system. Such a system is comprised of actors (firms, trade associations, government, research organizations, consumers, etc.), institutions (such as norms, values and formal policies or regulations), technologies or materiality (such as plants, infrastructure) and the interactions between these system components. Systems develop or transform through the co-evolution of these system components as innovation cannot take place in a vacuum (Edquist, 2005). Exogenous factors like climate change may exert pressure on an existing ST&I system, driving it to change along a technological trajectory, e.g. through the development of energy efficiency improvements, or, when external pressure is strong enough, destabilizing the existing systems enough for it transition to a new system, which typically revolves around new technology (Geels, 2004).

To understand the technological change in EPIs, this paper distinguishes between incremental innovations that follow existing technological trajectories, and radical innovations that constitute new technologies. Utterback (1996, p. 200) defines radical innovation as “change that sweeps away much of a firm’s existing investment in technical skills and knowledge, designs, production technique, plant and equipment”. For EPIs this definition typically means investing in novel technologies for the basic process (such as going from coke and coal in blast furnaces to renewable electricity for electrowinning) or to changing feedstock which involves significant changes to the primary production process (for example for bulk chemicals going from petroleum based plastics to bio- and electricity based plastics).

To understand low carbon transition dynamics, this paper also distinguishes between innovations that range from marginal to significant (described as low carbon innovation) emission reductions. These innovations may purposefully or not (sometimes emissions reductions are only a by-product, for example of energy efficiency and recycling), directly or indirectly (e.g. when emissions are captured during use of the product like CO_2 absorbing concrete) reduce emissions

We use the structural components of ST&I systems and the innovation typology to structure the discussion of the factors that influence the innovation processes in EPIs and how this may affect the transition to deep decarbonization.

Research design

To position EPIs within the transition literature, this paper first characterizes the ST&I system of EPIs in terms of stylized facts, i.e. broadly generalized and simplified representations of empirical findings. The stylized facts presented in this paper build on experience and data on EPIs in climate ambitious, industrialized countries like in Europe, the US and Japan and are not necessarily generalizable to the global level.

After characterizing the ST&I systems of EPIs through stylized facts, literature on EPIs is analysed to infer how these may influence low carbon transition. The literature gaps identified in this process are formulated into a research agenda that aims to further transition studies on EPIs.

Innovation system characterization of EPIs

Figure 1 provides an overview and describes in terms of stylized facts, the most important actors, networks and institutions that characterize ST&I systems in EPIs and embeds these systems within the larger value chain. This overview shows that EPIs are very different from the energy, buildings and transport sectors conventionally studied by the transition literature, not only in terms of their position along the value chain, but also in their ST&I system characteristics. The remainder of this section further discusses these stylized facts, followed by a reflection on their differences between EPIs.

Industry structure

The industrial structure of EPIs is generally characterized by strong economies of scale and high energy and capital intensity. EPI plants are energy intensive because the processing of raw materials typically requires chemical conversions taking place at high temperatures or requires energy intensive breaking of chemical bonds. Significant energy efficiency and organizational economies of scale can be achieved by large scale processing of raw materials, combined with the high fixed costs and, results in large scale processing plants (Crompton and Lesourd, 2004). These large scale, often highly automated, processing plants are complex, often producing several different qualities of products, interlinked to other industries, and require high upfront costs. High fixed costs in large processes need to be earned back in cyclic markets with large variations in prices. High capacity utilization is important in order to cover high fixed cost and plants may keep operating at an overall loss as long as prices are higher than variable production costs. On the other hand, plants may be very profitable during periods of high demand and high prices. Investment cycles for major reinvestments can typically range between 20-40 years, but actual lifetimes may vary widely in practice (Worrell & Biermans, 2005). However, plants are more regularly refurbished, resulting in debottlenecking, increased productivity, and improved energy efficiency. These cycles vary for different technologies, from 4-6 years for chemical facilities to 10-20 years for glass tanks (Scalet et al. 2013) and blast furnaces (Fischedick et al. 2014b).

The scale, energy and capital intensive business case results in high barriers to market entry. Any new entrants that wish to compete, have to cooperate with, but more generally are absorbed by, established players. The high sunk costs also impose barriers to exit. This is why, in most industrialized countries, brown field investments in existing factories are more typical to create new production capacity than building new factories (i.e. green field investments). Expansion of production capacity in US mini-mill steel plants has been larger in existing plants than in new greenfield sites (Worrell & Biermans, 2005), while the rapidly expanding production capacity in developing countries is primarily found in new greenfield sites. Due to these barriers, many EPIs are characterized by a few consolidated multinationals that own factories across the world and may have a dominant position in the supply of basic materials. The European glass Industry for example consist of more than 1000 companies but more than 80% of the glass is produced by less than a dozen multinationals (Wintour, 2015).

Innovation strategies

Innovation strategies in EPIs are strongly shaped by industry structure. They are predominantly technological as organizational structures and business cases are seen as stable. With little room for product differentiation in the bulk basic materials segment, EPIs rely mostly on process innovation. Downstream product differentiation into specialized market segments is however possible and will be discussed below. These process innovations tend to follow predefined technological trajectories through incremental innovation aimed at enhancing productivity. Through learning by doing, the engineers operating the factories generate incremental process innovations that trigger partial reinvestments. However, most of the process innovations used by EPI-firms are outsourced to, or co-developed with, technology providers.

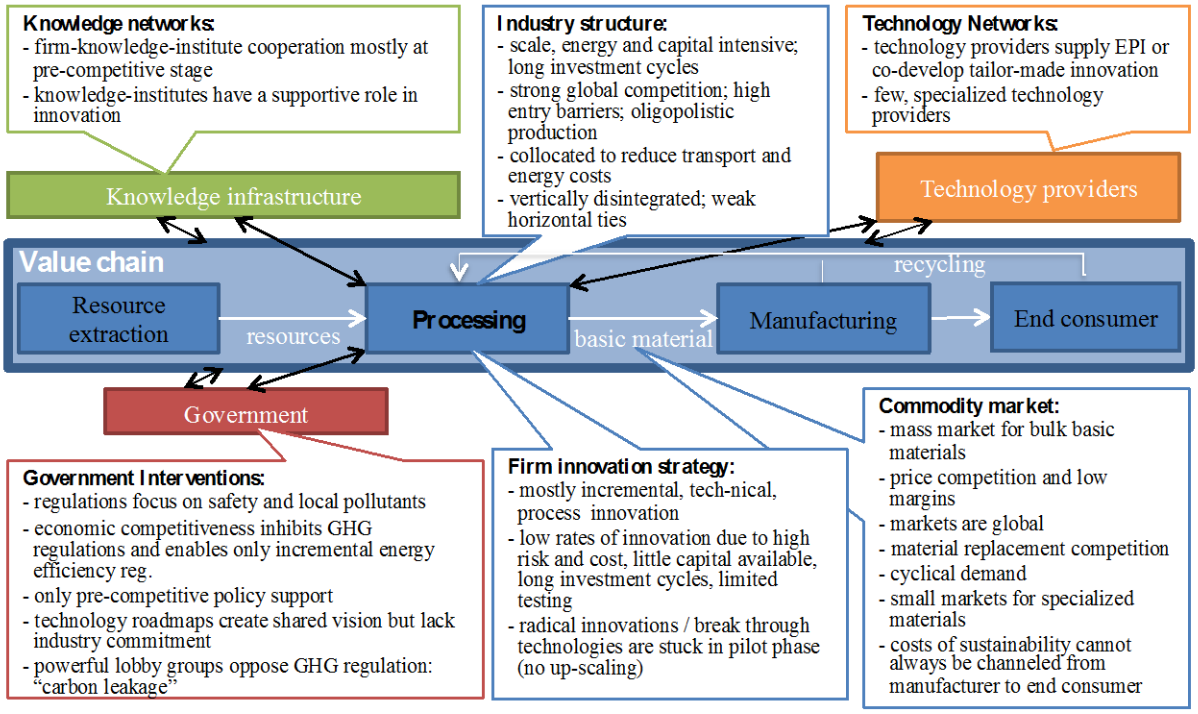

Figure 1, Overview of the different structural components of EPIs and their characteristics

With the exception of chemicals, R&D investments in EPIs are low (EC, 2015), resulting in low rates of innovation that can be explained by several factors. First, the long investment cycles provide few windows of opportunity for changing technology (Worrell & Biermans, 2005). Second, due to the characteristic low, cyclical profit margins in EPIs, investment capital is often not available and return on investment times are very long (SPIRE, 2013). Third, there is a high risk perception regarding innovation as technical failures that impair the production process are extremely costly and may directly result in loss of market share. Fourth, there is limited opportunity to test the technology and become familiar with it on a small commercial scale. Finally, many of the core process technologies have been improved considerably over the past decades (and longer[1]), leaving room only for incremental improvements, resulting in a disadvantage for radical innovations that have not accumulated these incremental improvements. Another bottleneck for the industrialized, climate ambitious countries is the focus on refurbishing existing large-scale factories through brown field investments, which does not always enable the integration of radical innovations.
Many radical innovations are perceived as very risky, costly, hard to integrate, unable to compete with scale-economies of established technologies and therefore unable to overcome the valley of death that characterizes the early stage of scaling up in the technology life cycle. Radical innovations have however developed historically, driven by enhanced productivity (Oster, 1982; Luiten, 2001), better feedstock (Bennet and Pearson, 2009) or demand-pull supported by regulation (Bergquist and Söderholm 2015; Yarime 2009); contemporary examples include thin slab casting (iron and steel) and oxy-fuel gas firing (glass). Other radical innovations are only competitive under specific conditions (such as access to specific resources), like the Corex process, which renders obsolete the coking and sintering plants but has a lower production capacity than currently found in most blast furnace-operated integrated iron and steel plants.

Networks

Instead of in-house development, EPI companies often outsource or collaborate intensively with a small number of technology providers on process innovation and factory upgrades. These technology providers are specialized engineering firms that supply machinery to industrial customers around the world. Because the technologies used by EPIs are very specific, tend to be intellectually protected (EC, 2015), low in demand and with long

[1] See e.g. De Beer et al. (1998) for a discussion of the long-term trends in iron and steelmaking.

lifetimes, relations between technology providers and EPI firms can be very strong. Analysis of a limited number of key energy-efficient innovations in the steel and paper industry has shown that strong, so-called mini-networks of one or a few suppliers and potential users are essential for the success of an innovation (Luiten, 2001).

Although local collocation amongst rival EPI companies may take place around transport nodes such as ports to enable low-cost import of globally sourced resources through relatively cheap bulk shipping, formal research collaborations between these firms and knowledge institutes typically takes place at the national and supranational scale, i.e. North-America, Europe or Asia. Because no single firm can carry the high R&D costs and risks of radical innovations alone, competitors collaborate extensively with each other in networks that also include technology providers and knowledge institutes. Through such multi-stakeholder formal partnerships, organizations are able to pool ideas, knowledge and resources – often complemented with public funding. Although these collaborative projects are effective at developing innovation at the pre-competitive stage, (inter)national competition regulations and IPR struggles impair the collective translation of these ideas into commercialization. Similarly, collaborations between firms and knowledge institutes are typically limited to the pre-competitive stage, although some collaborations extend to application-driven innovations.

Supply chains in EPIs are organized in different ways, with strongly varying degrees of vertical integration among different EPIs and EPI companies. Customer-supplier (both provider-EPI as well as EPI-manufacturer) ties are stronger and fewer when the natural resource or basic material has a more narrow application or is more scarce (e.g. special ores or high-quality steels). Historically, local clustering and close network formation took place between companies along the value chain to reduce transport and energy costs.

Government intervention

EPIs are often well-regulated when it comes to local air, water and soil pollution and safety; firms risk losing their license to operate if they do not comply with these regulations. Local stakeholder groups may pressure policy makers to make these regulations even stricter. To safeguard economic competitiveness, the regulations for GHG emission control are however often lenient. EPIs also typically pay lower energy taxes, compared to other energy users[2]. Due to their economic importance and the so far lacking urgency for more radical innovation, EPI-focused policies tend to focus on incremental innovation. This holds also true for the Best Available Techniques (BAT Reference documents) which have been established under the IPPC and the IED Directives although they aim at “ambitious consumption and emission levels” (Schoenberger, 2009). However, sometimes regulation has been able to stimulate more substantial innovation, such as local air pollutant regulation for the glass industry, which successfully stimulated oxy-fuel gas furnaces (Schep, 2009). Finally, voluntary or negotiated agreements are used, but are criticized for being ineffective, as industry typically only agrees on what they can achieve with business as usual (Ashford, 2005).

EPIs are characterized by well-coordinated, powerful lobbying groups that can oppose regulatory interventions. These lobbying groups comprise industry associations that have close ties with trade unions that represent the workforce, and with local and regional policymakers in regions where they are concentrated. Due to the economic importance in these regions, local influence is particularly important to oppose local/regional regulatory initiatives. As in other industries, the industry associations tend to take the position of their most conservative member and oppose any regulations that they perceive as threatening their competitiveness (Wesseling and Van der Vooren, 2016).

Government funding can be important to develop radical innovations throughout their early stages of development, but may not be essential when the innovation generates important productivity benefits. This is evidenced by the development path of the shoe press in papermaking and thin slab casting in steelmaking (Luiten, 2001). Long-term policies for radical innovations to meet societal challenges often take form at the European and national level. Public Private Partnerships that involve the collaboration between industry, research institutes, academia and government to come up with technology roadmaps, i.e. shared visions on the directions of future industry developments, have been used in the US since the 1990s (DOE, 2001), in EU member states, and are increasingly coordinated at the European level (SOURCE). Such initiatives could be a first step towards overcoming the uncertainty and riskiness of radical innovations in EPIs.

Markets

EPIs supply their basic materials to two types of markets: basic material markets that trade in bulk and smaller specialized material markets.

Markets for basic materials

The mass markets for bulk basic materials, like construction steel, flat glass, cement, and polyethylene, are by far the largest in EPIs. There is little room to differentiate in bulk materials that strongly compete on price. With the exception of some commodities like cement or glass-wool (where long-range land transport is costly), markets

[2] Energy intensive companies in Germany are e.g. largely exempted from levies to support renewable electricity generation.

for bulk materials have a global scope. Fast developing and industrializing countries like China and India pose a competitive threat to the European EPIs with an active industrial policy favoring production volumes by offering e.g. lower energy and capital costs and favorable market access (Haley and Haley, 2013).
The market for bulk materials is often characterized by strong price volatility. Prices and profit margins swing with market demand and with international overcapacity in global and regional markets. This creates cyclical profit margins. Because of the high fixed costs of operation and inflexible production technologies, EPIs are unable to fully exploit these cyclical profits.

Markets for specialized materials

Although there are little opportunities for product differentiation in the mass markets, firms can target smaller market segments for specialized (high quality) materials. These segments are low-volume (demand is typically limited to one or a few discrete manufacturers), add more value and compete less on price and more on quality, reliability and timing of delivery (these factors may differ per EPI). Because specialized demand is limited, specialized materials are often developed in cooperation with the customer which creates long-lasting ties based on trust. The competitive focus on quality, reliability and timing and the role of trust results in reduced price-elasticity of specialized products and creates higher and more stable profit margins.
Due to the competitive threat of emerging industries in an increasingly global market for bulk materials, the specialized materials segment has become increasingly important for EPIs in industrialized countries, enabling their firms to leverage their superior expertise and to partially compensate for the lower profit margins in bulk markets. Examples are Dutch producers of solid cardboard, French producers of high quality steel used for high speed railways and Swedish producers of metal powders. Innovations that enable smaller scale production in downstream processing steps, like continuous slab and thin strip casting (steel), may be particularly beneficial for these low-volume segments as they may enable collocation with specialized monopolistic buyers. Finally, material replacement competition is particularly strong in these specialized segments; high-end steels, aluminum and plastics, for example, compete for car applications (Miller et al., 2000). Hence, ST&I system characteristics for specialized markets are somewhat different from those for mass markets.

Sector specific deviations from the EPI characterization

The above described characterization of EPIs does not apply for every sector to the same extent. Table A.2 in the Appendix provides an overview of the stylized facts and whether the EPI experts perceived them as applicable to each EPI sector. It shows that the experts agreed most stylized facts are applicable to all sectors, as there are only 3 instances where the stylized facts do not apply to certain sectors, and 19 that remained unclear. More specifically, breakthrough technologies do not enable smaller scale aluminum or cement production. Market segments for specialized materials are furthermore more prominent in steel, aliuminum and chemical industry and less developed in cement and glass industry.

Decarbonization of EPIs

While there is potential to reduce energy intensity and carbon emissions with commercially available processing and recycling technologies and practices, meeting long term emission targets requires a transition to low carbon process innovations. These innovations are often complementary and enable the replacement of fossil fuels with electricity or biomass (e.g., electric glass melting, electrowinning in steel or biofuel in lime kilns), replacement of feedstock (such as geopolymers in cement or bio-based plastics) or integration of CO_2 emission capture (CCS) into the process design. These low carbon innovations, the level of technical change compared to established technologies (i.e. the radicality of the innovation), the estimates of their technology readiness levels (TRL) and their technology-specific drivers and bottlenecks are listed in Table 1[3].
Because of its significant environmental and economic benefits, recycling has been developed in many EPIs to create a sustainable feedstock stream (Worrell and Reuters, 2014; UNEP, 2013). However, today most recycling results in sub-optimal down-cycling. Relying on higher inputs of recycled material to achieve deep reductions in GHG emissions will require novel technologies (e.g. smart DNA-marking) and ICT to guarantee sustained material quality. Processing recycled materials requires different capabilities and often provides lower quality products, which is why recycled materials are blended in with raw (virgin) materials and traded on separate markets. With current technologies, raw materials will always be needed and, with the exception of some scarce resources, are unlikely to deplete in the next few hundred years (Henckens and Driessen, 2014; UNEP, 2013).
The remainder of this Section places the previously identified stylized facts on EPIs in the context of low carbon transition, by exploring how they the development, diffusion and adoption of the low carbon innovations listed in Table 1. This section furthermore identifies literature gaps that are formulated into an agenda for advancing transitions research on EPIs.

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[3] In Table 4.1 “I” signifies incremental innovation; “R” refers to more complex innovations that do not significantly change existing production structures; “RR” implies new technologies that require change in production facilities and systems; “RRR” refers to innovations at very early stages of development that would radically change the production system.

Table 1, Overview of low carbon innovations per sector necessary for 2050 emission target, and their drivers and bottlenecks to implementation. Sources: Lechtenböhmer et al., 2015a;b; Van Lieshout, 2015)

Sec-tor:	Technology	Type of innovation: Incremental or Radical and technical description		TRL	Drivers (what are the benefits of the innovation):	Bottlenecks (why hasn't it been implemented yet):
all EPI	CCS	I/R	typical end of the pipe technology, can be incremental, but typically needs significant additional space and technology, which can make it radical; needs infrastructure to transport captured CO_2	up to 6	less CO_2 (++)	additional energy demand, costs, infrastructure, acceptance by local public
	Material Efficiency & Recycling	I/R	Reduce the (primary) material intensity of supplying material services through improved product design, product re-use, high-quality recycling, and different business models		Resource efficiency less CO_2 (++/+++)	Low resource vs. high labor costs, traditional supply chain organization
Iron & Steel	Recirculating Blast Furnace & CCS	R	currently under R&D (e.g. ULCOS project) needs high integration into existing plants which might need major changes in plant / site setup	4 - 5	less CO_2 (++)	higher energy demand, costs, infrastructure, acceptance
	Smelt reduction & CCS	RR	makes obsolete coke ovens, BF & BOF of conventional steel factories	3 - 4	less CO_2 (++/+++)	costs, infrastructure, acceptance
	DRI with H_2	RR	makes obsolete coke ovens, BF & BOF of conventional steel factories, but is combined with electric arc furnace; needs H_2 supply infrastructure		less CO_2 (+++, with Res H_2) (potentially excess electricity converted to H_2)	Costs, infrastructure & technology
	Electrowinning	RRR	makes obsolete coke ovens, BF & BOF of conventional steel factories, needs large electricity supply; technology only on lab scale available	2 - 4	Less CO_2 (+++ with RES electricity) smaller, probably lower CAPEX	only available in lab; low coal/CO_2-prices and high electricity prices
Aluminum	advanced (inert) anodes	I	technology development necessary	4	less CO_2 (++), lower energy demand	availability of technology, research needed
Chemicals	advanced steam crackers & CCS	I	advanced furnace materials, gas turbine integration, use of membrane technology for separation, catalytic cracking	4 - 5	less CO_2 (++) (higher efficiency compensated by CCS)	costs, infrastructure, acceptance
	electroplastics (with RES-Methane)	I	needs conversion to bio or electricity based feedstocks (and respective supply infrastructures)	5 - 6	Less CO_2 (+++, depending on RES-share)	costs, availability of renewable electricity and hydrogen
	electroplastics (with Fischer Tropsch)	R	needs integration into existing plants to use excess heat	4 - 6	Less CO_2 (+++, depending on RES-share of electricity)	costs, availability of renewable electricity and hydrogen
	Bio-based polymers	RR	New process technologies, new feedstock (with limited experience at most companies), may need new platform chemicals	4 - 7	Less CO_2 (++) partially new properties	Relative high costs of biomass, economies of scale
Glass	electric melting	I/R	currently in use but not for large scale float glass applications, unclear if electric melting technology can be upscaled or larger change of production process is needed	6 - 7	less CO_2 (+++, depending on RES-share of electricity)	high electricity price, size of technology
Cem	Geopolymers	R	requires a new way of making cements with different input materials	3 - 4	less CO_2, lower (++ ???)	Requires new resource streams; unproven long term performance; stringent norm compliance

ent	Self-healing concrete	RR	Requires new production techniques to manage bacteria that regenerate concrete to enhance durability	3 - 4	Less CO2, longer durability, lower cost long term	Requires new resource streams; unproven long term performance; stringent norm compliance
	CCS	I	end of the pipe technology; needs infrastructure to transport captured CO2	6	Less CO2 (++)	cost
Paper & Pulp	Efficiency	I	Increase efficiency to make pulp and paper industry 100% bio-based	8	Less CO2	Cost compared to alternatives
	CCS	I	end of the pipe technology; needs infrastructure to transport captured CO2	6	Less CO2 (+++, even negative)	Cost
Refineries & petrochemical	Biorefinery development	RRR	Biorefineries could potentialy replace refineries. Biorefineries can merge with paper and pulp industry	4 - 6	Less CO2 (+++)	Feedstock availability and cost (competition for biomass)
	Electrofuels/ plastics	RRR	Fuels and chemicals can be replaced with electricity and CO2 based soultions. Might also merge with biorefienry	4 - 6	Less CO2 (+++)	Electricity cost
	CCS	I	end of the pipe technology; needs infrastructure to transport captured CO2	5 - 6	Less CO2 (+)	Cost

"I" signifies incremental innovation; "R" refers to more complex innovations that do not significantly change existing production structures; "RR" implies new technologies that require change in production facilities and systems; "RRR" refers to innovations at very early stages of development that would radically change the production system. Less (fossil) CO2: + refers to up to 33% reduction vs. reference technology; ++ 33 - 66% reduction; +++ more than 66% reduction.

How industry structure affects deep decarbonization

How EPI's industry structure affects deep decarbonization has been insufficiently studied. One important implication of the industry's long investment cycles is that new factories installed today need to be ready to comply with 2030 and 2040 emission reduction targets (Worrell & Biermans, 2005). The scale, energy and capital intensity of EPIs and their oligopolistic production form significant barriers to entry both for EPIs (Dewald and Achternbosch, 2015) and their technology providers. Such barriers may inhibit transition since new entrants have been identified as important drivers to low carbon transitions in other sectors, like automotive (Wesseling et al., 2014) and energy (Jacobsson and Lauber, 2006). Some radical innovations that enable processing at a lower temperature and smaller scale may reduce such entry barriers. The dependency on brown field investments in industrialized countries may limit the introduction of many low carbon innovations that require radical technical changes that are not facilitated by existing infrastructure (see Table 1). Related to industry structure, research agenda topics include the analysis of:

- Opportunities for step-wise upscaling (i.e. niche accumulation - Raven (2007)) of low carbon innovations
- Opportunities for retrofitting existing plants with low carbon innovations
- Opportunities to exploit scale-reducing effects of radical innovations
- How concentrated ownership affects low carbon innovation
- Ability of new firms to enter EPIs with low carbon innovation

Low carbon innovation strategies

EPI firms typically engage little in low carbon innovations, not only because of the numerous bottlenecks to innovation in general that were discussed above, but also because of reasons specific to low-carbon innovation. EPI firms for example often perceive no competitive advantage in lowering emissions. Consequently, only few companies partially internalize the costs of carbon in their decision making and low carbon innovation tend to be successful only when they provide productivity increasing and cost lowering co-benefits, like energy or material efficiency gains (Luiten, 2001). Emission reduction is in those cases often not the main goal but a side-effect. In some cases, like for some low carbon cements, product properties might even decrease (Wesseling and Van der Vooren, 2016). End-of-pipe technologies like CCS provide nothing but higher cost in return for emission reductions and require major innovation and reinvestment for most EPIs in core processes (IEA, 2013). Fuel-replacing low carbon innovations, in turn, are for their profitability dependent on how the electricity price develops in relation to fossil fuel prices. These and the factors discussed below partly explain why the often risky and costly technologies in Table 1 are not breaking through commercially. Hence, sustainability is not perceived as a competitive advantage in EPIs and inhibits low carbon transition, while sustainability in the automotive and energy sectors is an important means of product differentiation and boosting brand name perception and drives transition (see e.g. Wells and Nieuwenhuis, 2012; Wesseling et al., 2015).

To reduce emissions, EPI-firms currently focus mostly on incremental process innovations, exploiting co-benefits with specialized materials where possible, on recycling and, to a lesser extent, changing feedstock and fuels[4] (Skjærseth et al., 2013). However, the tendencies to realize these incremental innovations differ strongly between firms, as some do not even have a well-functioning energy management system, and therefore lack the organizational structure to engage effectively in even these incremental emission reducing innovations. In Europe, this has improved with the monitoring, reporting and verification requirements of the EU ETS (Skjærseth et al., 2013). Some EPI-firms argue (also in their lobby against GHG regulation) that they produce specialized materials that may cause more emissions during processing, but result in emission reductions in down-stream applications. Examples are lighter and more durable steel and concrete with enhanced CO_2 absorption (Andersson et al., 2013).

In sum, the limited body of available literature indicates that low carbon innovation strategies are lagging behind and hampering low carbon transition for various reasons (some of which apply to innovation in general; others to low carbon innovation specifically); relevant research agenda topics to delve further into these strategies include:

- Systematically analyzing rates and types of low carbon innovation and related R&D, e.g., are firms becoming increasingly dependent on publically funded R&D for this?
- Analyze why some firms even lack the well-functioning energy management systems needed to engage in incremental emission-reducing process innovations
- Identifying effective policy measures to help low carbon innovation through the pilot stage
- Analyzing ways of reducing risk for low carbon innovation (such as public procurement and long term policies)
- Systematically analyzing the co-benefits of low carbon innovation
- Analyzing the solutions to enhance investment opportunities for low carbon innovation

How industry networks affect deep decarbonization

Little research has been done on the effect of the differing levels of value chain integration on low carbon innovation, on the role of technology providers in deep carbonization, or on the effect of EPI's dependency on the fossil fuel energy system for a switch to low carbon fuels.

With the acceptance of international, long term GHG reduction targets, policy makers have initiated public-private partnership (PPP) with firms and knowledge institutes from different sectors to develop shared future vision on low carbon innovations and pool financing and expertise throughout their early stages of development. They are particularly important when the low carbon innovations are costly and bring little co-benefits. One example is the Ultra-Low Carbon dioxide Steelmaking project, were 48 European companies, including all major steel makers, energy and engineering firms, and research collaborate under support of the EU (ulcos, 2016). The Sustainable Process Industry through Resource and energy Efficiency (SPIRE) roadmap, established to make the European process industries "more competitive and sustainable" (SPIRE, 2013, p.4), is another example. PPPs are also used outside of the EU, e.g. Japan's Course50 and the US's APRA-E. Hence, outside the effects of PPPs, little research has been done on how industry networks affect decarbonization; although they are effective in stimulating low carbon innovation at the RD&D stage, they lack commercial application. Research agenda topics include:

- Analyzing how the co-dependence of EPIs and technology providers affects low carbon innovation
- Studying how the weak network ties affect low carbon innovation
- Analyzing the role of knowledge institutes and intermediary organization in low carbon innovation

How government intervention affects deep decarbonization

As indicated in the previous section, GHG emission control regulations in EPIs are often lacking or not enforced, for reasons of economic competitiveness. EPIs are, for example, largely shielded from the direct cost of the European Emission Trading Scheme (EU ETS) (Åhman and Nilsson, 2015) and have resulted in less low carbon innovation than other affected sectors (Skjærseth et al., 2013). EPIs also typically pay lower energy taxes, compared to other energy users. The regulations that are in place focus on incremental innovations that also have economic benefit, like energy efficiency improvements, some fuel shifts and minor process improvements. In the Netherlands for example, factories have to adopt the most energy efficient measures every five years, although this is not sufficiently enforced (Abeelen et al., 2014). These regulations drive firms to prioritize investments needed to maintain the license to operate (e.g. pollution abatement to meet regulatory standards) over GHG emission control. Support programs, such as RD&D are furthermore limited to the pre-competitive pilot stage, which is where most radical innovations are stuck. In sum, although govern support low carbon innovation

[4] This is particularly the case in the concrete (Christensen, 2013) and paper and pulp industries (Gulbrandsen and Stenqvist, 2013).

throughout the RD&D stage, effective regulations or demand-side support is lacking and inhibits low carbon transition. While such regulations and support are also underdeveloped in the agricultural sector (Klerkx et al., 2012), they seem to be developed more (at least in some countries) and form important drivers to sustainability transition in the automotive and energy sectors (Jacobsson and Lauber, 2006; Kemp et al., 2007; Wesseling, 2016).

The well-coordinated lobby groups of these economically important sectors typically oppose GHG emission regulations, perceiving them as cost drivers (Skjærseth et al., 2013). These groups have made extensive use of the "carbon leakage" argument, stressing that regulatory burdens will increase compliance costs, resulting in a significant competitive disadvantage in a highly globalized market, forcing affected companies to move their production to other, less regulated countries, where they will emit the same or more than they did originally. This argument has been influential in relaxing the EU ETS for the concrete (Christensen, 2013), steel (Wettestad and Løchen, 2013) and paper and pulp industries (Gulbrandsen and Stenqvist, 2013). In practice, this carbon leakage argument only holds to some extent for markets of global, price-competitive bulk materials, but not for specialized materials markets. Lobbyists also argue that emissions from EPIs are off-set during the use of their materials and that compliance with other environmental regulations, such as pollution and dust prevention, requires more energy and therefore increases GHG emissions. Finally, although no systematic evaluations have been made of the impacts of technology roadmaps, a study on the concrete industry suggest they might be captured by industry interests, making them more conservative than academic forecasts (Wesseling and Van der Vooren, 2016).

Research agenda topics include:

- Analyze why GHG emission control policies are lacking (what are predominant policy rationales and goals and how do they interact?)
- Analyzing how policy can drive down GHG emissions without affecting industry competitiveness:
  - If allowed under EU legislation, mandating the use of clean materials could for example protect the European market from developing countries' low-cost, high-emission materials
  - Low carbon policy support may profit industry, as Mazzucato (2013) showed for Danish wind turbines
  - Consumer oriented policies could be used to shift the costs of carbon from upstream producers to the consumers
- Analyze to what extent GHG emission regulations really inhibit competitiveness
- Analysis of low carbon policy instruments to facilitate policy learning, e.g.
  - Opportunities for public procurement in infrastructural projects
  - Policy options that integrate push and pull mechanisms, e.g. feebates to support the development and uptake of new technologies while pricing the externalities
  - Facilitating commercialization of innovation (impaired by IPR and EU competition) from collaborative EU projects
  - (carbon price volatility created by) the current EU ETS
- Analyze to what extend expectations in industry roadmaps conflict with scientific literature[5]
- Analyze the political influence of the lobby groups in frustrating GHG regulations

How market segments affect deep decarbonization

EPIs supply other companies and are therefore less subject to consumer pressure to become more sustainable. This pressure trickles down the value chain when big manufacturers of end-products, such as IKEA, decide to demand more sustainable basic materials. Customers of EPIs are however typically not willing to pay a price premium for cleaner basic materials, believing they cannot channel this premium to the end-consumer, even though the net price impact is very small[6] (Wilting and Hanemaaijer, 2014). One reason is intransparency, since, so far, consumer products typically do not show the carbon foot print of the materials they use. Wesseling and van der Vooren (2016) show, for concrete, that there is simply no willingness to pay this price (and risk) premium; not even by public agencies, which are the most important buyers of concrete. Channeling the price premium to the end-consumer is particularly troublesome in the price-competitive mass markets for basic materials, but may be easier in the smaller market segments for specialized materials with higher value added that compete more on quality and less on price. The distance of EPIs from the consumer and the ensuing lack of demand for clean materials is an important inhibitor to low carbon transition. Public visibility drives transition in consumer sectors, like agriculture and especially the automotive and energy, where driving electric vehicles or installing solar panels on rooftops signals the consumer's sustainable lifestyle (Spaargaren, 2003; Tran et al., 2013).

Research agenda topics include:

[5] Wesseling and Van der Vooren (2016) find that for concrete they are too conservative and unable to meet 2050 emission targets.

[6] FSC paper is an exception (and closer to the end-consumer than other EPIs)

- Systematically analyze future market opportunities for low carbon innovations:
    - In markets for bulk or specialized materials?
    - What drives large consumers of basic materials (like LEGO) to start buying sustainable basic materials?
    - How can transparency in the carbon footprint of basic materials in consumer products be enhanced?
- Cross-sectoral analysis of how globalization affects the diffusion of low carbon innovations
- Analyze effects of material-replacement competition on sustainability

ST&I system-holistic research topics

In addition to the previously mentioned research topics that are specific to components of the ST&I system, also system-holistic topics are identified for further research. First, although many technology assessment studies have focused on the low carbon technologies listed in Table 1 (e.g. Fraunhofer ISI et al. 2011), socio-technical analyses are limited. These technologies should therefore be studied from ST&I systems perspectives like the Technological Innovation Systems (TIS) perspective to identify technology-specific drivers and barriers to innovation (see for example Dewald and Achternbosch (2015)).

Second, it would be interesting to analyze the low carbon transformation of mature EPI sectors, from a multi-level perspective, as done by Karltorp and Sandén (2012) for paper and pulp industry, or from an innovation systems perspective as done by Wesseling and Van der Vooren (2016) for the concrete industry. Once more case studies on the transformation of EPIs are available, comparative case studies could identify similarities and differences in transition processes across EPIs, adding to existing transition pathway typologies (Geels and Schot, 2007; Geels et al., 2016). Building on the sectoral taxonomies of technical change by for example Pavitt (1984), such comparisons could also start with systematically analyzing how the role of certain ST&I system components in transition differs across sectors (as this paper mentioned for the role of new entrants, low carbon competitive advantage and consumer visibility, and sectoral protection from regulation), which may lead to a better understanding of why transitions unfold differently across sectors.

Conclusions and policy recommendations

This paper concludes that the ST&I systems of EPIs are characterized by a set of stylized facts that set them apart from other industries. These stylized facts are likely to affect low carbon transitions in EPIs differently from conventionally studied sectors, but how they precisely influence transition processes remains unclear due to the underdeveloped body of transitions literature on EPIs. Filling the gaps in this literature, will provide a better understanding of how to facilitate and steer low carbon transition processes in EPIs in order to meet long term emission targets, which is important for providing effective policy recommendations. Such an understanding may furthermore enrich ST&I systems perspectives, by identifying new transition dynamics and constellations of systemic lock-in and by broadening the scope for sectoral comparisons of transition processes.

Policy recommendations

The identified EPI structures, innovation strategies, networks, government interventions and markets have implications for policy recommendations aiming to facilitate low carbon transition e.g.:

The identified lack of demand for clean basic materials necessitates stronger **market-pull policy**. So, when low carbon innovations are closer to commercialization, policy should move beyond RD&D support to enable innovation to move beyond the demonstration stage. Particularly in public sectors that demand a lot of basic materials, like infrastructure, public procurement should reward low carbon innovation (e.g. through functional procurement or providing fictitious discounts in tender processes based on emission reductions). Other demand-side policy measures stimulating voluntary efforts (e.g., LEGO´s search for a green plastic); labelling to create carbon foot print transparency; regulation (e.g., banning petroleum based plastic bags); quota based systems and feed-in-tariffs for green materials; and carbon pricing also on chemical feedstock.

To overcome directionality failures, stakeholder-oriented low-carbon **scenario, vision and pathway processes** are important tools to learn, strategize, communicate, coordinate, direct and legitimize transitions (Weber and Rohracher, 2012); also in the EPI. Critical aspects such as technology options, co-evolution with decarbonized energy systems, conflicting goals and interests, and policy options can be explored and assessed through such processes. The EU Low Carbon Roadmap recognized this (EC, 2011): “As solutions are sector-specific, the Commission sees a need to develop specific Roadmaps in cooperation with the sectors concerned.” So far however, roadmaps have been dominated by industry associations, which may use them to secure their vested interests (Wesseling and van der Vooren, 2016). This powerful transition tool therefore instead needs to be developed in cooperation with other stakeholders.

To overcome the problem of carbon leakage (resulting from the price-competitive, global markets for bulk basic materials) and the lack of investment capital (resulting from the low profit margins in these market segments and high innovation costs), a **globally coordinated policy approach** would be important (Åhman et al, 2016).

Finally, the **governance** challenges in the EPIs are greater than in other sectors, notably due to high mitigation costs, lack of co-benefits or competitive edge to clean materials, the economies of scale and capital intensity, and international trade and competition. Risks and costs must be shared between industry and governments without overcompensating industry or distorting markets in unintentional ways. Investment opportunities are few, come in large pieces, and commodity markets are often cyclical. Balancing different interests will therefore be a great challenge and governing the transition will require high levels of expertise in the evolving institutional frameworks that will shape technology, innovation, market, state-aid, trade and industrial policies for decarbonization.

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Appendix

Table A.2, overview of applicability of stylized facts to individual EPI sectors.

	Description of characteristics of the EPI's core processes:	**Steel**	**Aluminum**	**Chemicals**	**Cement**	**Glass**	**Paper & Pulp**
Industry structure	scale, energy and capital intensive production of basic materials	Y	Y	Y	Y	Y	Y
	new technologies need to fit in existing factories (brown fields)	Y	Y	Y	Y	Y	Y
	some breakthrough technologies enable smaller scale production	Y	N	Y	N	Y	?
	oligopolistic production	?	Y	Y	?	Y	Y
	high entry barriers	Y	Y	Y	Y	Y	Y
Firm strategy	low rates of Innovation	Y	Y	Y	Y	Y	Y
	predominant focus on incremental, technical process innovation	Y	Y	Y	Y	Y	Y
	most breakthrough technologies stuck at pilot stage	Y	Y	Y	Y	Y	Y
	Innovation is risky and expensive	Y	Y	Y	Y	Y	Y
	low profit margins inhibit investments in innovation	Y	Y	?	Y	Y	Y
	long investment cycles provide little opportunity for innovation	Y	Y	Y	Y	Y	Y
Networks	EPIs do not always own the technology they operate with	?	N	?	?	?	?
	strong relation with technology provider to out-source or co-develop innovation	Y	Y	Y	Y	Y	Y
	Strong horizontal networks (of firms, knowledge institutes) mostly at pre-competitive stage	Y	?	Y	Y	Y	Y
	disintegrated supply chain / weak vertical network ties (bulk materials freely available on market)	Y	Y	Y	Y	Y	Y
Governmen t intervention	regulations focus on local pollutants and safety but are lax on GHG emissions	Y	Y	Y	Y	Y	Y
	economic competitiveness inhibits GHG regulations	Y	Y	Y	Y	Y	Y
	GHG are only affected through incremental energy efficiency regulations	Y	Y	Y	Y	Y	Y
	only pre-competitive innovation policy support	Y	Y	Y	Y	Y	Y
	technology roadmaps provide long-term guidance but lack industry commitment	Y	?	Y	Y	Y	Y
	Powerful, unified industry associations oppose regulations that drive cost	Y	Y	Y	Y	Y	Y
Markets	high-volume markets for low-end basic materials	Y	Y	Y	Y	Y	Y
	Small market segments for specialized materials	Y	Y	Y	?	?	?
	markets are global	Y	Y	Y	?	?	Y
	strongly price-oriented competition	Y	Y	Y	Y	Y	Y
	small and cyclical profit margins on bulk materials due to price competition	Y	Y	Y	Y	Y	Y
	some material replacement competition	Y	Y	?	Y	?	?