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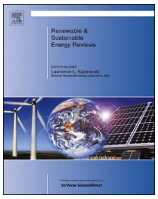

The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research

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ABSTRACT

Energy-intensive processing industries (EPIs) produce iron and steel, aluminum, chemicals, cement, glass, and paper and pulp and are responsible for a large share of global greenhouse gas emissions. To meet 2050 emission targets, an accelerated transition towards deep decarbonization is required in these industries. Insights from sociotechnical and innovation systems perspectives are needed to better understand how to steer and facilitate this transition process. The transitions literature has so far, however, not featured EPIs. This paper positions EPIs within the transitions literature by characterizing their sociotechnical and innovation systems in terms of industry structure, innovation strategies, networks, markets and governmental interventions. We subsequently explore how these characteristics may influence the transition to deep decarbonization and identify gaps in the literature from which we formulate an agenda for further transitions research on EPIs and consider policy implications. Furthering this research field would not only enrich discussions on policy for achieving deep decarbonization, but would also develop transitions theory since the distinctive EPI characteristics are likely to yield new patterns in transition dynamics.

1. 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, silicon dioxide and biomass into iron and steel, aluminum, chemicals, cement, glass and paper. These are essential material building blocks on which our society relies [1]. Globally, industry is responsible for over 30% of all greenhouse gas (GHG) emissions, of which the majority is emitted by EPIs [2]. Over the past decades, these industries have made significant resource and energy efficiency improvements [2,3]. However, meeting the EU 2050 emission reduction target of 80–95% compared to 1990 requires further, extensive low carbon innovation that is often of a radical nature [4,5]. The “well below 2C” target, recently adopted in Paris requires EPIs to decrease emissions to zero before 2070 [6,7]. Such deep decarbonization involves not only changes in technology through low carbon innovation, but requires a broader sociotechnical transition that also entails changes in user behavior, culture, policy, industry strategies, infrastructure and science [8–10]. However, this (deep) decarbonization transition at present proceeds at a very slow pace [11]. To facilitate and steer this transition process, more insight into the socio-technical drivers and barriers that affect the transition process is needed [5,12–15].

Studies employing sociotechnical and innovation systems (ST & I systems) perspectives have provided valuable insight into the socio-technical drivers and barriers to the development and diffusion of new, low carbon technologies and practices, and in understanding the lock-in of existing regimes around established, carbon-intensive technologies. These insights have shaped public policy to more effectively facilitate and steer sustainability transitions [16–19]. Empirical analyzes of sustainability transitions have so far, however, focused on the energy, buildings and transport sectors and have insufficiently studied sectors like EPIs, where such insights could help stimulate the decarbonization transition. This study aims to position EPIs within the transitions literature to develop such insights.

There is also a theoretical contribution to studying EPIs from an ST & I systems perspective. The few transition studies that focused on

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EPIs, including the tile [20], paper and pulp [21,22], steel [23] and cement and concrete industries [24,25], show that many barriers to low carbon innovation result from distinctive EPI characteristics. The lack of demand for cleaner basic materials, for example, may be related to EPIs being far removed from the end-consumer, while regulatory pressure is affected by the fear of disadvantaging domestic industries in a highly globalized and price competitive commodity market. These distinctive ST & I systems characteristics provide opportunities for theoretical enrichment of the transitions literature, for example by identifying new transition dynamics or lock-in mechanisms [25].

By positioning EPIs within the transitions literature and by providing a research agenda, this paper broadens the empirical application of the literature's theoretical concepts and enables future work to develop these concepts and to formulate more effective policy recommendations on facilitating and steering the transition in EPIs towards deep decarbonization.

This paper is structured as follows. Section 2 discusses the theoretical framework and methods. Section 3 first systematically describes the characteristics of ST & I systems in EPIs with stylized facts. Subsequently, Section 4 reviews, based on the limited data available, how these stylized facts may affect decarbonization transitions in EPIs and specifies an agenda that identifies fruitful venues for further transitions research on decarbonization of EPIs. We refer to a decarbonization transition instead of a sustainability transition, because we are primarily interested in climate related sustainability. The paper is concluded by reflecting on the emerging field of decarbonization transitions in EPIs and by providing policy implications based on existing knowledge.

2. Approach

2.1. 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 and transitioning of ST & I systems. The goal of these systems is to develop and diffuse innovations and goods to meet current and future societal demands. They are comprised of structural components that include 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 system components. The systems can be delineated to the societal functions they fulfil (i.e. a socio-technical system) or to specific technologies, sectors, regions or nations (i.e. different types of innovation systems).

ST & I systems develop or transform through the co-evolution of system components as innovation cannot take place in a vacuum [26]. Exogenous factors like climate change may trigger new societal demands, such as environmental sustainability, that drive the existing ST & I system to change in ways that accommodate the new societal demand. Depending on the force of the exogenous factor and the stability of the ST & I system, this systems change involves a transition along existing technological trajectories (such as the development of energy efficiency improvements) or the transition to a new system configuration that revolves around new (low carbon) technologies [27]. Some system components or misalignment between components may (purposefully or not) inhibit the development and diffusion of new technologies or frustrate the transition process (so-called system problems, failures or bottlenecks). Policy makers aiming to facilitate or steer system growth and transition, should focus on overcoming these system problems [28,29].

To understand technological change in EPIs, this paper distinguishes between incremental innovations that follow existing technological trajectories, and radical innovations that constitute new technologies. Utterback [30, 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 conversion process or for changes in feedstocks.

To understand the dynamics of the decarbonization transition in EPIs, this paper also distinguishes between innovations that range from marginal to significant (described as low carbon innovation) GHG emission reductions. These innovations may reduce emissions purposefully or not (sometimes emissions reductions are only a co-benefit, for example of energy efficiency and recycling), as well as directly (e.g., emission capture) or indirectly (e.g., lower electricity demand).

We use the structural components of ST & I systems and the aforementioned innovation typology to structure our discussion of the factors that influence the innovation processes in EPIs (in Section 3) and of how this may affect the transition to deep decarbonization (in Section 4).

2.2. Research design

To position EPIs within the transition literature, this paper first characterizes the ST & I system of EPIs with stylized facts. Stylized facts are broadly generalized and simplified representations of empirical findings. To come to these stylized facts, we have gone through a series of research activities aimed at co-developing and inventorying knowledge between the six authors, which include experts in the field of innovation and transition studies and experts in the field of EPIs. These research activities are listed in Table A.1 in the Appendix and include explorative discussions, two questionnaires and three workshops intermitted by consecutive rounds of coordinated writing and triangulation with documented sources. Such triangulation was however not always possible due to limited and often technology or sector-specific documentation. The years of research, including interviews and working with EPIs, by the EPI experts provides a basis for understanding the key characteristics of these industries and their innovation dynamics that extends beyond what can be found based on documented data and scientific literature. For the purpose of identifying EPI-overarching stylized facts, this research approach is deemed more suitable than relying on the limited existing documentation alone.

After characterizing the ST & I systems of EPIs with stylized facts, we review the literature and documentation on EPIs to infer how these stylized facts may influence decarbonization transitions. The literature gaps identified in this process are formulated into a research agenda that aims to inform and stimulate future transition studies on EPIs.

Our subsequent discussion of the EPI characteristics and implications for decarbonization transition is structured by the ST & I system components identified as the most important; they include industry structure, corporate innovation strategies (which are influenced by and reinforce the industry structure), networks, basic material markets and government policy.

3. Characterizing the ST & I systems of EPIs: stylized facts

Fig. 1 provides an overview and describes with stylized facts, the most important actors, networks and institutions that characterize ST & I systems of 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 the stylized facts that capture these characteristics, followed by a reflection on their differences between EPIs (in Section 3.6).

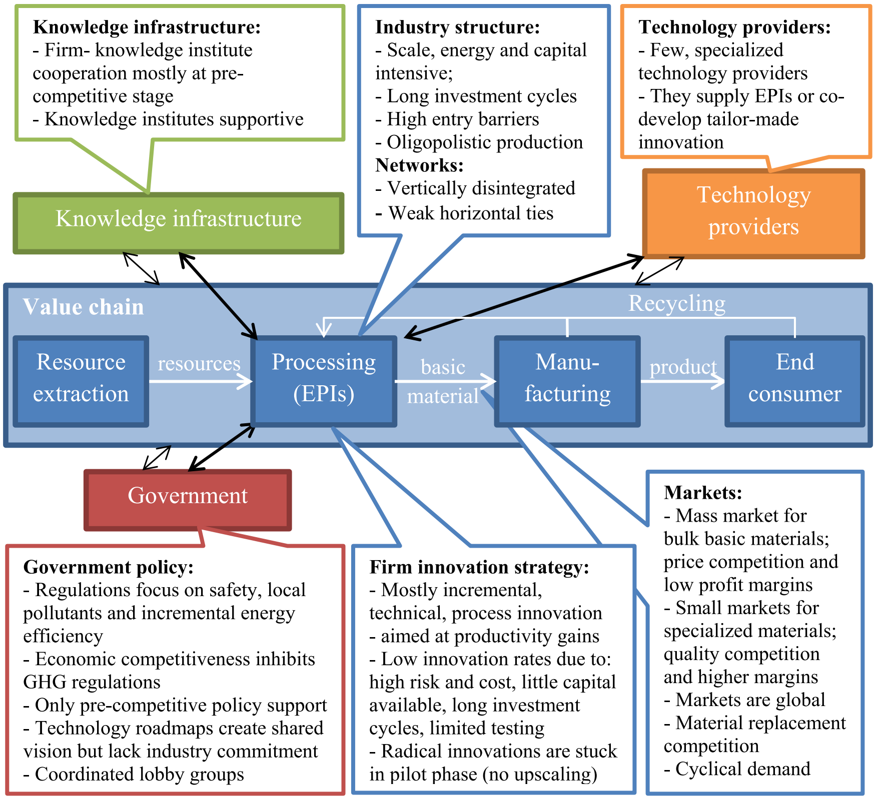

Fig. 1. Overview of the different structural components of EPIs and their characteristics (see also Table A.2 in the Appendix).

3.1. 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. Such processes involve high fixed costs and have potential for significant energy efficiency and organizational economies of scale, which results in large scale processing plants that require high upfront costs [31]. These plants are complicated to run as they are highly automated, often produce several different qualities of products and are interlinked to other industries. The high fixed costs need to be earned back in cyclical markets with large variations in prices and profit margins [32], resulting in uncertainty and long payback times and investment cycles. High capacity utilization is important in order to recover the cost, meaning that plants may keep operating at an overall loss as long as prices are higher than variable production costs. Plants may also be very profitable during periods of high demand and high prices.

Investment cycles for major reinvestments can typically range between 20 and 40 years, but actual lifetimes may vary widely in practice [33]. Plants are more regularly refurbished to increase productivity and improve energy efficiency. These cycles vary for different technologies, from 4 to 6 years for chemical facilities to 10–15 years for glass tanks [34] and blast furnaces [35].

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). For example, expansion of production capacity in US mini-mill steel plants has been larger in existing plants than in new greenfield sites [33], 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 large multinationals that own plants around the world and may have a dominant market position. 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 [36].

3.2. Innovation strategies

Innovation strategies in EPIs are strongly shaped by industry structure. Innovations are predominantly of a technological nature, with traditional organizational structures and business cases. Product innovation is only possible through downstream product differentiation in specialized market segments (see Section 3.5.2) but lacks in the bulk segments for standardized basic materials. Instead, EPIs rely mostly on process innovation that tends 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. Also, many of the process innovations used by EPI-firms are outsourced to, or co-developed with, technology providers.

With the exception of chemicals, R & D investments in EPIs are low [37], resulting in low rates of innovation that can be explained by several interlinked factors listed in Table 1. Many radical innovations are perceived as very risky, costly, hard to integrate, unable to compete with the economies of scale 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 [38]. Radical innovations have however developed historically, driven by enhanced productivity [39,40], better feedstock [41] or demand-pull supported by regulation [42,43]; 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). For example, smelt reduction processes in ironmaking (available to date) renders coking and sintering obsolete and has a

Table 1
Overview of barriers to innovation in EPIs.

Barriers to innovation in EPIs:

- Long investment cycles provide few windows of opportunity for changing technology [33]
- The low, cyclical profit margins in EPIs reduce the availability of investment capital and increase the return on investment times [32]
- The high costs and potential loss of market share due to failures in the production process increase the risk perception of innovation
- Little opportunity for testing and upscaling of innovations
- The incremental improvements to core process technologies over the past decades, often century, disadvantage radical innovations, leading to lock-in [44]
- The focus on refurbishing existing large-scale plants (*so*-called brown field investment), particularly in industrialized countries, inhibits more radical innovation

lower production capacity than currently found in most blast furnace-operated integrated iron and steel plants.

3.3. Networks

Instead of in-house development, EPI companies often outsource to, 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 [37], are low in demand and have long 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 successful innovation [39].

Firms engage in research collaborations with competitors, technology providers and knowledge institutes to pool ideas, knowledge and resources because single firms typically cannot carry the R & D costs and risks of radical innovations alone. Such collaborations may be supported by public funds and typically take place at the national and supranational scale (i.e. North-America, Europe or Asia). ULSAB is an example that was instigated to collaboratively develop high strength steel for automotive applications to compete with aluminum and plastics [45]. Although these collaborative projects are effective for developing innovation at the pre-competitive stage, (inter)national competition regulations and IPR struggles impose restrictions when commercialization nears. The role of knowledge institutes tends to be limited at this stage as well.

Supply chains in EPIs are organized in various ways, with strongly varying degrees of vertical integration among different EPIs and EPI companies. Customer-supplier ties (both provider-EPI as well as EPI-manufacturer ties) are stronger and fewer in markets for specialized natural resources and basic materials (e.g. special ores or high-quality steels) than in the bulk markets for commodities. Due to low profit margins and high costs of (transporting) raw materials, EPI location has historically been driven by resource availability (e.g. forests, coal, iron ore, limestone) or closeness to markets (e.g., for construction materials). Location drivers have however changed due to improved access via international shipping of (high quality) feedstock and materials.

3.4. Government policy

Under pressure of local stakeholder groups, 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. To safeguard economic competitiveness, the regulations for GHG emission control are however often lenient. In many countries, EPIs also pay lower energy taxes, compared to other energy users. Due to their economic importance and the perceived lack of urgency for more radical innovation, policies targeting EPIs tend to focus on incremental innovation. This also holds true for the Best Available Techniques (BAT Reference documents) established under the IPPC and the IED Directives, despite their aim at “ambitious consumption and emission levels” [46]. In some cases regulation has been able to stimulate more substantial innovation, such as the local air pollutant regulation for the glass industry that successfully stimulated oxy-fuel gas furnaces [47]. Finally, voluntary or negotiated agreements are used, but are criticized for being ineffective, as industry typically agrees to little more than what would be achieved under business as usual conditions [48].

EPIs have well-coordinated, powerful lobbying groups that tend to take the position of their most conservative member and oppose regulations that they perceive as threatening their (current) competitiveness [25]. These lobbying groups comprise industry associations that have close ties with policymakers in important industrial regions. Due to the employment and other economic benefits EPIs provide in these regions, their political influence at local/regional levels is often strong.

Public funding is important for early stage radical innovation, but not necessary for innovations that generate significant productivity benefits, as evidenced by the development path of the shoe press in papermaking and thin strip casting in steelmaking [49]. Long-term policies for radical innovations to meet societal challenges often take form at the national and European level. They include the aforementioned public-private research collaborations as well as technology roadmaps, i.e. shared visions on the directions of future industry developments, which have been used in the US since the 1990s [50] and are increasingly coordinated at the European level [51]. Such initiatives could be a first step towards overcoming the uncertainty and riskiness of radical innovations in EPIs.

3.5. Markets

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

3.5.1. Markets for basic materials

The mass markets for bulk basic materials (i.e. commodities) 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 cements, glass-wool and some forms of paper and pulp (where long-range land transport is costly), markets for bulk materials have a global scope. In these global markets, 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 [52].

The markets for bulk materials are often characterized by strong price volatility. Prices and profit margins swing with international supply-demand imbalances. This creates cyclical profit margins [32]. Because of the high fixed costs of operation and inflexible production technologies, EPIs are unable to fully exploit these cyclical profits.

3.5.2. Markets for specialized materials

Although there are little opportunities for product differentiation on 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, timing and 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.

Table 2
Overview of low carbon innovations per sector necessary to meet the 2050 GHG emission target, their TRL and drivers and bottlenecks to implementation.[1],[2]

Sector:	Technology	Type of innovation: Incremental or Radical and technical description		TRL	Benefits of the innovation:	Bottlenecks to diffusion of the innovation:
All EPIs	Energy efficiency	I/R	Reduce energy consumption through best available technologies in steam, motor, heat pump and combined-heat and power systems[a]	All	Less energy and CO_2 (+)	Costs, lack of awareness and expertise
	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; includes cross-sectoral symbiosis products	All	Resource efficiency less CO_2 (++/+++)	Low resource vs. high labor costs, requires organizational and technical innovation, lower quality materials
	CCS	I/R	Typical end of the pipe technology, can be incremental, but typically needs significant additional space and technology for integration in process design, 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
Iron and 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
	Direct reduction with H2	RR	Makes obsolete coke ovens, BF & BOF of conventional steel factories, but is combined with electric arc furnace; needs H2 supply infrastructure	3–4	Less CO_2 (+++, potentially excess electricity converted to H2)	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	2–3	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	Avoids oxidation and consumption of anodes and the CO_2 emissions resulting from this	3–4	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
	Electro-plastics (with RES-Methane; with Fischer Tropsch)	I; R	Needs conversion to bio or electricity based feedstocks (and respective supply infrastructures); 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 applications, unclear if electric melting technology can be up-scaled 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
Cement	Geopolymers	RR	Requires a new way of making cements with different input materials and different material characteristics and costs	3–4	Less CO_2, lower (++)	Requires new resource streams; unproven long term performance; stringent norm compliance
Paper & Pulp[b] and Bio-refineries	Separation and drying technologies	I/R	New separation and drying technologies are key to reduce the energy intensity, allowing for carbon neutral operation in the future	All	Less energy and CO_2 (++), lower capital and operating expenditures	Investments in new paper machines limited by market dynamics, small number of technology providers, upscaling costs
Cross-sectoral	Biorefinery development	RRR	Biorefineries could potentially replace existing petro-refineries by providing a range of bio-based chemicals and feedstock for the paper and pulp industry	4–6	Less CO_2 (+++)	Feedstock availability and cost (competition for biomass)

[a] See Napp et al. [59] for an overview of technologies and their energy reducing potential.
[b] Through better energy efficiency and utilization of by-products, this industry can potentially be carbon neutral and with the use of CCS even CO_2 negative [71].

These markets enable the leveraging of superior expertise and partial compensation 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 a Swedish producer 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 co-location with important specialized buyers. Finally, material replacement competition is particularly strong in these specialized segments; high-end steels, aluminum and plastics, for example, compete for car applications [53]. Hence, ST&I system characteristics for specialized markets differ somewhat from those for mass markets.

3.6. *Sector specific deviations from the EPI characterization*

The above description of EPI characteristics does not apply for every sector to the same extent. Table A.2 in the Appendix provides an overview of the stylized facts and to what extent the EPI experts perceived them as applicable to each EPI sector, distinguishing between yes (Y, indicated 125 times), no (N, 2 times) and partially (P, 23 times) when the fact applied only under certain conditions. The table shows that almost all stylized facts are, at least partially, perceived

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[1] In Table 2 "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) CO_2: (+) refers to up to 33% reduction vs. reference technology; (++) 33–66% reduction; (+++) more than 66% reduction.

[2] In Table 2 the following technical abbreviations are used: BF = blast furnace; BOF = basic oxygen furnace; CAPEX = capital expenditure; CCS = carbon capture and storage; CO_2 = carbon dioxide; RES = renewable energy sources/supply; R&D = research and development; ULCOS = ultra low carbon steelmaking project

as applicable to all sectors. Only the cement industry is not characterized by small market segments for specialized materials and is not characterized by material replacement competition.

4. Decarbonization of EPIs

While there is potential to reduce energy intensity and GHG emissions with commercially available processing and recycling technologies and practices (see rows 1 and 2, Table 2), meeting long term emission targets requires a transition to low carbon process innovations. These innovations enable the replacement of fossil fuels with electricity, hydrogen or biomass (e.g., electric glass melting, hydrogen direct reduction 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. There is a growing literature where such technical options are assessed, see e.g. [54–61]. Building on a review of this literature, Table 2 lists such key 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), ranging from basic R & D to commercial diffusion (see [62]); and their technology-specific benefits and bottlenecks to diffusion.

The remainder of this Section places the previously identified stylized facts on EPIs in the context of the transition to deep decarbonization by exploring how they affect the development and diffusion of the low carbon innovations listed in Table 2. This section furthermore identifies literature gaps that are formulated into an agenda for advancing transitions research on EPIs.

4.1. 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 GHG emission reduction targets [33]. The scale, energy and capital intensity of EPIs and their sometimes oligopolistic production form significant barriers to entry both for new EPI firms [24] and for new providers of their technology. Such barriers may inhibit transition since new entrants have been identified as important drivers to sustainability transitions in other sectors, like automotive [63] and energy [64].

Some radical innovations that enable processing at a lower temperature and smaller scale may reduce these entry barriers. For example, the use of thin slab casting in combination with scrap-based mini mills, allowed the US firm Nucor to develop from a marginal steel producer to the largest steel company in the U.S. today [65]. The dependency on brown field investments in industrialized countries may limit the introduction of low carbon innovations that require radical technical changes in the existing infrastructure (see Table 2). This dependency on brownfield investments tends to be lower in other sectors. Related to industry structure, research agenda topics include:

- Analyze how concentrated (multinational) ownership affects low carbon innovation
- Systematically analyze the ability of new firms to enter EPIs with low carbon innovations
- Analyze opportunities for step-wise upscaling of low carbon innovations, e.g. through niche accumulation [66]
- Systematically analyze opportunities to exploit scale-reducing effects of radical innovations
- Analyze where opportunities lie for retrofitting existing plants with low carbon innovations

4.2. Low carbon innovation strategies

In addition to the barriers to innovation listed in Table 1, EPI firms have had little motivation to seriously reduce GHG emission through low carbon innovation, given the lack of demand and limited policy support for these innovations [49,67]. Low carbon innovation tends to only be successful when providing economic co-benefits, like energy or material efficiency gains [49]. Emission reduction is in those cases often a side-effect. In cases like some low carbon cements, product properties might even decrease. Furthermore, end-of-pipe technologies like CCS also require changes in the core processes of most EPIs, which raise variable and investment costs but yield no co-benefits [68]. Fuel-replacing low carbon innovations, in turn, are for their profitability dependent on how alternative fuel and electricity prices develop in relation to fossil fuel prices. These and the factors we discuss in Sections 4.3–4.5 partly explain why the low carbon technologies in Table 2 are not breaking through commercially.

Where EPI firms perceive sustainability not as competitively advantageous, firms in business-to-consumer sectors like automotive, food, and energy perceive sustainability as an important means of competitive product differentiation and of boosting brand name perception (see e.g. [69,70]). The lack of sustainability as a means of differentiation is thus a unique barrier to decarbonization transition in EPIs, at least so far.

To reduce GHG emissions, EPIs currently focus mostly on incremental process innovations, exploiting co-benefits with specialized materials where possible, recycling and, to a lesser extent, changing feedstock and fuels[3] [67]. 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 incremental low carbon innovation. In Europe, this has improved with the monitoring, reporting and verification requirements of the EU ETS [67].

Relevant research agenda topics related to low carbon innovation strategies include:

- Systematically analyze rates and types of low carbon innovation and related R & D; are firms becoming increasingly dependent on publically funded R & D?
- Analyze why some firms even lack well-functioning energy management systems needed to engage in incremental emission-reducing process innovations
- Analyze ways of reducing risk for low carbon innovation (such as public procurement and long term policies)
- Systematically analyze co-benefits of low carbon innovation
- Analyze solutions to enhance investment opportunities for low carbon innovation

4.3. How networks affect deep decarbonization

Little research has been done on the effect of the varying levels of value chain integration on low carbon innovation, the role of technology providers in deep carbonization, or 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 emission reduction targets, policy makers have initiated public-private research collaborations with firms and knowledge institutes from different sectors. These collaborations aim to develop shared future visions on how to competitively decarbonize EPIs and pool financing and expertise to facilitate the development of low carbon innovation. Such collaborations are particularly important when the low carbon innovations are costly and bring little co-benefits. The Sustainable Process Industry through Resource and energy Efficiency (SPIRE) roadmap for example was established to make European process industries “more competitive and sustainable” [23, p. 4]. Such formal

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[3] This is particularly the case in the concrete [81] and paper and pulp industries [91].

collaborations can be found at different governmental levels across the world; collaborations for clean and competitive steel for example, include the European ULCOS, the Japanese Course50 and the US AISI technology roadmap program [72]. Despite being often restricted to pre-commercialization, such PPPs are generally identified as important governance tools to stimulate and guide sustainability transitions [73,74].

Fruitful research agenda topics include:

- Analyze how the co-dependence of EPIs and technology providers affects low carbon innovation
- Study how network ties and value chain integration affect low carbon innovation
- Analyze how the dependency on the fossil fuel energy system affects deep decarbonization in EPIs
- Analyze the role of knowledge institutes and intermediary organization in low carbon innovation
- Analyze the role of PPP and industry collaboration in technology development and potentially diffusion
- Analyze the factors that contribute to the success of PPPs for (low carbon) technology development

4.4. How government policy affects deep decarbonization

Economic competitiveness is the main barrier to implementing and enforcing GHG emission control regulations in EPIs. These industries are for example largely shielded from the direct cost of the European Emission Trading Scheme (EU ETS) [51], resulting in lower emission reductions than other targeted sectors [67,75]. Furthermore, EPIs typically pay lower energy taxes, compared to other energy users; German EPIs even profited from the Energiewende through lower energy prices [76]. The regulations that are in place focus on incremental innovations that also have economic benefits, examples are energy efficiency improvements, fuel shifts and minor process improvements. In the Netherlands, for example, plants have to legally adopt all energy efficient measures with a payback period of less than five years, but this is not sufficiently enforced [77]. 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.

So although government supports deep decarbonization throughout the R & D and pilot stage, support for upscaling through a stronger demand-pull and effective regulations are lacking [38]. Such support and regulations are also underdeveloped in some other sectors, like agriculture [78], but seem to be applied more in the automotive and energy sectors, where they form important drivers to sustainability transition [64,79,80].

The industry associations typically oppose GHG emission regulations because they perceive them as cost drivers that affect their global competitiveness and consequently employment [67]. They argue that regulatory burdens will increase compliance costs and cause a significant competitive disadvantage which, in a highly globalized market, would force affected companies to move their production to other, less regulated countries, where they might emit the same or more than they did originally (i.e. the “carbon leakage” argument). This argument has been influential in relaxing the EU ETS for the concrete [81], steel [82] and pulp and paper industries [83]. In practice, the argument may only hold for some markets for specific global, price-competitive materials, and not for complete sectors. Lobbyists also argue that the extra emissions of specialized basic materials are off-set during their use (e.g. lighter and more durable steels; EPS for building insulation) and that compliance with other environmental regulations, such as pollution and dust prevention, requires more energy and therefore increases GHG emissions. Finally, Wesseling and Van der Vooren [25] suggest that industry interests use roadmaps in the cement industry to create conservative visions on low carbon innovation that are unable to meet 2050 GHG emission targets.

Fruitful research agenda topics include:

- Analyze to what extend GHG emission regulations really inhibit competitiveness
- Analyze the opportunities to design policies that can reduce GHG emissions while safeguarding industry competitiveness:if allowed under EU legislation, mandating the sales of clean materials could protect the European market from developing countries’ low-cost, polluting materials
  1. Policy support for low carbon innovation may benefit industry, as Mazzucato [84] showed for Danish wind turbines
  2. Analyzing consumer-oriented policies that put the burden of GHG emissions on the consumers instead of upstream sources
- Explore new types of policy instruments to support low carbon innovation, including:
  1. more effective public procurement in infrastructural projects
  2. integrated push and pull mechanisms, e.g. fee-bates (i.e. bonus-malus) to support the uptake of clean materials while pricing the externalities
  3. the commercialization of innovation from collaborative EU projects
  4. (mitigated carbon price volatility created by) the current EU ETS
- Analyze to what extend expectations in industry roadmaps conflict with scientific literature
- Analyze how to negate lobby groups’ opposition to GHG emission regulations

4.5. 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. However, customers of EPIs are 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 often very small[4] [85,86]. One reason is in transparency, since so far, consumer products typically do not show the carbon footprint of the materials they use. An analysis of the concrete industry shows that there is no willingness to pay this price (and risk) premium; not even by public agencies, which are the most important buyers of concrete [25]. 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 the decarbonization transition. Public visibility of clean products stimulates demand and public pressure for these products and is found to facilitate 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 [87,88]. Research agenda topics include:

- Systematically analyze future market opportunities for low carbon innovations:
  1. In markets for bulk and specialized materials
  2. What drives large consumers of basic materials (like IKEA, LEGO or H & M) to start using more sustainable basic materials
  3. Ways of enhancing transparency in the carbon footprint of basic materials in consumer products

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

- Cross-sectoral analysis of how globalization affects the diffusion of low carbon innovations
- Analyze effects of material-replacement competition on sustainability

4.6. ST & I system research topics

We also identify research topics that cover the whole ST & I system. First, although many technology assessment studies have focused on the emergence of low carbon technologies (e.g. those listed in Table 2), socio-technical analyses are limited. To get a richer understanding of the socio-technical drivers and barriers to the development and diffusion of such emerging technologies, they could also be studied more from technology-specific ST & I systems perspectives like the Technological Innovation Systems perspective as is done e.g. by [24].

Second, it would be interesting to analyze the transitions of mature EPI system configurations to deep decarbonization in their entirety. This can be done from a multi-level perspective (e.g. Karltorp and Sandén [21] for the pulp and paper industry) or from an innovation systems perspective (e.g. Wesseling and Van der Vooren [25] for the concrete industry). To understand the slow decarbonization transition, it would be fruitful to assess if and how interdependent systemic problems form closed feedback loops that constitute systemic lock-in; see e.g. [25].

Once more case studies on the transition of EPIs are available, comparative studies could identify similarities and differences in transition processes and lock-in patterns across EPIs, adding to existing transition pathway typologies [27,89]. Building on the sectoral taxonomies of technical change by for example Pavitt [90], such comparisons could also start by systematically analyzing how the role of certain ST & I system components in transition differ across sectors. This may lead to a better understanding of how transitions may be governed and unfold differently across sectors.

5. 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 sectors. These stylized facts are likely to affect the deep decarbonization transition in EPIs differently from sustainability transitions in conventionally studied sectors. However, how they precisely influence deep decarbonization remains unclear due to the limited literature on this topic. The transitions literature on EPIs should be further developed to better understand how deep decarbonization can be facilitated and steered in order to meet the 2050 GHG emission targets. For this purpose, the paper has specified a series of fruitful research topics, which are summarized by fourteen research questions in Table 3.

A more developed understanding of decarbonization transitions in EPIs may enrich ST & I systems perspectives. It may do so empirically by broadening the empirical scope of the field. It may also do so theoretically, by identifying distinctive transition dynamics and constellations of systemic lock-in. The transitions field would benefit from a systematic comparison of transition processes across a wider range of sectors.

5.1. General policy recommendations

The identified EPI structures, innovation strategies, networks, government policies and markets have implications for policy recommendations aiming to facilitate the decarbonization transition. Based on the assessment of stylized facts and drawing on insights from ST & I systems studies in other sectors this paper provides, without suggesting to be exhaustive, policy recommendations that should be complemented and refined as the field develops.

The identified lack of demand for clean basic materials necessitates stronger **market-pull policy** that supports low carbon innovation to move beyond the demonstration stage. This has proved effective in renewable electricity, biofuels and electric vehicles. In public sectors like infrastructure, public procurement should reward low carbon innovation. Other demand-side policy measures include subsidizing renewable energy for EPIs to facilitate fuel switching (e.g. German policy); 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. Government should reverse its recent trend in becoming more risk averse in its support for innovation and should accept the risk that is inherent to the more radical forms and early stages of low carbon innovation.

To overcome directionality failures and enable long term direction of technology development, stakeholder-oriented, **low-carbon scenario, vision and pathway processes** are important tools to coordinate, direct, legitimize and learn about transitions [28]. Critical aspects such as technology selection, co-evolution with decarbonized energy systems, conflicting goals and interests, and policy options can

Table 3
Research agenda to further transitions research on EPIs.

Focus:	Research questions:
Industry structure	1. EPIs are characterized by high levels of industrial concentration and firm ownership. How do these factors affect the transition to deep decarbonization?
	2. EPIs have high entry barriers. How does this affect the decarbonization transition and where lie opportunities for new firm entry?
	3. Business cases in EPIs revolve around exploiting high scale-intensities and long investment cycles, which impairs upscaling of innovation from the pilot phase. How can these bottlenecks be overcome to facilitate deep decarbonization?
Innovation strategies	4. Low carbon innovations without co-benefits are perceived as generating no competitive advantage. How can business cases be created for these innovations?
	5. The long-term profitability of low carbon innovations is strongly reliant on external factors. What measures and mechanisms can be identified to reduce these uncertainties?
	6. EPI firms differ significantly in their low carbon innovation strategies. How can these differences be explained?
Networks	7. EPI firms depend strongly on their technology providers for innovation. How does this affect deep decarbonization?
Government policy	8. EPIs lack GHG emission control policies because they are believed to hamper international competitiveness and due to opposition from industrial lobby groups. What (mixes of) policy measures can be designed to effectively manage and stimulate industry efforts for deep decarbonization, while at the same time safeguarding their competitiveness?
	9. How can this policy design be shielded from overly conservative industrial lobbying pressures (including biased roadmaps)?
Markets	10. EPI markets are segmented in demand for bulk and for specialized materials. How does this segmentation affect deep decarbonization?
	11. Some business end-users in the value chains of EPIs have started to demand low carbon basic materials. How does this affect low carbon innovation in EPIs and how can this trend be supported?
	12. EPIs can be far removed from the end-consumer. Can the demand from these consumers for low carbon basic materials be enhanced through greater transparency and labelling mechanisms?
Whole system	13. What drivers and bottlenecks affect the development and diffusion of emerging low carbon technologies?
	14. What systemic problems and patterns of lock-in inhibit the transition of existing ST & I-systems towards deep decarbonization in EPIs?

be explored and assessed through such processes. Such processes can however be dominated by industry associations, which may use them to secure vested interests [25]. This powerful transition tool therefore needs to be employed more in cooperation with other stakeholders.

To overcome the problem of carbon leakage (resulting from the price-competitive, global markets for bulk basic materials) and of the lack of investment capital, a **globally coordinated policy approach** would be important, that would enable common innovation efforts along with an acceptable differentiation of climate ambitions and an acceptable level of domestic EPI protection between countries [6]. For example, reorienting trade policy towards meeting societal goals, like reducing GHG emissions while at the same fostering industrial development would help overcome the carbon leakage argument.

Finally, the **governance** challenges are particularly great in EPIs compared to other sectors, due to high mitigation costs, capital intensity, investment cycles, global competitiveness and the lack of co-benefits or competitive edge to clean materials. Risks and costs must be shared between industry and governments without overcompensating industry or distorting markets in unintentional ways. 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 shape innovation, state-aid, trade and goal or challenge-oriented policies for deep decarbonization.

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Appendix

See Tables A.1 and A.2 here.

Table A.1
overview of research activities in chronological order.

Activity:	Description:
Discussions	Explorative individual discussions on innovation in EPIs between innovation studies scholars (dr. Joeri Wesseling and prof. Lars Coenen) and EPI scholars (prof. Ernst Worrell, prof. Lars Nilsson, dr. Max Åhman and prof. Stefan Lechtenböhmer)
Questionnaire 1	Innovation scholars developed questionnaire 1 (79 questions on stylized facts) based on the former discussions, complemented with factors deemed relevant from an ST & I systems perspective Questionnaire 1 was filled out by EPI scholars
Workshop 1	1) develop a shared understanding based on the outcomes of the questionnaire and 2) discuss the most important characteristics of EPIs to structure the ST & I systems analysis of this paper
Structuring findings	Innovation scholars integrate the results in a draft document, identifying knowledge gaps EPI scholars attempt to fill in these gaps; they edit and comment on the same document and each other's input
Workshop 2	Clarifications, critical discussions on the new inputs, addressing the remaining knowledge gaps and formulating venues for further research
Structuring and triangulating findings	Innovation scholars update the draft document, identifying final knowledge gaps and triangulating the findings using a literature review EPI scholars again all fill in these gaps, edit and comment on the same document and each other's input, complement the literature review
Questionnaire 2	Innovation scholars draft questionnaire 2 that forms the basis of Table A.2 (27*6 questions) EPI scholars fill-out the questionnaire
Workshop 3	Clarifications, critical discussions on the new inputs and questionnaire 2, addressing the remaining knowledge gaps and formulating a research agenda
Triangulating findings	Innovation and EPI scholars update the draft document, triangulating the findings using a literature review and finalizing the paper and research agenda

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	Y	Y	Y	Y	Y	Y
	new technologies need to fit in existing factories	Y	Y	P	Y	P	Y
	oligopolistic production	P	P	Y	P	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	Y
	long investment cycles provide little opportunity for innovation	Y	Y	P	Y	Y	P
Networks	Innovations are developed in cooperation with, or outsourced to, technology	Y	Y	P	Y	Y	Y

(continued on next page)

Table A.2, *(continued)*

	Description of characteristics of the EPI's core processes:	Steel	Aluminum	Chemicals	Cement	Glass	Paper & Pulp
	providers						
	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	P	P	Y	P	Y
	disintegrated supply chain / weak vertical network ties (bulk materials freely available on market)	Y	Y	Y	P	Y	Y
Government intervention	regulations focus on local pollutants and safety but are lax on GHG emissions	Y	P	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	P	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	Y
	Powerful, unified industry associations oppose regulations that drive cost	Y	Y	Y	P	Y	P
Markets	markets are global	Y	Y	Y	P	P	P
	high-volume markets for low-end basic bulk materials (commodities)	Y	Y	Y	Y	P	Y
	small and cyclical profit margins on these bulk materials due to price-oriented competition	Y	Y	Y	Y	Y	Y
	Small market segments for specialized materials	Y	Y	Y	N	P	Y
	some material replacement competition in specialized markets	Y	Y	P	N	P	Y

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