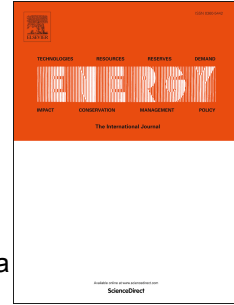


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Technology Innovation System analysis of decarbonisation options in the EU steel industry

Tadeusz Skoczkowski, Elena Verdolini, Sławomir Bielecki, Max Kochański, Katarzyna Korczak, Arkadiusz Węglarz



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## **CRedit author statement**

# **Technology Innovation System analysis of decarbonisation options in the EU steel industry**

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# Technology Innovation System analysis of decarbonisation options in the EU steel industry

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## Abstract

Decarbonisation of the iron and steel (I&S) industry is crucial in the efforts to meet the EU GHG emission reduction objectives in 2030...2050. Promoting decarbonisation in this sector will necessarily require the identification, development, and diffusion of breakthrough technologies for I&S production.

This paper uses an approach inspired by the Technology Innovation System (TIS) to analyse the development of technology in the EU I&S industry and identify potential avenues of its decarbonisation. We have described key elements of the TIS, analyse the functioning of these elements and their interactions in a more general context of innovation dynamics and policy design; The focus has been put on the role of actors and the identification of the main specific blocking and inducement mechanism in the TIS to better explain its functioning. Risks and uncertainties have also been discussed.

We argue that deep decarbonisation in the I&S industry is feasible but its TIS requires firm support, mostly political, to finance intensive R&D and reduce the business risk. To this end, all actors shall support more effectively the invention and implementation of new radical production technologies. The recommendations are mostly addressed to politicians although stressing the importance of collaboration of all actors.

**Keywords:** Technology innovative system, decarbonisation of industry, iron and steel industry, low-carbon technologies

## Highlights:

- Problems, boundaries and difficulties in the I&S industry decarbonization.
- TIS structural components, links and interactions of I&S industry decarbonisation.
- Mapping of functional patterns and evaluation of TIS functionality in I&S industry.
- Blockades, incentives and innovation risks in the I&S industry decarbonisation.
- TIS analysis as a tool for granting public funds for I&S projects.

## List of abbreviations

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CCS(U)	Carbon Capture Storage (and Usage)
CENELEC	European Committee for Electrotechnical Standardisation
DRI	Directed Reduced Iron
EAF	Electric Arc Furnace
EC	European Commission
EII	Energy Intensive Industry
EC	European Commission
EU	European Union
EU ETS	EU Emission Trading System
EEA	European Environment Agency
GHG	Green House Gas
H-DR	Hydrogen Direct Reduction
I&S	Iron and steel
ICT	Information Communication Technology
IED	Industrial Emission Directive
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardisation Organisation
IT	Innovative technology
LCA	Live Cycle Assessment
MS	Member State (of the EU)
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
RES	Renewable Energy Sources
SLR	Systematic Literature Review
TIS	Technology Innovation System
WTO	World Trade Organisation

## 1. Introduction

### 1.1. Need for decarbonisation

The iron and steel (I&S) industry is important for the world's economy with steadily increasing production despite the periods of stagnation following the world's economic crises, e.g. this of 2008, [1], [2], [3], [4]. Global crude steel demand rose 3.3% per year from ~0.65 Gt in 1990 to ~1.5 Gt in 2015, which coincides with the growth in China's economy and is currently 1.8 Gt per year [5]. Total global steel production is predicted to grow by 15...40% by 2050 [6],

[5]. Global overcapacity for primary steel is currently more than 20%. Globally in 2017, the I&S industry invested 5.9% of revenue in capital investment projects, research and process improvement [4] CO<sub>2</sub> emissions from industry to limit global warming to 1.5°C are projected to be about 65...90% lower in 2050 relative to 2010, and 50...80% for global warming of 2°C [7]. The I&S industry is responsible for 5% of the world's total energy consumption and with a share of 2.9 Gt CO<sub>2</sub> amounts to 19.3% of the total annual emission from industry (2014) [8] accounting for 4...7% of the world's CO<sub>2</sub> emissions [9], [4], up to 8% in 2016 [5].

The I&S in the European Union (EU), with an output of over approximately 9.3% of the global market in 2018 (14.8% in 2008), is the second steel producer in the world after China [4]. The industry remains an important EU industry as far as the value of production (€147.8 billion), direct Gross Value Added (€25.4 billion) and employment with 330,000 direct employees in more than 500 steel production sites across 23 EU Member States (MSs) [10], [11], [12]. The I&S industry in the EU emitted 160 Mt CO<sub>2</sub>-equivalents of greenhouse gas (GHG) annually (2016), of which 63 Mt are emissions from industrial processes and product use and 97 Mt are emissions related to energy [13].

In light of the EU commitment to an emission reduction target of 80...95% in 2050 compared to 1990, EU industry must inevitably transform a low carbon economy sector [14], [15], [8], [16]. Several analyses show that industry is unlikely to meet this target without a major change in the policy framework [15], [17].

The deep decarbonisation of electricity, transport, industry, and buildings is an environmental priority for Europe and can ensure the EU industry's long-term economic competitiveness and sustainability [18].

In EU Green Deal [19], it is stressed that “Energy-intensive industries, such as steel, chemicals and cement, are indispensable to Europe’s economy, as they supply several key value chains”. The Paris Agreement “well below 2°C” target envisages that the Energy Intensive Industry (EII) emissions will fall to zero before 2070 [20], [21]. There are more ambitious scenarios assuming full decarbonisation of the EU I&S industry by 2050...2070 what seems to be a very challenging goal [6], [22].

The I&S industry contribution to decarbonisation is twofold – through lowering own energy consumption, lowering emission technologies and by manufacturing better quality products, e.g. higher quality steel. Unfortunately, the I&S production is very hard to decarbonise [23], [21]. Firstly and foremost, I&S production is almost entirely based on high-temperature processes which at large extent rely on fossil feedstock, e.g. coal as a reductant of iron ore to steel, and fuel-based technologies, e.g. coal for melting iron ore and producing on-site power (coal-intensive industry) [24]. World's average energy consumption is 20 GJ/t crude steel [25]. It is estimated that coal is responsible for 70% of the energy used in the I&S industry, e.g. in coke ovens, sinter production or blast furnaces (BFs) [26]. Secondly, the I&S industry is characterised by strong economies of scale, high upfront capital intensity<sup>1</sup>, high global concentration<sup>2</sup> and a low degree of vertical integration compared with many other commodity industries. Upstream integration by steelmakers has been driven by the desire to secure supply and increase profit margins in the value chain [27]. The cycle of investments in I&S industry is long, and may vary from 10...15 up to 40 years depending on the technology, with lifetimes exceeding 50 years [28], [8], [5].

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<sup>1</sup> The I&S industry in the EU spent €3.9 billion annually on new machinery and building work (2017) [11].

<sup>2</sup> The top ten companies represent 26% of production globally in 2018 [4].

The I&S industry is on the good track reducing CO<sub>2</sub> emission by 116 MtCO<sub>2</sub> between 1990 and 2017. However, observation of the efforts carried out in the I&S industry to increase energy efficiency, confirms that currently there is not enough incentive to encourage steel producers to autonomously undertake more sustainable and less GHG intensive production [21], [5]. Although increasing efficiency may lead to further savings, the industry has to make much effort to accelerate the development and diffusion of novel technologies to get out of the current standstill. This requires a technological change of a breakthrough nature [29], [30], [31], [21], [32], [8], [19], [16], [33], [34].

A few breakthrough technologies have been proposed years ago [35], [36], [9], [13]. Although up to now, despite multiannual R&D works followed by the extremely long demonstration phase, these technologies are still not at the market phase [9]. Therefore it is of research interest to analyse the reasons for such a low rate of technology development.

### 1.2. Aim of the article

This article aims to analyse decarbonisation options in the EU I&S industry using the Technology Innovation System (TIS) approach to deliver policy recommendations. Apart from standard elements of TIS, this analysis tries to embed considerations of sustainability (which include environmental, equity and competitiveness perspectives).

Therefore, the article has two purposes in the context of I&S industry decarbonisation:

1. Identify the key elements of the innovation system.
2. Study the functioning of such systems as a basis for policy recommendations.

This paper contributes to this task by harnessing the technology innovation system (TIS) approach [37], [38], [39], [40] to highlight the potential levers and barriers to promoting technological innovation in this I&S industry. TIS is a useful heuristic framework that relies on the analysis of success or failure of a technology based on the performance of the surrounding technological system and trace development and diffusion of innovations. TIS approach enables to include socioeconomic elements to the analysis [41]. Twomey and Gaziulusoy [41] deliver an overview of concepts and frameworks for understanding and enabling transitions to a low carbon built environment. Along with TIS, they examine similar frameworks, e.g. Multi-level perspective (MLP), Strategic niche management (SNM), and Transition Management (TM). A comprehensive review of the literature on innovative theory can be found in [42]. Diercks et al. [43] stress that "...socio-technical understanding of innovation provides several appropriate analytical concepts that can help to shape our thinking and understanding of transformative innovation policy".

The TIS is considered as useful for policy recommendations and practitioners as it may provide for both sides novel insight in the understanding of functioning innovative systems. We use the TIS approach to evaluate how the I&S industry is performing in a low-carbon transition with regards to some crucial aspects, e.g. a shrinking market in Europe, and long transport distances to customers outside of Europe. a hydrogen economy, Smart Grid development, including RES booming, possible "green steel" market building.

### 1.3. Literature critical review

Deep decarbonisation calls for an in-depth sociotechnical transition that also covers changes in users' behaviour, culture, policy, industry strategies, infrastructure, and science. If a TIS analysis is to aim at improving policies or activities needed to a cost-effective and equitable transition, it must specifically account for sustainability and society implications. In-depth knowledge on innovation systems is needed to plan and control the transition process more effectively by providing the politicians with research-based conclusions [20].

Oda et al. [44] investigated, based on an intensive and in-depth survey of steel-producing

facilities and energy-efficient technologies in the steel sector. [45] underline the importance of supporting the industry in their research efforts to make the innovations, often taken for granted, a reality from 2020 on. They stress how important it is to keep the values of the decision-making criterion, e.g. payback period, close to normal business conditions to exploit the possibilities offered by the prospective innovative technologies in this industry to the full, and the need to close the efficiency gap by making use of the policy options available.

In the literature, a few analyses of national I&S industry development are to be found. Two national cases of Germany and Sweden are worth commenting as the two countries have a specific position in the EU I&S industry – the former is the larger EU steel producer with traditional high technological culture, the latter boasts the high technologically advanced steel industry much focused on energy efficiency improvements. Arens et al. [28] claim that the German steel sector has two options to achieve its European CO<sub>2</sub> emissions reduction target for 2030 - if it strongly decreases its production output or technological changes are introduced. In this option, first, alternative steelmaking processes need to be developed including low-emission technologies and CO<sub>2</sub>-free processes, e.g. H-DR -EAF or electrolysis-based steel production with both routes based on CO<sub>2</sub>-free electricity. Secondly, there should be a path on incremental CO<sub>2</sub> reductions in the short to medium term, e.g. heat recovery from BF slag, and from waste heat in EAF, production of high-quality steel from scrap-based secondary steelmaking, and the utilisation of by-products. Arens and Worrell [46] examined the diffusion of six key energy-efficient technologies in the German steel industry and their impact on energy intensity. Some novel technologies diffused at a quicker rate at the initial stage but since the 1990s the rate levelled off. The diffusion rate depends much on developments in the sector, e.g. shutdowns or application of energy-efficient technologies. They estimated the primary energy efficiency potential of the selected technologies at 4.5% for 2012. In 2013, the steel industry in Sweden adopted a vision leading up to 2050 with three pillars - to lead technical development, to nurture creative individuals, and to create environmental benefits. These undertakings demonstrate importance on technological innovation with clear objectives in societal value creation and sustainability [47]. The efforts of the Swedish I&S industry to improving energy efficiency and implementing new technologies are very well documented [48], [49], [50]. The main conclusion might be that the industry is aware of energy efficiency importance, but more effort is required as energy-saving potential remains untapped. Regarding breakthrough technologies, Sweden is proud of the HYBRID project aimed at producing hydrogen by electrolyzing water and then using the hydrogen to make direct reduced iron (H-DRI) [51], [52].

The EU reach is rarely addressed. Recently, Mayer et al. [53] made a top-down macroeconomic analysis of a currently considered technological change in the EU I&S industry towards carbon-neutrality, based on techno-economic bottom-up literature. They analysed economic conditions (electricity and CO<sub>2</sub> price) for switches in the type of production process towards process- emission-free iron and steel technologies required for reaching climate targets, even though the current degree of alternative technology maturation varies considerably. They argued that if minimal criteria of cost-competitiveness are reached, macroeconomic benefits are feasible. Yazdanparast et al. [54] compared the gaps between service, product, and process innovations in one of the European steel companies. They claim that innovation success depends on cross-functional collaboration among members of the innovation network to share and leverage resources that are hardly ever available to one company. The research identifies internal and external success factors and challenges of each of the three innovations. Vögele et al. [55] assessed, using modelling, impacts of the global challenges, e.g. floor prices, tariffs, carbon price, on the I&S

industry in the EU. They showed that moving EILs from the EU may increase global energy demand and CO<sub>2</sub>- emissions and bring disadvantages to developing countries participating in the value chain. They stressed the need for innovations to avoid relocations of production.

The literature on transitions has so far not much addressed EILs [20]. Searching for TIS analyses, we found that majority of them are based on the country-to-country and/or product-to-product analysis whereas our case is classified as “sectorial”. We cite a few recent examples. Andreassen and Sovacool [56] used TIS for analysing the hydrogen technological innovative system in Denmark and the US focusing on fuel cell development. They conclude that although these two countries applied remarkably different TIS strategy neither approach was effective. They also stressed the need for further research on TIS as “better conceptual models of TIS and innovation are needed”. Kočański et al. [57] applied TIS to analyse electricity smart meter in the EU. This an example of the TIS approach focused on a single product (smart meter) discussed in the wide EU context. Despite strong EU political support and the potential advantages for customers, the massive roll-out is slower than expected. They identified the major barrier at the level of implementation, e.g. insufficient regulatory framework which does not fully ensure interoperability, data protection, and security standards, or organisational effectiveness. Clear presentation of benefits for the end-users has also failed. Kushnir et al. [52] studied the TIS approach to adopting hydrogen direct reduction (H-DR) in the Swedish steel industry. They identified several potential barriers, particularly in timely co-ordination with the power system regarding new infrastructure for H-DR and EAF electricity demand and noted that the I&S industry will have to compete for RES-based electricity. They pointed out the necessity of political intervention to remove the barriers to make the Swedish I&S industry the first nearly fossil-free industry in the world after 2040.

The paper is organized as follows (Fig. 1). In Section 1, the economic importance of the I&S industry for the EU economy, the need for the industry decarbonisation is underlined, and the reasons why the industry is hard for decarbonisation are given. In Section 2, the methodology applied is outlined. The boundaries of the system under analysis are defined in Section 3. Section 4 provides identification and discussion on the role of all structural components of the TIS, namely infrastructure including physical, knowledge, financial and technology; actors; institutions and policies; institutions, and finally networks and interactions. In Section 5, the mapping of the functional patterns of the TIS is done and then, in Section 6, assessment of the functionality has been provided. Section 7 provides analysis and discussion of blocking mechanisms and inducements of innovation, and in Section 8 an outline of risks and uncertainties in the I&S industry is sketched. In Section 9, conclusions and policy implications are presented.

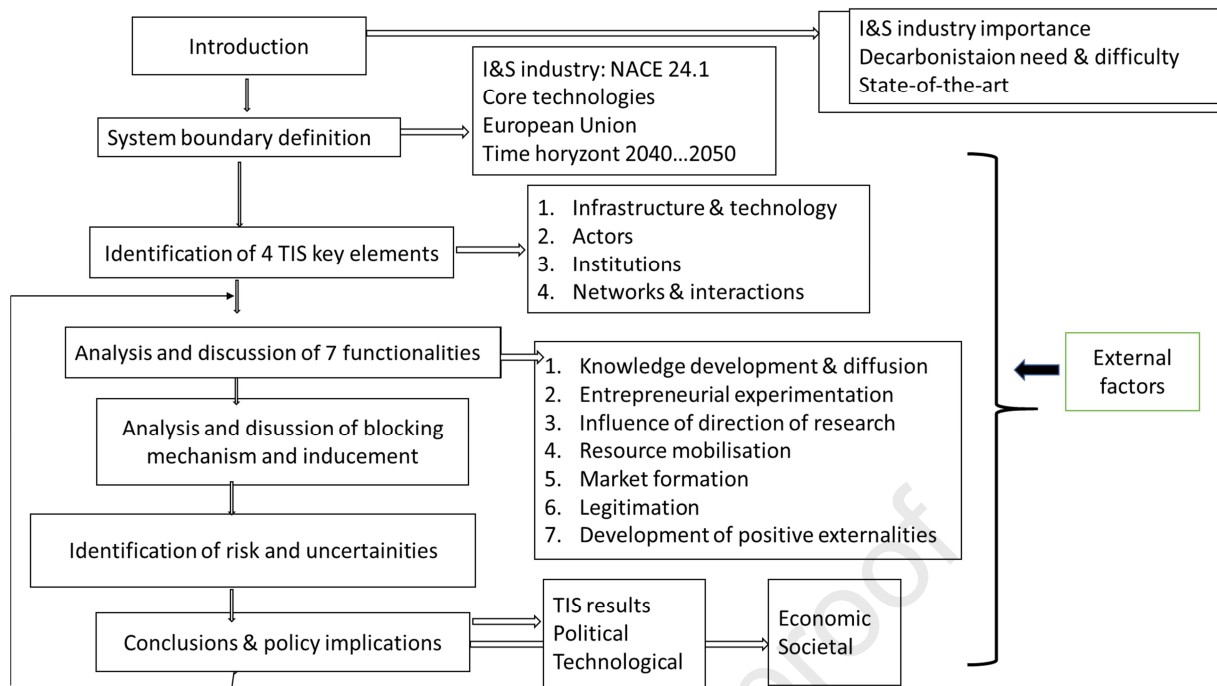


Fig. 1. TIS approach used for the I&S industry in the EU

## 2. Methodology

Because of the complexity, the innovation process cannot be approached by solely focusing on standard measurable variables such as economic criteria, e.g. revenues, productivity, and quantities. Understanding the dynamics of technological innovation requires the exploration and characterisation of the economic and social spaces in which the innovative activities take place and understanding of the interactions linking a wide range of actors and institutions [37], [39], [58], [59], [40]. TIS enables to identify key elements and then to analyse and assess the effectiveness of their functioning in multidimensional space which in majorities of analysis is simplified to fewer dimensions, e.g. technical and economic.

Tasks of this research covered:

- (a) mapping and description of key actors and institutions, and a qualitative assessment of how they interact at the supra-national, national, and sub-national levels, including a description of how the existing landscape evolved, and reasons for it,
- (b) mapping of innovation strategies, roadmaps and policy instruments across the innovation chain and their development and implementation,
- (c) identification of key barriers and inducements of innovation through desk research, and then adding supplementary comments on risks and uncertainties.

There are some crucial trends (external factors) which make such TIS approach in the I&S industry indispensable to make innovation feasible, e.g. global climate policy with the EU as a leader; "green" and circular economy; emerging hydrogen economy; transformation in the power system to the Smart Grid model which offers new symbiosis with industry, e.g. due to RES penetration; increasing storage capacities, grid flexibility.<sup>3</sup> There are also changes in

<sup>3</sup> Seeking analogy between TIS and the control theory, it can be stated that TIS is like control system of time-dependent dynamic nonlinear plant with highly distributed elements with a feedback. The plant is subjected to many, mainly stochastic noises which make its control highly unpredicted and difficult. Some of the signal and

the ways business operates nowadays, e.g. globalization, deregulation, advancements of information technology, and increasing customer demands which force the companies to continually deliver new products.

We built on the existing knowledge but unlike other analysis of I&S industry, development our TIS-based approach enables to a systematic analysis of the innovation system in a wider dimension than the standard methods, e.g. encompassing societal and environmental issues, networking, external factors. Our paper tries to analyse the whole sector, namely the I&S industry in the EU. Standard TIS approaches are narrower, e.g. focused on the comparison of product development in different countries or industry in one country.

To this end, following Bergek et al. [60], we use a 6-stage approach for the TIS performance assessment (Fig. 1):

1. Define system.
2. Identify the structural components of the TIS.
3. Map the functional pattern of the TIS.
4. Assess the functionality of the TIS.
5. Identify blocking and inducement mechanisms.
6. Specify key policy implications.

The advantage of this paper is that it strictly follows the methodology of TIS. First, we identify and described four key elements of TIS, namely Infrastructure and technology; Actors; Institutions; Network and interactions [61]. This approach highlights four constituent pillars which play a crucial role in innovation systems. Then we analyse processes that are needed in each TIS to stimulate technology development and diffusion. By mapping these processes (functions) over time, the insight into the dynamics of innovation systems can be understood. This step is based on the characterization of the seven functions specified in Table 1 and then detailed in Section 5.

The “functions” may be understood as key processes driving the development and diffusion of new technologies done in a wide sustainable context (Table 1). A comprehensive latest literature review of the functions can be found e.g. in [62].

*Table 1. TIS functions and their potential indicators*

Function	Indicators potentially suitable for the function assessment
Knowledge development and Diffusion	State-of-the-art in knowledge and manufacturing practices
	Patent and paper analysis (citations, volume, orientation, trajectories)
	Number, size of R&D academic, and industrial projects
	Modelling, learning curves <sup>4</sup>

components are of large inertia, i.e. technology development, infrastructure build-up, whereas other may act swiftly, e.g. market crises, feedstock and energy prices, interruptions in supply chain. Some, especially on limited territory (national, regional) may even have form of disruptions, e.g. closing of local steelworks.

<sup>4</sup> Learning curves methodology is not the right approach in breakthrough technologies in the case of too short period of application and limited number of experimental sites.

Entrepreneurial experimentation	Number of new entrants, including diversifying established firms
Influence on the direction of search	Visions, expectations, and beliefs
	Actors' assessments of the present and future technological opportunities growth potential
	Actors' perceptions of the relevance of different types and sources of knowledge
	Regulations and policy
	Articulation of demand from leading customers
	Technical bottlenecks
Resource mobilization	Crises in the current business
	Changing the volume of capital, including seed and venture capital
	Changing volume, quality, and mobility of human resources (e.g. educational data)
	Changes in complementary assets
	Number of different types of applications
Market formation	Breadth of technologies used, and the character of the complementary technologies employed
	Size and type of markets created
	Timing of market formation
Legitimation	Drivers of market formation
	The level of the legitimacy of the TIS
	Alignment between the TIS, current legislation and the value base in industry and society
	Legitimacy influence on demand, legislation and firm behaviour
Developing of positive externalities	Actors and their effectiveness in influencing legitimacy
	Emergence of pooled labour markets
	Political power of TIS actors
	Activities to increase confidence
	Development of needed human capital/knowledge
	Information and knowledge flows
	Collective social, environmental, and political benefits

Source: Adapted after [60], [63], [52]

TIS is very flexible in methods of gaining the necessary information, e.g. by case studies, event history analysis, multiple data sources, and interviews [62]. Our research method was based on a systematic review of the literature (SRL) since it provides context-specific

insights based on systematic, transparent and reproducible review procedures [64]. This choice is reasonable since the subject of our research, i.e. I&S industry has been very well described in academic literature, political documents, strategies and business reports which can hardly be supplemented by any complementary data acquisition. Additionally, the EU dimension of our study would enormously extend the scope of potential interviewees and business confidentiality would make it tough to get data beyond the publicly available. The papers analysed were identified via SCOPUS following the procedure described in Appendix A. We also grabbed from the EU and TIS national case studies - for the UK and Italy made within the INNOPATHS project [59].

In the TIS analysis the main technological drivers of transformation in the EU industry have been considered [65]: 1. Digitalisation (e.g. Industry 4.0), 2. Advanced materials development, 3. Complex and global supply chains, 4. Market competition and over-capacity, 5. Life cycle design, pollution prevention, and product recyclability, 6. Decarbonisation and energy efficiency, 7. Evolution of customer requirements.

### 3. Defining system

The object of study is the innovation system in the I&S industry in the EU and its capacity to adopt new core technologies. This research is limited to NACE 24.1 “Manufacture of basic iron and steel and of ferro-alloys” which is broad and covers numerous technologies and products. The scope of ITs considered is rather limited to iron ore reduction technologies and does not include the production of semi-finished products of steel and manufacturing of hot-rolled and cold-rolled products of steel. It is justified since most of the energy including electricity end-use in steel manufacturing is consumed by furnaces<sup>5</sup> [66]. The boundary for this analysis was confined geographically to the EU but essential externalities outside Europe were considered to eliminate the risk of missing essential external factors.

We consider that analysis of the I&S industry for the whole EU is feasible due to the high homogenisation of the whole surroundings secured by close integration of the MSs forced by legislative and regulatory harmonization, common internal market rules, and the common framework of R&D. Such an approach makes the result of our analysis useful both for the EU and MS levels. It is to note that Lutz et al. [67] observed that there cannot be a general approach for the transformation in the EISs since the capital structure may differ between countries and sectors. Therefore, for some countries, analyses must be conducted individually.

### 4. TIS key elements

#### 4.1. Infrastructure and technology

Infrastructure and technology encompass four categories: physical, knowledge, financial, and technology. Physical infrastructure includes artefacts, instruments, machines, etc.; financial infrastructure comprises subsidies, financial programs, and grants; and knowledge infrastructure encompasses knowledge, expertise, and strategic information [39]. Technology comprises the subset of knowledge about the full range of devices, methods, practices, and processes that enable the fulfilment of human purposes is a “specifiable and reproducible way” [59].

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<sup>5</sup> Indeed, as the 2004 study by the US DOE found in the US iron and steel industry, roughly 81% of energy use was consumed by furnaces, or “fired heaters,” with an additional 7% each by boilers and by “motor driven units,” such as rollers, pumps, fans, and other equipment. In addition, the 2004 study found that of the onsite energy used in steel manufacturing, roughly one-fourth of it was lost in conversion, distribution, and in motor driven units. Additional offsite losses were due to electricity generation [66].

Silva and De Carvalh [68] provide an extensive account of the history of the steel industry. Description of technologies in the I&S industry can be found anywhere, e.g. [29], [69], [28], [70], [71], who summarise the present status of different kinds of steels and relative technologies (incumbent and emerging), review steels over past decades and also forecast of advanced steels in the future. Over the last 50 years, the I&S industry in the EU has undergone significant changes, e.g. the elimination of production in the traditional blast furnace (BF-OHF), the doubling of the share of production through the Electric Arc Furnaces (EAF) technology (up to 59% now) and the almost complete transition to continuous casting [72], [73], [4].

Two main routes for steel production, i.e. Basic Oxygen Furnace (BOF) and EAF, are already well optimised thermodynamically, e.g. [74]. Since the 1960s, steel specific energy consumption in the European steel industry has dramatically decreased by 61%. However, technical energy efficiency potential of 15...20% still exists and will be essential to reduce emissions from existing, long-lived industrial assets [29], [45], [49], [75], [76], [50], [77], [78], [25], [5]. Specific CO<sub>2</sub> emissions in Europe are some of the lowest in the world - 1.3 tCO<sub>2</sub>/t of steel, as compared with the global average of 1.83 tCO<sub>2</sub>/t in 2017 (Global CCS Institute), aiming at 1.09 tCO<sub>2</sub>/t of steel in 2050 assuming hypothetical diffusion of breakthrough technologies in combination with CCS [6].

Based on our literature research, ten GHG mitigation options, which can align the I&S industry with the objectives of the Paris Agreement, were identified several means of GHG emission reduction [79], [80], [45], [73], [81], [82], [46], [83], [28], [84], [20], [85], [86], [87]:

1. Traditional:
  - a. Resource efficiency, e.g. feedstock.
  - b. Steel-intensive construction materials replacement.
  - c. Electrification of heat, e.g. EAFs.
  - d. Waste heat utilisation.
  - e. Combine heat and electricity production.
  - f. Strong material efficiency.
  - g. Strong energy efficiency (e.g. Energy Management).
2. Deep technology replacement:
  - a. Breakthrough technologies, e.g. H-DR, electrolysis.
  - b. Carbon Capture, Storage (and Use) (CCS(U)).
  - c. Extensive change of feedstock and energy mix, e.g. biomass, RES-based energy, hydrogen.

The IEA lists several innovative technologies within the I&S industry [88]: new smelting reduction process based on coal (TRL<sup>6</sup> 7-9); top gas recovery blast furnace (TRL 7-9); top gas recovery blast furnace with coke oven gas reforming (TRL 7-9); new direct reduction based on natural gas (TRL 6); direct reduction based on natural gas complemented with up to 80% electrolytic hydrogen (TRL 6); direct reduction based on hydrogen (TRL 6); direct use of electricity to reduce iron oxides (aqueous alkaline electrolysis, low-temperature 110°C) (TRL 5-6); direct use of electricity to reduce iron oxides (molten oxide electrolysis, high-temperature > 1500°C) (TRL 5-6); carbon capture and storage (CCS) applied to commercial iron and steel technologies (TRL 5-6); conversion of steel works arising gases to chemicals and fuels production (CCU) (TRL 7-9); smelting reduction based on hydrogen plasma (TRL 4); electrolytic production of hydrogen. Their market entry predicted in 2020...2030 is mostly delayed [82], [89], [90], [91], [92], [93]. The technologies recently identified by European

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<sup>6</sup> TRL- technological readiness level.

experts from the steel industry as innovative are improving energy efficiency beyond the state-of-the-art; new smelting reduction technologies; direct reduction technologies, based on natural gas; direct reduction technologies, based on hydrogen; direct use of electricity for iron ore reduction; use of biomass in steel production; more recycling of steel and other breakthrough solution paths for low-carbon steel production [70]. The list of technologies which can be classified as “off-shelf” embraces a few items only, e.g. H-DR [52]. This selection of reduction options which covers traditional stages of I&S production (e.g. coke making, sintering, BOF, EAF) as well as a few breakthrough technologies, was done according to the potential to decarbonization till 2050 [94], [76]. The best available technologies (BATs) have the potential of emission reduction of 15...30% in the EII, even when applied on a large scale [90], [95]. Current BAT may contribute to short-term energy and GHG emissions savings in the I&S industry, but the switch to innovative technologies by the mid-21st century is far more uncertain [96].

Other options for deep decarbonisation of the I&S industry are shifting to low carbon energy supply via either biomass, sustainable charcoal, nuclear energy, RES-based electricity or CCS [81], [97], [71], [96]. Additionally, energy management can serve as an effective tool in improving energy efficiency [98], [46], [49], [50], [28], [99].

The main conclusion from quantitative assessment has been that material and energy efficiency measures will help in decarbonisation process, but do not suffice to get the reductions needed.

#### 4.2. Actors

Actors within an innovation system “typically include individuals and organizations operating at multiple scales” [100]. Different categories of actors within different sectors have different characteristics, motivations, and strategies which must be appropriately described and understood [101].

The role of actors that contribute to the success/failure of the TIS in the I&S industry is manifold and presents a complex array (Table 2).

*Table 2. Actors and their roles of TIS in the I&S industry in the EU*

Actors	Role in I&S industry TIS
EC	<p>Develops long-term social and economic strategies like climate-energy policy, industrial policy</p> <p>Tries to improve co-ordination among complementary policies, e.g. innovation policy, tax policy, energy market regulation [102]</p> <p>Sets sustainable long-term priorities and objective strongly affected the I&amp;S industry, e.g. political support for climate policy and the following decarbonisation of industry</p> <p>Plays a crucial role in setting and the enforcement of climate-energy legislative framework (directives, regulations), e.g. EU legislation supporting deep industry decarbonisation, e.g. energy and material efficiency, EU ETS</p> <p>Introduces sectorial regulations and set market conditions via market regulations, e.g. taxes, import quotas</p> <p>Initiates and finances R&amp;D, e.g. finance I&amp;S industry programs, establish innovation centres e.g. numerous programs supporting innovation policy to keep up with the world’s innovation leaders</p>

	<p>Launches short-term intervention programs in times of economic stagnation or crisis or natural disasters</p>
National governments	<p>Implement relevant EU policies</p> <p>Develop national policies, socioeconomic priorities</p> <p>Set priorities, finance, and coordinate R&amp;D policy</p>
Local authorities	<p>Develop local development strategies</p> <p>Secure local socioeconomic objectives, e.g. employment</p> <p>Decide on investments, e.g. upon environmental criteria</p>
Companies	<p>Undertake entrepreneurial activities</p> <p>Company's management takes tactical and strategic business and R&amp;D decisions</p> <p>Launch, carry out and finance R&amp;D programs</p> <p>Establish R&amp;D centres in cooperation with universities being supported by public funds</p> <p>Employ technological improvements as a means of increasing competition and reducing environmental burden</p> <p>Struggle for lower costs of energy and material</p>
Lobby groups	<p>Organise political and social support in the interest of I&amp;S industry, e.g. against EU ETS obligations</p>
Energy regulators	<p>Play a crucial role in key aspects considering energy supply to I&amp;S industry</p>
Energy companies	<p>Set energy prices for industry (on the competitive market and in regulated network subsector)</p> <p>Play an essential role in taking decisions on energy mix, e.g. on RES share</p> <p>Set the pace of integration of energy sectors, e.g. waste heat and electricity</p> <p>Initiate Demand Side Management with I&amp;S industry</p>
Business associations	<p>Act as lobbyists at all stages of legislation preparation and enforcement in all I&amp;S industry-related areas</p>
Trade and sectoral organisations, platforms	<p>Play an active role in the preparation and coordination R&amp;D programs</p> <p>Communicate I&amp;S industry's challenges and successes to societies at national and global levels</p>
Technology providers	<p>Provide highly developed technologies, machines, and equipment and create markets for them</p> <p>Take part in R&amp;D</p>
Financial institutions	<p>Finance IT investments (with some possibly limits to non-sustainable investments)</p> <p>Assess business risks for IT</p>
Society	<p>Supports actions aimed at sustainable development, e.g. lower energy costs; mitigation of pollution emission; improvement of energy and</p>

	material efficiency Contributes to social and economic goals of sustainable development
Customers	Set demand for steel products on highly competitive global markets Drive demand for new high-quality products Big buyers create markets for high-quality products
Non-governmental organisations	Support deep decarbonisation in EII, e.g. demand mitigation of the negative impact of I&S industry Support circular economy Lead an intensive public discussion and support strong climate policy
International organisations	Set a global framework of environmental protection, e.g. UN, OECD, IPCC Set rules of fair competitions in global markets, e.g. WTO, World Bank Set technical standards, e.g. ISO, CENELEC
Academia	Researches in the I&S industry despite apparent “low scientific attractiveness” Opens new research areas, multidisciplinary approach Co-operates with I&S industry

Source: Own work.

#### 4.3. Institutions

Institutions are defined as a set of formal and informal rules, norms, decision-making procedures, beliefs, incentives and expectations that guide the interactions and behaviour of actors in an innovation system [37]. Institutions set the environment in which all actors operate [58].

The EC has warned that “Today, the European steel sector finds itself in a very difficult situation” [3], and to solve the issue, the EC has taken steps to strengthen the EU’s defence against unfair trading practices. The EC called for immediate action for a European industrial renaissance in 2014 [103]. The EC took planes to protect the industry from the unfair international competition including the steel industry, “...notably through modernisation and investments in innovation” [104]. In 2019, the EC reconfirmed: “Energy-intensive industries, such as steel, chemicals, and cement, are indispensable to Europe’s economy, as they supply several key value chains” [105] (Table 3).

*Table 3. Issues concerned as politically important for the I&S industry in the EU*

Area	Issues
Trade	Improving the speed and efficiency with which the EC can begin and resolve trade defence investigations Enabling better use of policy instruments to enforce trade defence Intensifying discussions through the OECD with major steel producers like China, Russia, and India to safeguard EU interests Improving the access for EU steel exporters to “third markets” Secure access to raw materials as crucial due to scarcity in the EU
Industrial	Using EU funds to modernise the I&S industry, including retraining and

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development	<p>reintegration of redundant steelworkers into the labour market.</p> <p>Engage high-level stakeholders in the industry to agree on a plan of action to modernise the industry</p> <p>Implement the EC's "circular economy" strategy to reduce waste and increase efficiency in manufacturing</p>
<hr/>	
Energy	<p>Compensate for energy prices as EU prices are higher than in most of its international competitors</p> <p>Supporting energy-intensive industries within existing State Aid rules</p> <p>Reviewing the EU ETS to ensure that the I&amp;S industry remains competitive whilst also reducing emissions</p> <p>Implementing the EU Energy Union</p>

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Source: Own work.

#### 4.4. Networks and interactions

Network and interactions describe the dynamic relationships and links between actors, but a "network" can also be seen as a higher form of "actors" organisation. Interactions may take place within networks and can be analysed at the level of both networks and the level of individual contacts [39]. Analysis of networking usually poses a great challenge in TIS research. Even when the other components of TIS are identified, to trace their interrelation is difficult both from the methodological and practical perspectives. The links may be multidimensional, overlapping, and tacit. Even when properly recognised, there is neither a standard methodology nor metrics to measure their strength therefore narrative description or tracing connections in literature or patents must suffice.

It is common to analyse an industrial sector as an isolated system with no or only a few links to the ambient constituted by other elements of the whole economy and society. However, combating climate change is such a global trend that it has enforced an interrelated transformation in other industries, e.g. a strong and immediate interdependence relationship between coal, power, chemical, and I&S industries [106]. European companies, operating in a high-wage region, to compete try to create additional value, e.g., more and specialised variants of steel offered, highly sophisticated logistical services, and excellent after-sales service [54].

Analysis of networks in the I&S industry should embrace a wide range of actors and types of collaboration, e.g. suppliers and manufactures in the whole chain, customers, energy end-users, research institutions, multinational research, pilot and demonstration projects, innovative platforms, industrial and trade associates [107]. R&D works in the I&S industry are often presented as cooperation among global players, e.g. top steel producers, novel technology providers, and leading research institutions. It is, however, to note that at the initial stage, the network also includes small companies, often not related to the specific sector, but with in-depth knowledge which can be supplementary to the steelmaking processes. The industry itself points at the overall immaturity of "collaborative solutions" and their frameworks [14].

The discussion between the I&S industry and other actors can be led in two ways [108]:

- The institutional channels as the steel community is a part of society at local and global levels e.g. acting in Corporate Social Responsibility, or participation in international initiatives, e.g. within UN (Global Compact), business associations or business circles.
- The science-based route related to the role of steel and analysed multidisciplinary as a mixture of soft and hard sciences.

### 5. Mapping of the functional patterns of the TIS

In this section, we will systematically analyse the seven functions of the TIS in the I&S industry providing indicators of each of these functions (Table 4).

*Table 4. Seven functions of TIS in the I&S industry*

Function	Identified indicators of TIS functioning
Knowledge development and diffusion	<p>Multiannual accumulated knowledge and manufacturing practice</p> <p>Few large long-term R&amp;D projects with participation of main industrial actors and the academia with substantial public support (EU, governments). Knowledge sharing</p> <p>Key industrial manufactures possess their research centres often co-operating with academia. Knowledge sharing restricted</p> <p>The crucial role of the development phase in the whole process of R&amp;D</p> <p>An exceptionally long time of reaching the market phase for innovation technologies</p> <p>Patenting activity in steel varies significantly across economies and over time and come from a wide variety of actors</p> <p>Low and insufficient investments in R&amp;D (both public and private) as compared with other EII, e.g. chemical</p> <p>Demonstration (pilot) projects carried out on very few industrial sites</p> <p>R&amp;D includes a variety of possible measures of decarbonisation applicable in I&amp;S industry</p> <p>The long process of learning-by-doing led to substantial progress in incumbent technologies</p>
Entrepreneurial experimentation	<p>Very few new entrants</p> <p>High awareness of all industrial actors about the needs for technology innovation due to environmental requirements</p> <p>Involvement of the main manufactures in R&amp;D, e.g. breakthrough technologies, Industry 4.0 technology [65], [109], [110]</p>
Influence on the direction of research	<p>The top priority of climate-energy policy sends a clear signal to policymakers on the necessity of deep decarbonisation in I&amp;S industry through technology innovation</p> <p>The high potential of material efficiency in the circular economy, e.g. scrap reuse, by-product utilisation</p> <p>The high potential of GHG reduction through breakthrough technology implementation</p> <p>Low expectations of a breakthrough in core incumbent technologies</p> <p>A few identified technologies with limited energy and material efficiency improvements</p> <p>Few emerging breakthrough technologies e.g. "green hydrogen", large use of RES-based energy, electrowinning, DIR, CCSU [13], [111], [53]</p>
Resource mobilisation	<p>Well established research institutions, e.g. at universities, industrial institutes, and centres, with highly competent staff</p> <p>Joint research centres of the academia and industry with public co-funding</p> <p>The co-operation of the main market players (manufactures) in R&amp;D projects</p>

	<p>Continuous sufficient inflow of educated staff at all levels of competence, e.g. trained workers, managers, engineers, scientists [112]</p> <p>Insufficient human and financial resources involved in the demonstrative phase of breakthrough technologies</p>
Market formation	<p>Mature market, without a niche, for steel products prone to economic cycles and crises</p> <p>Unfair trade rules exercised by some manufactures make innovation technologies difficult to enter into the market</p> <p>Evermore demanding environmental standards followed by penalty regulations accelerate R&amp;D and market adoption</p> <p>Market demand for improved products set by the main customers, e.g. automobile, construction sector (“learning by using”)</p>
Legitimation	<p>Global political agreement on the urgency of GHG emission reduction</p> <p>Broad consensus of all actors on the need to decarbonise the I&amp;S industry</p> <p>Actors, institutions are well established in multiannual historical processes</p> <p>Low interest of public opinion in technology innovation in the I&amp;S industry as such, but the high expectation to reduce environmental harm</p> <p>Visibility of effects of environment protection measures build-ups of local support, e.g. reduction of air pollution</p> <p>EU and national environmental targets, e.g. GHG emission reduction, set indirectly the targets on I&amp;S industry decarbonisation</p>
Development of positive externalities	<p>Acknowledged societal importance, national and local, e.g. retaining jobs</p> <p>Flow of knowledge among different TISs, e.g. RES-energy, chemical industry, cement industry, automobile, construction, resulting in mutual benefits</p> <p>Strong complementarities among technologies, e.g. steel-hydrogen-RES, electrolysis-RES; in by-products utilisation, e.g. cement industry</p> <p>Large potential contribution to the circular economy</p> <p>Participation in global trend to the decarbonisation of EII</p> <p>Realising the potential for GHG emission reduction and energy and material efficiency</p>

## 6. Assessment of the functionality of the TIS

### 6.1. Knowledge development and diffusion

Innovation systems in the I&S industry are even more complex than in other sectors since the connections among actors and institutions occur at many stages of the innovation process in multiple sectors and countries and different scales, and are not “visible” to the public. Additionally, the market is not directly driven by millions of customers as it happens in the case of many other products. Most of the I&S large companies are involved in developing ITs since they are aware of the importance of GHG emission reduction and their key role in it. They recognise the need for co-operation at different stages of technology development, particularly in R&D and pilot phases despite clear business competitions. Government’s support is materialised in funding via R&D programs and creation of research centres which

does not violate public aid rules and increases the attractiveness of the country to global manufactures [113], [114]. The rate of innovation in carbon mitigation related technologies in the I&S industry has been increasing over the last decades what supports the thesis that climate policy is a strong driver of innovation [115], [68].

The inertia of some TIS components, not strictly of R&D nature, may amount to years, e.g. in political or standardisation decisions (see work plan of [116], and shall be accounted for in the TIS assessment. The diffusion of technologies may therefore substantially vary. Grubler [117], compared the development of four technologies used for steel production which competed simultaneously with decreasing and increasing market shares. The diffusion trajectories of the processes were diverse, with time constant ranging from less than two decades (replacement of the crucible process) to nearly seven decades (diffusion of EAFs). The development of breakthrough technologies cannot take momentum also due to the complex and fast-changing externalities, e.g. energy and feedstock prices, fluctuation in demand for steel.

#### 6.2. Entrepreneurial experimentation

Our TIS operates in a well-established industry facing a strong need for decarbonisation, although, at the same time, the industry faces limited options for breakthrough technologies soon. Unlike many other industries, technological transformation should be mainly carried out with the active involvement of the industry through bottom-up initiatives rather than by new entrants or be directly transferred from academia to industry. The lack of new entrants in the mainstream business weakens the innovation drive among incumbent actors. The demonstration phase in the I&S industry is so risky that it cannot be jumped over or shortened radically. There are pieces of evidence of dropping or mothballing projects caused by economic hardships [118].

#### 6.3. Influence on the direction of research

Research challenges are well recognised and are mostly initiated by environmental requirements and only partially by a limited demand for higher quality products [119]. The EU and MS governments support R&D in the I&S industry but they have very limited possibilities to intervene directly into strictly business matters. The I&S industry in the EU can potentially remain a leader in ITs although competition from other countries is tough [120], [12].

#### 6.4. Resource mobilisation

The I&S industry people are aware of the importance of the EU internal market, growing competition from globalised markets, the influence of financial markets on corporate strategies, and commodification. The development of ITs has suffered from the lack of sufficient R&D financing and resulting human resources involved. Political support both at the EU and national levels despite different actions has not brought about the results expected by the I&S industry. Therefore, pilot and demonstration stages remain a “bottleneck” in the whole innovation cycle. The industry raises several key business-oriented aspects essential for low-carbon innovation: 1. Cost savings and competitiveness; 2. Carbon price; 3. Developing robust inter-industrial collaboration models; 4. Reduced environmental externalities (delivering Improved Corporate Sustainability Reputation); 5. International competition for low-carbon products [14].

#### 6.5. Market formation

At present, the energy consumption, GHG emission, and by-product utilisation in the I&S industry are serious political and public concerns that need to be addressed to avoid costs of pollution and make the technological processes sustainable. The I&S industry in the EU will be able to reduce its CO<sub>2</sub> emissions by 15% in an economically viable way until 2050, compared to 2010 levels, while the steel market will grow by 0.8% annually (to raise the EU

crude steel production to 236 Mt in 2050) [121]. The divergence between predicted GHG reduction possibilities and the production growth illustrates the market demand for breakthrough ITs. In response to these plans, the EU I&S industry declares that it will be able to reduce production's CO<sub>2</sub> emissions by 30% by 2030 and by 80...95% by 2050 if breakthrough technologies are adopted [122]. To end this, the I&S industry must undergo deep decarbonisation.

The EU regulatory framework does not favour any of the emerging technologies postponing in this way possible competition for a more mature phase of technology development. The economic impacts of technological breakthroughs in the I&S industry will likely be nonlinear as system thresholds are breached and have knock-on effects. The market for ITs will emerge from the first success pilot installations which will be multiplied on other sites depending on the expected revenues, the scale of investment needed, and the threat of stray assets [53].

#### 6.6. Legitimation

Steel as a product is very well recognised by people and enjoys high esteem [108], [122]. I&S industry is highly valued by politicians as an economically and socially important and prestigious sector [105]. Steel is a key element of an industrial society and thus for meeting Sustainable Development Goal 9<sup>7</sup> [123]. Communities in which the steelworks are located also appreciate its importance to the local labour market and prosperity [124].

The I&S industry tries to demonstrate its commitment to all aspects of "green economy", e.g. energy and material efficiency [125], [1], [25], [122]. These efforts impact politicians although do not much affect the public therefore the I&S industry receives much less public attention as the environment polluter as compared e.g. with the power sector.

#### 6.7. Development of positive externalities

The ITs in the I&S industry and other industries demonstrate in some respects close synergy, e.g. with power, automobile, construction, chemical, defence industries. The positive influence of each other results from common interests and objectives, e.g. these driven by RES-based energy, material, and energy efficiency, complementary of technologies, easiness to adopt. The benefits of "spilling over" from one TIS to another have not been yet fully recognised and valued although the symptoms of such synergy are "visible" and a prevailing tendency for the interdisciplinary research helps to create joint R&D programs and research centres.

### 7. Identification of barriers and inducements. Discussion

Competition between the incumbent systems and the emerging ones is a key element in the development of TIS. It is considered in categories of "blocking mechanisms" and "inducement" [126]. The inducement mechanisms are understood as "believed in growth potential and government R&D policy" [60]. Presenting barriers and inducements against the functionalities increased the readability of the text.

#### 7.1. Infrastructure

##### 7.1.1. Physical

*Table 5. Examples of blocking mechanism and inducements in the I&S industry in the EU.*

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<sup>7</sup> Build resilient infrastructure, promote sustainable industrialization and foster innovation

*Category of structural elements: Infrastructure. Subcategory: Physical*

Blocking mechanisms	Inducements (enablers)
Global overcapacity with the diminishing share of EU in the global capacity (risk of stranded assets) [127], [122]	Ageing of current capacity leads to “greenfield” investments or at least to “brownfield” retrofits
Large existing capacities block low-emission technologies (slow rate of capital stock turnover) [128], [5]	The main players in the EU steel industry recognise the decisive role of technological innovation in seeking global market advantage
High concentration of capacity in few global companies limits the number of the parties involved	
Very high investments cost in core technologies and long investment time, high business risk and perceived long pay-back time [129][129]	
The unwillingness of undertaking new investments beyond times of high economic prosperity	
Large intensive emission capacity in countries with low environmental standards (Pollution Havens)	
Preferences to refurbish existing large-scale plants hinders more risky innovation	
A small number of innovative companies in the I&S industry as compared with truly innovative industries	
The vulnerability of R&D programs to external factors, e.g. economic crises	

Source: Own work.

R&D investments are needed, both in human resources and physical capacity, otherwise, rates of innovation and technology diffusion are apparent, and the support of different actors within the low-carbon innovation system is lacking. Establishing industry and academia joint research programs and centres, e.g. in Private-Public Partnership, gets the key actors closer [130]. A high level of research in a country and public support helps to save domestic capacity from closing down [131].

Globalisation and overcapacity do not facilitate ITs in any EIs unless innovation secures high profits with short pay-back time [127], [5]. Low cost remains the decisive criterion in purchasing decisions on the global market with overcapacity of around 440 million tonnes in 2019, equivalent to almost 25% of global steel production capacity what effectively discourage innovative investments [33]. There are several general trends in global development that give new impulses to technology change and innovation boost. These tendencies help to reject the traditional dogma of cost-effectiveness as a major criterion in technology assessment. On the other hand, periods of overcapacity are suitable for deep technological changes as there is no risk of losing important markets and customers

assuming the company remains financially stable. Additionally, local capacities will also weight, e.g. availability of qualified workforce, accessibility to RES-based energy or RES-hydrogen, community acceptance for CCS [8], [132]. The reduction of environmental burden due to innovative technology always builds better relationships between the investors and the community.

### 7.1.2. Knowledge

*Table 6. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Infrastructure. Subcategory: Knowledge*

Blocking mechanisms	Inducements (enablers)
Demand for new innovative products only from a fraction of customers	Slow but steady progress in some R&D programs leads to more advanced technologies at the pilot and commercial scale
Methodological and practical problems with a reliable assessment of energy and material consumption in complex multioperation technological processes	All major actors of the I&S industry are active in the field of digitalisation this industry [110], [65]
Biased methodological approaches in the assessment of innovative technologies, e.g. too optimistic or pessimistic	Integration of I&S technologies with other technologies, e.g. chemical, power industry, ICT

The R&D trajectories are set and it is hard to expect novel technologies to appear soon [119], [83]. The progress in developing the currently researched breakthrough technologies is very slow and therefore requires public support at the EU and national levels [108], [133]. More concentrated public financial support for R&D and then for breaking the demonstration and market barrier is a prerequisite if the I&S industry in the EU is to remain competitive especially in the light of the expected increase of costs due to the EU ETS participation [122].

R&D in the I&S industry is not considered highly innovative and, thus, is not a priority for governments in their national development strategies, neither for research institutions<sup>8</sup> [106], [18] even though these technologies are game-changers for deep decarbonisation. Yet, the high value, traditionally attributed in the I&S industry to technological progress and innovation, allows the industry to remain highly advanced although progress in core technologies remains slow. It had been predicted that the currently used (standard) technologies would dominate until 2025 [76], [13]. Now it seems that the time horizon is likely to be pushed till 2040...2050.

A large number of technological projects in the I&S industry is co-financed from EU funds, e.g. the ULCOS (Ultra-Low Carbon dioxide (CO<sub>2</sub>) Steelmaking) is a consortium of 48 European entities (all major EU steel companies, some engineering partners, research institutes and universities) [14], [134], [13]. However, EU R&D programs seem to be too much dispersed, weakly focused on crucial decarbonisation challenges, and not tackled in a truly interdisciplinary way in a long-term perspective [120], [134], [135].

<sup>8</sup> Manufacture of basic metals (NACE 24) is classified as medium-low-technology [106].

## 7.1.3. Financing

*Table 7. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Infrastructure. Subcategory: Financial*

Blocking mechanisms	Inducements (enablers)
The difficult economic position of the EU I&S industry in recent years – the dilemma of cost-cutting or the need for investments in new capacity	The high share of energy in costs of final products (up to 40%)
Possible unwillingness to finance industry operating at highly competitive markets at times of economic instability and hardship	Rising costs of energy make ITs more profitable
Possible lack of access to investment capital especially in the difficult economic standing of the company	The large share of public funds allocated for “green economy” envisaged in the EU financial perspective for 2021-2028
The funding gap between TRL 6-9 (“valley of death”) [136], [14],	Growing unwillingness or even ban on financing non-sustainable investments (like coal power stations) with a risk of extension on other EII, e.g. I&S industry
Inadequate availability of risk capital [128]	The expected positive impact of EU ETS on low-carbon technological up-take in I&S industry after 2020 (Modernisation Fund, Innovation Fund)
High capital involvement and low rate of return from financing high-emission investments	
High costs of demonstration installations	
Lack of upfront clarity about the funding [120]	
Not fully recognised benefits of IT in LCA	
Low R&D private funding insufficient to overcome barriers of pilot implementation at acceptable risk	
Insufficient targeted economic incentives for TI, e.g. in the form of tax reduction, risk-sharing or loan guaranties from private and public financial institutions, governmental quarantines	
Business risks and risks of perturbation in production deter large investments which may result in losing markets, crucial clients, or penalty payments	
Lack of “green” criteria in public procurement [137]	
Low profits in incremental technological improvements	
Moderate incentives for low-emission	

technologies from environmental funds

Lack of new business models in I&S industries rewarding TI

Source: Own work.

Very high investment costs in core technologies and long investment time in the unstable global market deter low-emission, high-cost transformation. Financial incentives are indispensable to overcome the barriers for such investments to support private capital, e.g. via Private-Public-Partnership [138], [139], [53], [122]. For example, a demonstration HIsarna technology plant of industrial size (0.5...1.0 Mt/y) will require an investment of €300...350 million [134]. Public intervention should complement and not overlap with existing EU and national funding programmes [14]. There is a need for viable and robust business models for long-term and deep decarbonisation beyond incremental and short-payback measures. Rules of support should be more flexible, e.g. simple two-stage application procedure, aligning the timing of support with funding needs (“funding against milestones”), ensure complementarity between different EU funds [14].

The breakthrough technologies can hardly be classified as competing at this stage of their development when their actual costs and benefits are not yet properly assessed in the market scale [46], [90]. Their implementation will, to a large extent, depend on several criteria, sometimes local, e.g. availability of RES-based energy and local feedstock, demand for waste heat, cost, and price structures in a specific country [140], [141]. Also, the time of implementation of process emission-free “high-cost” technology, e.g. 2020 or 2035, plays its role as early implementation may increase the range of negative GDP implications in 2050 [53]. The emission abatement in industry, e.g. in I&S, may turn out to be much more technologically challenging than emission reduction from energy use [18]. The innovation diffusion in EIs exhibits a natural long time constant resulting from long decision cycle and investment phase even in pilot installations [46], [45]. Securing sufficient and stable financing would substantially reduce the duration of the premarket phases and lower the business risks.

The EC intends to “support clean steel breakthrough technologies leading to a zero-carbon steel making process by 2030” [105]. The EC is aware of the costs of such large-scale innovative projects and plans to use for this purpose the funding from the European Coal and Steel Community. Financing options for modernisation opened by EU ETS reform (2021-2030) seems to be the desired step but with some doubts about its potential for a truly deep technological transformation in the I&S industry.

The I&S industry may in the future encounter a barrier of assessing to bank financing for high emission investments like it occurred in the power sector in coal-based technologies [142], [143].

#### 7.1.4. Technology

*Table 8. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Infrastructure. Subcategory: Technology*

Blocking mechanisms	Inducements (enablers)
Lack of breakthrough technology successfully implemented at the industrial scale, e.g. CCS, RES electrolysis, “green	Steel products are constantly evolving, driven in part by R&D conducted in collaboration with steel-using industries [68]

hydrogen”	A shift towards EAF would help I&S industry to move towards a circular value chain
Incremental improvements to core process technologies slow down pursuit for “breakthrough” technologies (lock-in)	Development of energy service market, e.g. energy management, energy audits, energy-saving obligation, enables quicker adoption of energy-efficient innovations [144], [49], [68]
Low use of RES-based energy in technological processes, e.g. hydrogen RES steel electrolysis	High quality of domestic products reduces the risk of replacement of domestic products by import (“carbon leakage” consequence) [53]
High usage of coal in technologies where lower emission substitution is possible, e.g. as an energy carrier or feedstock	The growing share of RES in the EU power capacity may make RES-based steel technologies economically viable [145]
Not fully recognised impact of energy and material efficiency on operational costs	Natural obsolescence of some installations opens option for deep technology change
High technological uncertainty between research and demonstration phases and then full commercialisation (scale uncertainty)	
“Energy efficiency gap” – insufficient interest in energy savings in auxiliary technologies, e.g. waste heat recovery, electrical drives	
Insufficient involvement in Demand Side Management, e.g. in EAFs	

The I&S industry, due to its characteristic is not predisposed to radical breakthroughs. The I&S technology although based on well-established knowledge when implemented is not straightforward replicable and on each site requires adaptation which creates additional risk. Moreover, high technological integration entails that any change of one technological process requires changes to other parts of the process which increases the costs and the risk of technological incompatibility.

The TIS distinguishes between incremental innovations that track existing technological trajectories and radical innovations that lead to new technologies. The progress in the I&S industry mostly consists in the process innovation that tends to follow predefined technological trajectories through incremental innovation aimed at enhancing productivity [20]. The radical case typically means investing in novel technologies for the basic conversion process or changes in feedstocks and low-carbon energy supply. For example, the EAF shift suitably combined with RES-based energy could lead to the entire decarbonisation of steel production.

Since this deep decarbonization transition at present is proceeding very slowly, therefore, even incremental ITs can serve as an effective tool in GHG reduction [9], [28], [120], [13]. Through learning by doing, the practising engineers facilitated incremental innovations that triggered partial reinvestments. The leaders in the I&S industry employ many ancillary means of energy and material efficiency, e.g. waste heat utilisation, variable electric drives, advanced measuring and control systems, if only these are economically viable [94], [50], [129]. However, these can only suitably complement mainstream measures.

The variety of technologies under research, although not vast, will enable to compose the future technological structure in most suitable configuration depending on different

geographical, social, economic, institutional environments criteria which characterize the different MSs. For example, the mature technologies available for using biomass as fuel and feedstock in steel production are financially more attractive than the electrification of heat at electricity prices above approximately \$20/MWh [8]. Electricity prices will be decisive in the choice between electricity-based decarbonization and CCS [86].

Innovations in the I&S industry are predominantly technological, with traditional organisational structures and business cases [20]. I&S producers can use other options, e.g. consolidation and structural capacity reduction, customer orientation and commercial excellence, operational optimisation including material and energy efficiency [146], [5].

## 7.2. Actors

*Table 9. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Actors. Subcategory: Civil society*

Blocking mechanisms	Inducements (enablers)
Low recognition of I&S industry decarbonisation importance as compared with e.g. power systems, buildings	Determination to build low-carbon EU economy with ambitious reduction goals
Industrial decarbonisation is usually not in the spotlight of public interventions in terms of economic strategy (bottom-up industrial initiatives are more visible locally)	Strong determination of citizens to meet at all price climate policy objectives
Unclear allocation of costs and benefits for citizen weakens public support	Local communities squeeze on removing large local polluters
Antagonistic assessment criteria due to divergent interests among actors	
Weakly organised citizens' movements supporting sustainable development	
Insufficient use of mass media in promoting societal benefits of I&S industry decarbonisation	

*Table 10. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Actors. Subcategory: Research*

Long-lasting insufficient progress may demotivate actors from launching intensive R&D programs	The concentration of R&D programs on breakthrough technologies as the solemn options for deep decarbonisation
The crucial role of the world's largest steel companies may impede innovation process in some countries while supporting in others	
Relatively slow deployment of BAT due to lack of legal obligations or clear economic benefits [45]	

*Table 11. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Actors. Subcategory: Organisations*

Insufficient information on ITs, e.g. technologies, barriers, benefits, financing sources, risk, uncertainties	The consensus among actors on the inevitability of I&S industry decarbonisation enables forming no antagonistic coalition of actors
	Well educated labour force (academic, non-academic, vocational)

The need for the I&S industry decarbonisation has been well recognised by all actors and is not questioned, see e.g. [120], [147], [122]. Since R&D directions in the I&S industry have been defined years ago, noting low pace of progress, and still pending pilot phase of key technologies, it can be assumed that further progress requires a strong involvement of key actors, i.e. the EC, MS governments and the I&S industry who shall play the leading role in acceleration the transformation. The other actors, i.e. the researches, are also important but innovative acceleration depends on the coherent action of the former group.

That EU strong determination of decarbonisation helps to get synergy but has up to now turned out to be too weak to cause deep innovative changes. Uncertainties around post-Paris policy, unconvincing EU industrial policy which does not reflect the high climate ambitions and lack of economic incentives make main global I&S manufacturers reluctant to get fully involved in the IT transformation. They remain unwilling to take the lead in R&D as long as EU financial incentives are apparent, and policies do not secure future stable regulatory framework. The push must, therefore, come from the actors who from different reasons have an interest in lowering GHG emission, namely the EC, MS governments, and society. For them, environmental protection is the common denominator enabling co-operation.

### 7.3. Institutions

*Table 12. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Institutions. Subcategory: Hard*

EU climate and environmental legislation and regulatory policy insufficiently supports low-carbon transition in I&S industry	EU, as the world's leader in low-carbon energy and climate policy, gives IT strong political support
Lower EU priority of industry decarbonisation as compared with other sectors, e.g. power, building, transport	EC political declaration that Europe remains an important steel-producing region
Delayed EC industrial policy weakly supporting the low-carbon transformation	Industry decarbonisation, including I&S industry, is one of the main pillars of EU climate-energy policy
Weak correlation of low-carbon industry transformation with the energy sector, circular economy, and other policies	Recent EC support for reindustrialisation as a key element of EU competitive economy
Limited option of intervention from governments due to free trade regulations e.g. public aid rules, lack of import barriers	Need for compliance with steadily harder environmental requirements
Large subsidising by some governments	Strong support for RES and other low-emission energy technologies

which own steel industry assets, e.g. in the Countries of Independent States [128]	Efforts to remove distortion in the internal energy market to make it more competitive
Regulations and standards acting as barriers to innovation (general)	Development of circular economy enforces better energy and material circulation, e.g. steel scrap, feedstock, by-material usage
Instrument introduced by the Energy Efficiency Directive are not appropriate for I&S industry, e.g. energy labels, voluntary agreements	
Lack of or weak support from governments to I&S industry not considered as innovative	
Lack of effective long-term EU strategy of industry transformation (Industry 4.0)	
Lack of market incentives to invest in innovative technologies	
Relatively slow rate of I&S industry preparation to Industry 4.0 as compared with highly innovative industries	
Highly competitive global markets and weak faith in substantial benefits due to the fast implementation of breakthrough technologies conserve the “cost-efficient” criterion of technology development	
Legislation insufficiently forces eco-innovation	
Developing or often-changing regulatory framework for less mature technologies, e.g. CCSU and hydrogen infrastructure [14]	
Ineffective use of EU ETS revenues for low-emission technology transition in the steel industry [148]	
I&S industry’s objective to increase competitiveness may not coincide with cost optimal GHG emission reduction	
Lack of interest to force the inclusion of external costs of energy into total costs of industry	
Lack of agreed sectorial targeted energy and GHG reduction goals among big emitters, e.g. power, chemical, and steel	
Incoherence of many EU politics and strategies aimed at supporting innovative technologies [149]	
Inadequate regulatory or legal frameworks	

to support innovative technologies, e.g. tax realise, subsidies, public support to R&D

Steady risk of import substitution to the EU and difficulty with adoption common EU market defence and expansion strategies

Weak political, the organisational and economic power of few new entrants

*Table 13. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Institutions. Subcategory: Soft*

<p>The corporate style of management in large companies (multinational) impedes decision-making process and internal networking functioning [150]</p>	<p>Natural trend of advancing technology towards more sustainable and competitive</p>
<p>Corporate culture may not sufficiently support ITs</p>	<p>High pressure from employees and union trades on improving work conditions that can partly be accomplished by IT implementation</p>
<p>Difficulties to place deep decarbonisation projects as a priority in long-term strategies of I&amp;S plants</p>	<p>Growing power of “green”-oriented parties on the EU political arena</p>
<p>ITs are not a priority in the steel industry practice</p>	
<p>Energy and material saving objectives not well integrated into operational, maintenance or purchase procedures</p>	
<p>Low priority of improving industry corporate image as a “green” business (Corporate Social Responsibility)</p>	
<p>Entering of products into the market without obligation to trace “carbon foot”</p>	
<p>Low interest of top management in implementing ITs especially in time of economic hardships or uncertainty</p>	
<p>Unwillingness to undertake innovative projects by technical staff due to possible personal responsibility and the lack of financial gains or option for promotion</p>	
<p>A limited number of benchmarks mostly due to the unwillingness of industry to reveal energy, environmental and economic data [99]</p>	

Since the EU needs a long-term strategy to increase industrial competitiveness, a framework for building a new decarbonised industry and innovation policy strategy is required [151]. The

actual I&S industry decarbonisation options do not match the ambitious climate goals set by the EC [152], [53]. The gap has been poorly assessed by politicians and the needed counteractions are not in place according to the I&S industry [122]. The EU I&S industry is deeply embedded in the global business chain with the growing use of external subcontractors as part of their manufacturing operations, while changes of technological infrastructure on the national level require significant investments and, more importantly, a harmonised decarbonisation strategy of the whole national economy. This implies the need for tight coordination of actions among the key players in the long run.

There are not “countervailing” policies which would intentionally impede the decarbonisation. The indirect impact is mainly by environmental legislation. The energy efficiency-related directives, e.g. Energy Efficiency Directive [153], Eco-Design Directive [154] exert a weak impact on the I&S industry<sup>9</sup>. The EU ETS much helped to bring GHG emissions to corporate routines and culture and raised priority of the low-carbon technologies in the business hierarchy to strategic importance, e.g. by promotion Energy Management Systems [155]. Similar to the analysis of the EU ETS impact on the power sector [156], research on I&S industry interactions with RES-based energy, chemical industry (RES-hydrogen), and CCSU would bring interesting findings concerning R&D [13].

Unlike other sectors being under decarbonisation, EU legislation is less effective at enforcing the I&S industry decarbonisation by market rules, e.g. energy certificates for buildings, compulsory minimum energy efficiency regulations, appliance energy labels, car emission standards effectively help to support decarbonisation in other sectors. Therefore, the EU should try to use indirect pull levers, e.g. public procurement and recent circular economy regulations affecting main steel-consuming industries, in particular the automotive, buildings and construction [157], [104], [158]. Similarly, to other EIs, energy costs are one of the main drivers of competitiveness for the EU I&S industry since energy costs represent up to 40% of total operational costs. Intensification of markets for a quality product could be done by widening the scope of the Eco-Design Directive, e.g. to better address co-design of products for material efficiency, durability, repairability, reuse, and recycling; public procurement, focusing on sustainable products and product design requirements [122], [5]. Assessing the necessary intervention in the post -COVID-19 economy, it is recommended to increase funding for the acceleration of R&D and roll-out of pilot projects of low carbon technologies, also in the I&S industry, e.g. hydrogen-based steel making [159], [160].

The number of industrial installations covered by the Industrial Emission Directive (IED) and BAT conclusions may serve as metrics of the effectiveness of EU regulation in establishing clean technologies and processes in the industry. The EEA reports that there is continued progress in the number of installations covered by in the I&S industry, 341 in total [123]. A strong link between BATs and reductions in air pollutants achieved was identified. As compared with what emissions would have been based on 2016 steel production data and emission factors from 2012 (per unit of steel produced), emissions of SO<sub>x</sub> had been reduced by 29%, of NO<sub>x</sub> by 14 %, of PM<sub>10</sub> by 25% and mercury by 26% [123].

Decarbonisation of the I&S industry does not encounter hostile coalitions in the EU, however, the roles of the two main actors, namely the EC and the manufacturers, have not been assigned. The I&S industry in the EU does not oppose decarbonisation being aware that the process is unavoidable [122]. However, the I&S industry finds itself “squeezed” by the GHG reduction constantly forced by the EU ETS, global competition, and perceived inability of the

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<sup>9</sup> See for example Concerto Action EED <https://www.ca-eed.eu/Homepage>

EC to protect the EU industry against unfair competition [27], [103], [104]. The main global manufactures may threaten national governments with “carbon leakage” when seeking favourable economic privileges to continue or restore their business. The power of national governments seems to be inadequate and too weak to steer the I&S industry operating domestically towards more innovative transformation than it is due to the EU policies. Therefore, the industry has tabled several postulates to the politician to empower the transformation and let this UE sector to survive [6], [122]. Many of them call for higher support to ITs through fostering the R&D works [121], [134].

The EU steel companies were successful to achieve free allocation in Phases I–III of EU ETS mostly due to effective lobbying. Concerning participation in the EU ETS the I&S industry constantly raises two issues – lack of abatement opportunities and inability to pass through costs. Okereke and McDaniels [161] found that these arguments are only partially supported by evidence because of information asymmetry between the industry and politicians, inherent inappropriateness of adopting political decisions on environmental regulations, and privileged treatment in the EU ETS,

#### 7.4. Networks and interactions

*Table 14. Examples of blocking mechanisms and inducements in the I&S industry in the EU. Category of structural elements: Networks Interactions. Subcategory: Networks. Individual contacts*

Blocking mechanisms	Inducements (enablers)
Improprate internal organisation, e.g. lack of knowledge, lack of capital, incompetent staff, difficulties with knowledge transfer in global companies	Existing public support to EITs, including the I&S industry, through preferable energy prices for industry, tax reduction and exemptions from the energy efficiency obligation (short-term driver)
Poor connectivity among actors due to divergence business interests, lack of channels of communication, convoluted (obtrusive) not fully recognised interlinks often of a global or international dimension	International positive publicity about the I&S industry vs. negative e.g. about the power sector
Uncertain assessment of obligatory changes enforced by politics, e.g. climate or energy	Some well-functioning networks co-operating with R&D institutions, e.g. private research institutions, academia, industrial laboratories
Uncertain assessment of future markets for products manufactured by IT only	High public pressure on diminishing negative impact on the environment
Antagonistic business interests of global business actors despite co-operation in R&D programs and sector associations	The effective functioning of trade chambers, industrial associates supporting ITs
Reluctance to finance industrial networks and technology platforms by main business actors	Building closer links between staff, management, and owners to meet objectives beneficial to all

Despite that all the key elements of the TIS are in place and work towards the low carbon goal, the transition rate is low. Seeking the obstacles, the ambiguous and weak industrial policy towards EII of the EU can be blamed. This entails insufficient R&D public support to make a real breakthrough in ITs in the I&S industry. The global manufactures may benefit from the EU technology innovative system. The EU financed knowledge “leak” through global companies has also to be considered as a braking factor as the companies can control the rate of innovation according to their current business interest. On the other hand, using their R&D capacities, they also support EU research institutions [134].

There are many policies and instruments the effect ITs in the I&S industry. They may embrace energy efficiency, e.g. energy audits, Energy Efficiency Obligation schemes, Voluntary Agreements; energy policy, e.g. energy taxes; environmental policy, e.g. emission taxes and emission permits; financial incentives, e.g. subsidy-based “technology push” instruments, reward-based “market pull” instruments, and access to capital measures; regulatory measures, e.g. codes and standards; information and feedback provision [115], [136], [162]. Their interaction is complex and exacerbates the importance of policy coordination to secure the policies’ effectiveness [163], [133], [164].

The innovation system in the I&S industry unlike such systems in other non-EIIs has not been driven by all customers pressing on radically improved products (“demand-side innovation”) [102]. There are customers demanding quality, but even they do not expect radical improvements due to innovative breakthroughs in technologies. The currently used high-emission technologies are capable to deliver the desired products at highly competitive prices. Therefore, most customers show no direct interest in GHG reduction by the I&S industry and do not squeeze on the manufactures. The creation of the EU market for “green steel” is, therefore, if politically agreed, one of the fundamental steps to radically improve the economic viability of breakthrough technologies. Public procurement (using shadow carbon prices as a bid criterion or setting limits on carbon intensity) and “green labelling” shall become the initial actions. Then, more radical measures should follow, e.g. creation of investment incentives while ensuring “carbon leakage” protection by spreading carbon pricing globally, adjusting carbon prices at the border and stopping free allowance allocation, material “feed-in-tariffs”, contracts for difference, applying consumption charges, promote the recycling of materials, also by extending producers’ responsibility for the management of their end-of-life products. [18], [5].

More attention must be paid to the industrial symbiosis and integration of I&S technologies with other technologies [108], [141], [165], [122]. ITs from the I&S industry have very limited options to diffuse to other sectors because of their specific technology orientation. This limits the circle of their potential users (“market scale”) and does not build up the inter industrial synergy. In the industrial symbiosis, the three most effective symbiotic measures for CO<sub>2</sub> abatement are BF gas recycling, coke oven gas recycling, and BF slag sold to the cement industry [166], [167], [168]. Participation in Demand Side Management (DSM) ideally suitable for EAFs should also be more exploited as a synergy with the power sector.

Conversely, it is predicted that radical technological change to the I&S industry will come from other industries, e.g. with RES-based energy, “green hydrogen” technologies, electrolysis at affordable cost, and economically viable CCSU [44], [9], [145], [169]. CCSU underscores coupling between the I&S industry and the chemical industry [13]. At electricity prices below approximately \$35/MWh, hydrogen use for greenfield steel production sites is more cost-competitive than applying CCS to conventional production processes [8]. More extensive use of EAFs would increase electricity demand. The EUROFER [122] predicts that the demand of the I&S industry for RES-based energy in the EU amounts to approximately

400 TWh a year by 2050 (including for the production and use of hydrogen). This in turn would require public support for RES and hydrogen industries to remain globally competitive [53], [122].

Power grids are getting pivotal for all industries facing the option of intensive electrification. EAF, H-DR technologies are only feasible when the availability and reliability of huge amounts of cheap energy are secured. H-DR gets cost-competitive with an integrated steel plant at a carbon price of €34...68 EUR per tonne CO<sub>2</sub> and electricity costs of 40 €/MWh [170]. This will take advantage for countries with well-developed RES capacity and power systems meeting the standards of the Smart Grid. This requires closer than today long-term planning between the power sector and I&S industry in technical and co-financing aspects to retain energy security of the I&S industry [52]. There is a threat that there may be competition for RES-based electricity among different industries, e.g. transport, chemical. Phasing-out nuclear capacity in some countries shall also be analysed in terms of being replaced by RES-based energy especially in the light of options of use of hydrogen in steel production utilizing nuclear process heat [171]. State ownership of the I&S industry and/or power enterprises poses an interesting challenge of large scale private-public partnership. Novel technological options, e.g. Hot Briquetted Iron from the DRI combined with local RES capacity may lead to a relocation of reduction/pelletisation and steel production sites to avoid power grid congestions [170]. The IEA proposes identifying geographic clusters where key energy infrastructure can be built to support the decarbonisation of industry [172]. Lack of proper sectorial coordination between the I&S industry and the power sector may lead to a shift from process-related emission to combustion-related emission especially in countries with a high share of fossil fuels (coal, gas) in the energy mix [53]. Planning of the power system for a substantial increase in RES is declared as one of the four key policy priorities to foster the EU energy transition [18].

Decarbonisation in the I&S industry may have a far-reaching impact on other industries, e.g. the global coal demand, and, consequently, poses societal problems in heavy steel and coal-dependent regions (“fair transition”) [173], [123]. Alongside efficiency improvements, this means that coal use in the I&S industry declines by around 50 million Mtce<sup>10</sup> by 2040 [174]. Breakthrough transformation in core technology will entail deep changes in the entire supply chain, e.g. coal, gas, scrap, which will have to be restructured around these new methods [5].

Networking within the company or group in the same industry, between industries, and suppliers has been proved important for effective energy management [50]. Internal networking help to exchange ideas and discuss common strategies and future legislation, e.g. on the environment. Industry calls for enabling and incentivization of cross-sector collaboration by supporting consortia with cross-sector technologies, e.g. to enlarge value chains, increase cross-industry cooperation, and to innovate horizontally applicable, integrated solutions and innovation that result in services replacing or complementing existing products. [14]. Public and political awareness needs to be increased by setting up communication channels, e.g. forums and platforms [175].

Okazaki and Yamaguchi [176] investigated possibilities of accelerating the effectiveness of the global voluntary sectoral approach for transfer and diffusion of energy-saving technologies in the I&S industry. The authors claimed that the success depends on the four

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<sup>10</sup> Mtce – million tonnes of coal equivalent (equals 0.7 Mtoe).

factors - sharing of information, the establishment of challenging numerical targets voluntarily, utilize communications, especially among experts, promoting more widespread use of technologies to achieve the set targets, and setting up and sharing of a common long-term vision. The findings show that non-technological factors, difficult to be included in the modelling, play important role in technology diffusion (see also [53]).

The I&S industry in the EU is very well managed and supported by many organisations and platforms which work as lobby organisations, e.g. represent the industry in talks with the EC, co-ordinate EU wide activities, organise R&D programs [14], [83], [12]. The I&S industry should more actively use the opportunity of building a positive atmosphere around the industry by participating in Corporate Social Responsibility programs and “green” labelling the products to receive stronger public support for its decarbonisation needs [177].

International collaboration and industry-government cooperation will be needed to further improve the energy and environmental performance of the I&S industry [68],[9], [178], [122]. In some instances, coordinated action across multiple stakeholders may be required, e.g. sharing best practices driving innovation across industry groups [179].

### 8. Risks and uncertainties

TI development in the I&S industry brings some long-term risks and uncertainties, some of them will become permanent barriers if timely not removed [179], [53]. Bachner et al. [180] studied uncertainties in macroeconomic assessments of low-carbon transition pathways in the EU I&S industry. They show that effects strongly depend on technology choice, prevailing macroeconomic states as well as regional characteristics and to less extent on the underlying socio-economic development and the climate policy. Based on our analyses, we provided a list of risk and uncertainties around technological innovation in the EU I&S industry (Table 15).

Table 15. Risk and uncertainties around technological innovation in the EU I&S industry

Type of risk	Risk Uncertainty	Description/Comments
Policy	Political risks of industrial policy	<p>Ambiguous EC politics about the development of industry in the EU</p> <p>Lack of coordination between main policies</p> <p>Weak and dispersed support for innovative technologies</p> <p>Failure of the EC and MS governments to shape industrial policies towards a low-emission model</p> <p>Insufficient incentives for energy and material savings</p> <p>Looming risk of “carbon leakage” and limited counteraction measures from the EC [53]</p> <p>The unwillingness of MS to support I&amp;S industry because of high GHG emission vs. economic and social insignificance</p>
	Political risks of climate policy	<p>Uncertainty about future climate policy, e.g. the Paris Agreement future and the parties’ commitments</p> <p>Ambitious EU commitment not sufficiently supported by all MSs and other global GHG emitters</p> <p>Possible cascading process of withdrawal after the COVID-19 crisis (US “followers”)</p>

		<p>The low share of costs of pollution in total manufacturing cost, e.g. these caused by the EU ETS</p> <p>No progress in including “external costs” in EILs operation, e.g. in power sector “externalities are not priced”)</p> <p>The continued gap between energy and environmental policies</p> <p>The inclination of some governments to “sacrifice” I&amp;S industry at the price of meeting national climate objectives</p> <p>Symptoms of “silos” among responsible central government bodies (“poor governance”)</p>
Technology	Technological risks	<p>Complete technical failure of some breakthrough technologies</p> <p>Envisaged technological objectives met only partially</p> <p>Wrong technological choices made by governments</p> <p>Limited adoption of standards and labelling by the private sector [136]</p>
	Economic risks	<p>The potential loss of market shares due to failures and delays in IT expected implementation</p> <p>The economic failure of some key innovative technologies, e.g. CCSU</p> <p>The volatility of iron ore, energy carriers and scrap on global markets [181]</p> <p>High and unpredicted costs of R&amp;D work and transition to the demonstrative phase<sup>11</sup></p> <p>Significant difficulties in obtaining commercial financing especially for basic and pre-commercial R&amp;D [136]</p> <p>Large steel demand plunged following a change in the global economy</p> <p>Volatility in financial markets and the vulnerability of emerging economies to a deterioration in financial conditions [12]</p> <p>Lack of “de-risking” instruments to reduce business risks</p> <p>The prevailing market tendency for “cheap products” over more costly “sustainable products” [8]</p> <p>Lack of reliable information, e.g. about future prices and costs, asymmetric information, principal-agent problems, learning by using [136]</p> <p>The tendency to revert from grants to risk financing options for higher advanced developments [120]</p> <p>Lack of clear criteria and a highly transparent set of requirements, procedures, and decision making processes in the public financing schemes [14]</p> <p>Rising protectionism [12]</p> <p>Risk due to post COVID-19 economic crisis [159]</p>
Socioeconomic		

<sup>11</sup> The European business community has asked for the Horizon'2020 Europe budget to be raised to at least €120 billion [12]. Through the analyses they identify some general trends which affect the I&S industry development through the diffusion of technologies.

	Unused funding due to lack of deal flow [136]
	The imposition of trade tariffs by third countries (i.e. USA) that tend to increase the endeavour of countries like China, Brazil or Russia to export more steel to Europe [55]
Societal risk	Prolonged low public awareness on innovation benefits [175]
	The public opinion focused on emissions of the power sector, not prioritising I&S industry
	Public acceptance to import cheaper “dirty product”
	Loss of legitimacy when public financial support is necessary [52]

Source: Own work.

## 9. Conclusions and policy implication

### 9.1. Benefits of TIS approach

The main aim of the analysis was to apply the TIS approach to highlight the actors, barriers, and inducements on the way of the I&S industry in the EU to deep decarbonisation. This paper identifies the key elements of ITs in this industry, and then analysis of the functions of innovation through the lens of the TIS approach. It facilitates more in-depth insight into the highly complex and dynamic political, technological, economic, and societal environment at this climate-decisive moment. The EEA warns “Past trends for resource efficiency, the circular economy, and climate and energy are encouraging; the outlook is less positive” [123]. Our research, integrating a range of technological and non-technological aspects and thanks to identifying the involvement of many actors, their roles, and links among them in the functioning of the TIS, should help to provide guidelines for political decisions. It contributes to a better understanding of sometimes divert interests among actors, to the prevention of duplication of efforts and to avoid excessive costs and stranded assets due to better coordination. This was indeed a challenging endeavour, yet worth taking because of its novelty.

Our TIS analysis is close to the mission-oriented innovation system (MIS) aiming to accomplish a widely shared societal challenge (mission) related to climate change. The notion of MIS defined by Hekkert et al. [164] as “*the network of agents and set of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission*” should increase public awareness of the necessity of low-carbon transformation in the I&S industry and make the relevant R&D higher valued among scholars. Power sector transformation to the Smart Grid concept, EII decarbonisation, stringent energy efficiency priorities, the digital revolution, closing material cycles are rather means than the individual initiative of completing the climate mission [182], [149], [183].

We show that that deep decarbonisation in the I&S industry is feasible but requires firm support, mostly political, to finance intensive R&D and reduce the business risk. To that end, all actors need to come to a common strategy followed by an action plan to realise the decarbonisation vision. They shall support more effectively the further refinement and market implementation of breakthrough technologies.

### 9.2. Politics

The major driving force for the low-carbon transformation in the I&S industry is the strategic vision of the all EU actors of radical reduction GHG emission through innovative technologies, and material and energy conservation [147], [105], [34], [122].

Involvement of the EC and MS governments is a crucial determinant of innovative industrial

technologies [18]. Policy, regulation, and energy price-induced technical change are well-documented drivers for innovative technologies [184]. Public authorities at different levels, including local, are essential players in facilitating the dialogue among parties to set clear visions, mitigate divergent interests, balance costs, and benefits. The “climate” mission is not sufficient for all, especially for “steel dependent” communities, thus it shall be supported by presenting a fair cost-benefit assessment of transformation.

The EC and the MS governments are firstly expected to support ITs by suitable legislation and regulations, e.g. setting realistic pollution limits, creation of “green steel” market, effective use of public procurement, setting material requirements for large steel consumers, reforming the EU ETS, setting barriers against unfair steel import, world’s regulation of scrap trade. The second desired support is to co-finance the decarbonisation under the state aid framework [113]. In this respect, suitable energy prices and financing all stages of R&D, particularly important in the early stages of the innovation cycle, are highly required [18].

There is a persistent state of the informational advantage of the I&S industry over politicians about costs and benefits of climate policy which in the long-term is harmful to both sides – does not enable to set effective and cost-efficient policies and adopt appropriate corporate strategy [161]. More reliable data from the I&S industry and better access to public data banks are essential to eliminate the asymmetry of information among all actors [185], [186]. Modern means of data processing, e.g. big data, Artificial Intelligence, analytics, create opportunities for better economic effectiveness in the whole I&S business chain.

### 9.3. Technologies

The requirements of climate and environmental protection are getting stronger so that incumbent technologies are reaching their inherent limits and lose social acceptance. I&S industry will not be able to get closer to the EU reduction targets unless breakthrough technologies are introduced and prove their cost-effectiveness [89]. Decarbonisation consisting in material and energy efficiency will help, but it is not sufficient to get the reductions needed. Other measures, e.g. organisational, managerial, logistical, business optimisation, can support but the technological breakthrough is a must. Thus, national, and supra-nation support to technology research, development, and deployment play a key role. Politicians should not allow breakthrough innovative investments to be placed outside of Europe [134].

The I&S industry is well suited to benefit from the increased priority of circular economy, e.g. recycle of scrap or utilisation of by-products or increased demand better products from other industries [187]. Reducing total steel demand via a shift to a more circular economy requires inter alia deep changes in the global scrap market [35], [138], [122].

### 9.4. R&D

The rate of diffusion of breakthrough technologies in the I&S industry is not clear [188], [189], [99], [127], [190], [122]. This analysis points to the need to accelerate R&D in the I&S industry to commercialise breakthrough core technologies and increase the role of material and energy efficiency. It also stresses the necessity of more RES-based energy and importance of hydrogen technologies. In addition to a very much needed research focus on the technological side, more research on socio-technical drivers and barriers is needed to manage the transition process successfully [108]. International collaboration and win-win industry-government cooperation will be essential to make a real breakthrough. Domination of China as manufacture and the country’s technological advances shall be carefully watched [191].

### 9.5. Economics

The economics of the transition implies political involvement throughout the whole innovation cycle, from the preferred cost of capital, covering a large share of R&D costs, building energy infrastructure, e.g. electric energy, hydrogen, to the creation of competitive markets.

The cost of deep decarbonisation in the I&S industry is high and therefore perceived unacceptable from a political point of view unless a trustful assessment of the long-term costs and benefits is presented and then accepted by the society which may take years. Therefore, to make the transition viable, the future policies and regulations, e.g. environmental, market, should be far-reaching and encourage investors to employ these today breakthrough technologies and not to conserve the current state. The future economic framework should be conveyed to investors well in advance to avoid stray assets [67].

Many concerns shall be shown to the future impact of the EU ETS on the I&S industry. The ineffectiveness of the EU ETS as a driver for low-carbon technological transformation deters the industry to embark on large innovative projects. The new innovative EU ETS built-in mechanisms are aimed to eliminate this insufficiency [14]. It is postulated that benchmark used as a criterion for public support should be replaced by LCA approach that can better value steel as a recycle product [192], [122]. There should be an incentive for “degree of innovation” which should reward breaking innovations [14].

Our research also suggests that EU policy should be more focused on the development of knowledge-intensive and technologically complex industries, including the I&S industry, as the main factor to retain industrial competitiveness. Such a policy should enable rapid diffusion of technological innovations through the production and distribution networks of global corporations.

This research is addressed to policymakers to elaborate an optimal policy strategy of technological change of the current functioning of the relevant technology-specific innovation system. It should lead to developing, modifying, and deploying the policy framework aiming at improving the functioning of TIS by removing the blocking mechanisms. Identification of structural elements of the TIS, discovering the internal links among them and dynamics of functioning, control input signals, noises (barriers) and feedbacks in the TIS have been done. The authors understand that more in-depth insight requires further research to build a coherent framework for IT and contribute to meeting economic, sustainable, and societal objectives. Further TIS analysis and full risk assessment including technology and market-specific risks would enable knowledge-based public funding granting for I&S projects, e.g. in Modernisation or Innovation Funds of the EU ETS. The research also provided a few recommendations for the managers, e.g. necessity for cost and risk management, the importance of building interfaces, and relations with supplier partners and customers [54].

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### **Annex A.**

The papers we analysed were identified via SCOPUS using the following keywords: “iron and steel production”, “innovative technologies in iron and steel industry”. These were combined into search strings using the “AND” operator. The search was done within the subject areas

of “energy”; “environmental science”; “social science”; “multidisciplinary” and “business; management & accounting”. This search was expanded via a snowballing procedure using the list of the literature of the collected contributions to gather additional sources. The literature on the TIS was gathered by searching standard entries: “entrepreneurial activities”; “knowledge development”; “knowledge diffusion”; “guidance of search”; “market formation”; “resources mobilisation”; “legitimacy”; “legitimation” and “positive externalities”. Additionally, considering a dynamic business characteristic of the I&S industry, the literature search was extended to cover the EC internet resources, political, and business websites. Therefore, the feature of our analysis is its wide scope of the analysed sources and documents, e.g. advisory groups, EU and government-sponsored research projects, industry alliances, which are creating specifications.

The SLR used had some disadvantages, e.g. it relied only on one peer-reviewed database, the combination of the keywords used might miss some relevant papers and institutional insights.

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# Technology Innovation System analysis of decarbonisation options in the EU steel industry

## Highlights:

- Problems, boundaries and difficulties in the I&S industry decarbonization.
- TIS structural components, links and interactions of I&S industry decarbonisation.
- Mapping of functional patterns and evaluation of TIS functionality in I&S industry.
- Blockades, incentives and innovation risks in the I&S industry decarbonisation.
- TIS analysis as a tool for granting public funds for I&S projects.

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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