REINVENT – PROJECT NR 730053

Climate Innovations in the Steel Industry

Deliverable 2.2

Stefan Lechtenböhmer, Clemens Schneider, Valentin Vogl, Cordelia Pätz

2018-10-30

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Abstract

Steel industry is the single biggest emitter of greenhouse gases in industry with high specific emissions – particularly due to the production of primary steel from iron ore. While in the past innovation in the sector was mainly focussed on productivity gains around energy and material efficiency last, years have shown a remarkable emergence of research projects to decarbonise primary steelmaking, together with a certain change in positioning of the industry towards deep decarbonisation.

This shift has shown that technical options are available to deeply decarbonise the sector. They come, however with a number of significant challenges, from technology development and deployment via huge investment needs for completely new technologies for primary steel production as well as significant infrastructure requirements for huge amounts of renewable electricity or for carbon transport and storage. Further these technologies have the potential to change locational factors and configuration of the industry and could result in changes in spatial structures of steel production.

The systemic perspective on the whole steel value chain – which is taken in the context of this work – shows that the integration of the whole steel value chain, i.e. strategies of dematerialisation, increased service efficiency while complete recycling could significantly contribute to a sustainable steel system and might offer new fields of value creation by steel industry if successful in rethinking and designing their market.

Finally, it seems to be clear from the innovation system characteristics of steel industry as well as the size of the challenge that the public sector needs to take an active role and carry a significant share of the investment risks and provide infrastructures for the industry to have a chance to become a low carbon steel industry.

1 Introduction

The REINVENT project serves to study and understand low-carbon transitions in the steel sector and other Energy-intensive Processing Industries (EPI) with high emission levels in the European context[1]. It aims at identifying innovations for decarbonisation by covering the whole production and demand system and includes also the financial sector.

The objective of this report is to provide a systematic review of existing knowledge of decarbonisation potentials and capabilities with a focus on the steel industry. A value-chain perspective is taken on in order to relate the different innovations to each other to analyse their decarbonisation potential. This systemic approach encompasses both technical and non-technical potentials. The review highlights interrelations within the value chain as well as inter-sectoral links. Although the paper focusses on European steel production and demand, steel and steel products such as cars, machines and even steel scrap are internationally traded.

Steel is a core material in modern societies, characterised by high versatility, stability as well as its full recyclability (Pinter 2016). It is essential for construction but highly demanded also by the automotive industry and required for machines and metal ware and others products (see below & Allwood 2016). The properties of steel can be adjusted to fit a wide range of applications by adding alloying elements and through casting and rolling into different shapes and physical properties.

Despite the advantages of steel as a material, the sector is one of the most energy intensive industries, causing 7% of global energy-related GHG emissions (IEA 2017). These GHG emissions are due to the use of fossil fuels as reduction agent and energy source for the production processes: reduction of iron ore, melting of the steel, the rolling, forming and fabrication as well as to the characteristics of steel as iron-carbon alloy (World Steel Association 2018b). The reduction of iron ore in blast furnaces thereby is the largest single emission source, accounting alone for 72% of overall GHG emissions related to the sector (IEA 2017).

The track record of innovations in the steel industry has been incremental and focussed on productivity and efficiency gains. The steel industry is characterised by large companies, high market entrance barriers (particularly to primary steelmaking) and a pressure to merge. The industry typically faces high fixed costs and low profit margins. In combination with long investment cycles the development and implementation of radical innovations has been slow. Focus was mainly put on increased productivity through material and energy savings (Wesseling et al. 2017).

This report firstly provides an overview on the European steel sector, its historical trends and projections for the future (section 2). Thereafter, section 3 provides information on the steel production processes, related GHG emissions and geographical and inter-sectoral relations. Section 4 brings an analysis of the steel sector as an innovation system, drawing on the concept of value chain capabilities. Options and methods for decarbonisation are discussed in section 5 and classified in line with IPCC schemes (Fischedick et al. 2014). Current initiatives on energy efficiency and deep decarbonisation as well as successes in and barriers for innovation are assessed in section 6. In section 7 potentials and barriers of different transition pathways are discussed. A conclusion of the report follows in section 8.

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[1] For more information on the scope of the project as well as other reports please refer to www.reinvent-project.eu.

2 Background

Steel is a core material in modern societies. Historically, after the end of World War II the European Community for Coal and Steel was founded in 1953 by France, Belgium, the Netherlands, Luxemburg, Great Britain and West Germany. It created the base for the set-up of the European Union. This supported the free trade of coal and steel and served the economic post-war recovery. In 1977, European steelmakers established the European Federation of Iron and Steel Industries (Eurofer) (Encyclopaedia Britannica 2018).

The history of steelmaking saw a series of major technological shifts. After 1870, the Bessemer converter, which had been dominating steelmaking, was outcompeted by the open hearth furnace, which from the 1920 lost ground to the electric arc furnace and from the 1960s onwards was replaced by the basic oxygen converter (Åhman et al. 2018). The latter two are the dominant production methods today, often referred to as primary (basic oxygen converter) and secondary (electric arc furnace) steelmaking. These radical innovations, in combination with continuous process improvements lead to significant advances in the energy efficiency of steelmaking, as shown in Figure 2-2-1 (World Steel Association 2018b).

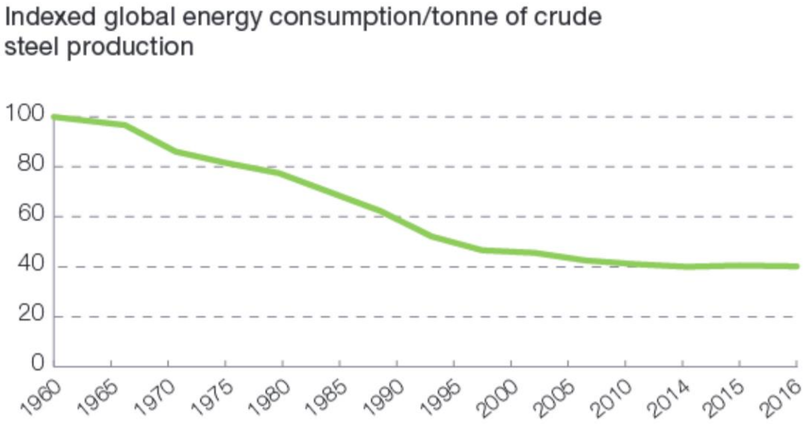

Figure 2-2-1: Historical trend of energy consumption in steelmaking (World Steel Association 2018b).

The European Union is the second-largest steel producer with a share of 10% of global production after China with 50%. The total global production of steel was 1.7 Gt in 2017 (World Steel Association 2018c). Two thirds of European steel is produced integrated steelworks via the blast furnace route (also called primary route), whereas one third is produced from recycling steel scrap in so-called mini-mills (the secondary route). The largest primary producers within the European Union are Germany and France, whereas the main secondary producing member states are Italy, Germany and Spain. The EU steel sector employs over 300,000 people and operates over 500 production sites across 23 member states.

The economic crisis of 2008 affected the steel production only temporarily (Lechtenböhmer et al. 2018). However, 40,000 steel industry jobs have been lost in the years between 2008 and 2013 in the EU (European Commission 2013). Site and furnace closures were reported, for example, from France (Florange) and other sites (e.g. Port Talbot, UK) have been struggling against international competition and the danger of trade tariffs. Bulk steel is typically traded in global commodity markets, while niche markets with smaller numbers of competitors exist for higher performance alloy steels. However, recent international developments have had effects on international trade patterns. An overcapacity of temporarily up to 600 Mt was attributed in part to the rapid expansion of the Chinese steel industry, and led to subsequent oversupply of bulk steel to international markets. Recently, tariffs enacted by the US have changed the market, causing retaliatory actions, for example from the EU.

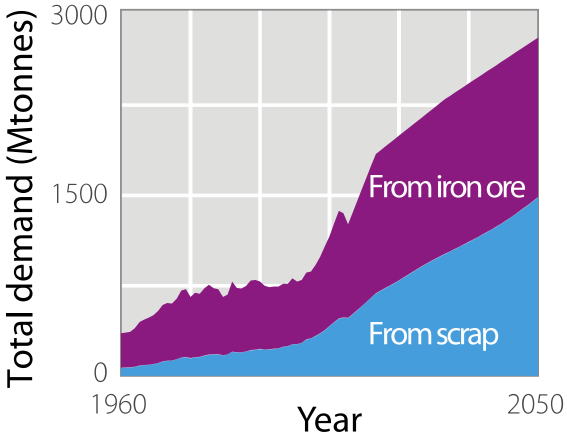

Figure 2-2-2: Total demand for steel from iron ore and scrap in Mt since 1960 and projected until 2050 (Source: Allwood 2016)

Today, yearly steel use in the EU is around 290 kg/capita (World Steel Association 2018c). Since steel products last on average 40 years, the total stock in the EU is around 12 to 13 tonnes per capita. This value, however, could be lowered down to 8 tonnes per capita, if measures of material efficiency and material demand reduction are employed (Energy Transitions Commission 2018; Pauliuk et al 2013b). Depending on the steel grade, the price of steel can vary between 300 and 2000 EUR. An average steel price of 1000[2] EUR/t equals average annual expenditures of 290 EUR/capita (Sekiguchi 2017), and yearly GHG emissions related to steel consumption of 400 kg of CO_2 per capita (Allwood 2016, Pauliuk et al. 2013a).

If downcycling is avoided, steel can in principle be almost completely recycled. It is globally traded as an intermediate product, as part of final products such as cars, machines, or as scrap. While in the 1960s the demand for scrap was significantly lower than today, largely increasing total demands for steel have resulted in increased production volumes of primary steel (from ore) and of secondary steel as well (from increasing amounts of scrap available). For the future this trend in global demand is expected to continue with increasing shares of steel from scrap, likely to surpass steel from iron ore by around 2050 (Figure 2-2). Material Economics (2018a) expect secondary steel production to surpass primary steel production in the EU in the 2020s, thus much sooner than in the rest of the world. According to a study for the Energy Transitions Commission (2018), European steel demand could – in theory – be met with scrap based steel by 2040 under the condition that steel scrap downgrading is avoided and no significant net scrap exports occur.

Most scenarios agree that global steel demand is set to increase during the 21st century. In their often cited study, Pauliuk et al. (2013a) projected development for worldwide steel demand under the hypothesis that "eventually, all world regions will benefit from the same services provided by steel stocks as industrialised countries do today" (p.3449). Figure 2-3 provides the resulting estimates

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[2] Average based on unit values of 2015 steel exports from Germany, France, Italy and Spain, weighted according to 2015 production data.

of global steel demand developments until 2100. Here, the Western European demand is predicted to slowly decrease while old scrap supply will continue to grow. China on the other hand is expected to have the highest steel demand increase, reaching its maximum in 2025 slowly followed by India, the African continent and Latin America.

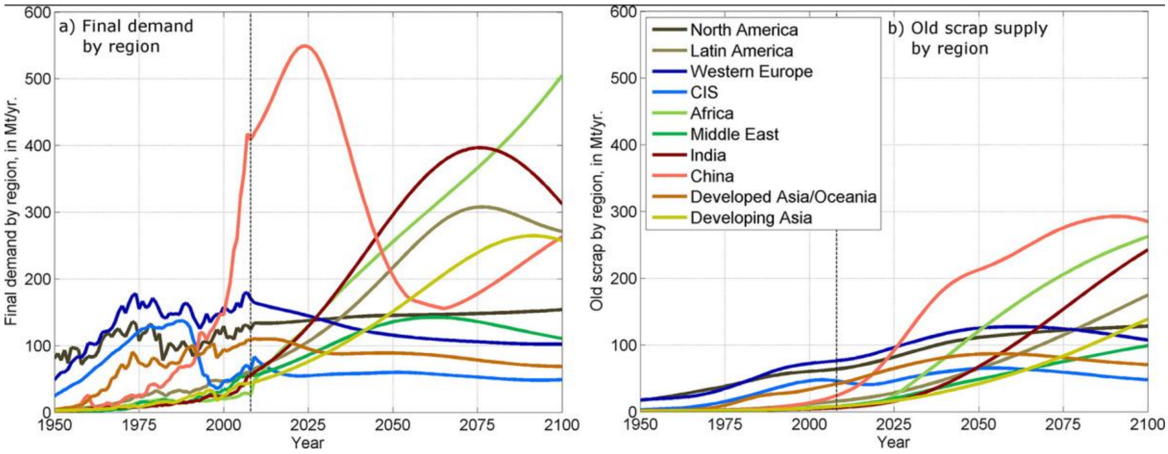

Figure 2-2-3: Historical steel demand and old scrap supply by region (Pauliuk et al. 2013a)

Overall this means that in “saturated” regions such as the EU all steel demand could in principle be sourced by available scrap soon, while expected global growth in steel demand will most probably lead to sustained growth in primary production for several decades.

3 The Steel Value Chain

The REINVENT project aims to take a more holistic perspective on basic materials such as steel. Therefore in the following not only steel industry but the whole value chain from virgin primary steel via products to recycling and secondary steel is described. This holistic overview of the “steel system” shall enable a more comprehensive perspective on potential low-carbon innovations around steel.

3.1 Steel metabolism in Europe

Steel is a widely recycled material already today. In Figure 3-1, a circular perspective on the steel value chain is illustrated. In Europe, recycled steel makes up roughly a third of the input to the manufacturing stage of the value chain. The remaining two thirds are provided by steel made from virgin iron ore, a process which causes ca. 70% of GHG emissions related to steelmaking in the EU (IEA 2017). Main inputs to the primary route are coking coal and iron ore, which are typically imported e.g. from Australia and Brazil, respectively.

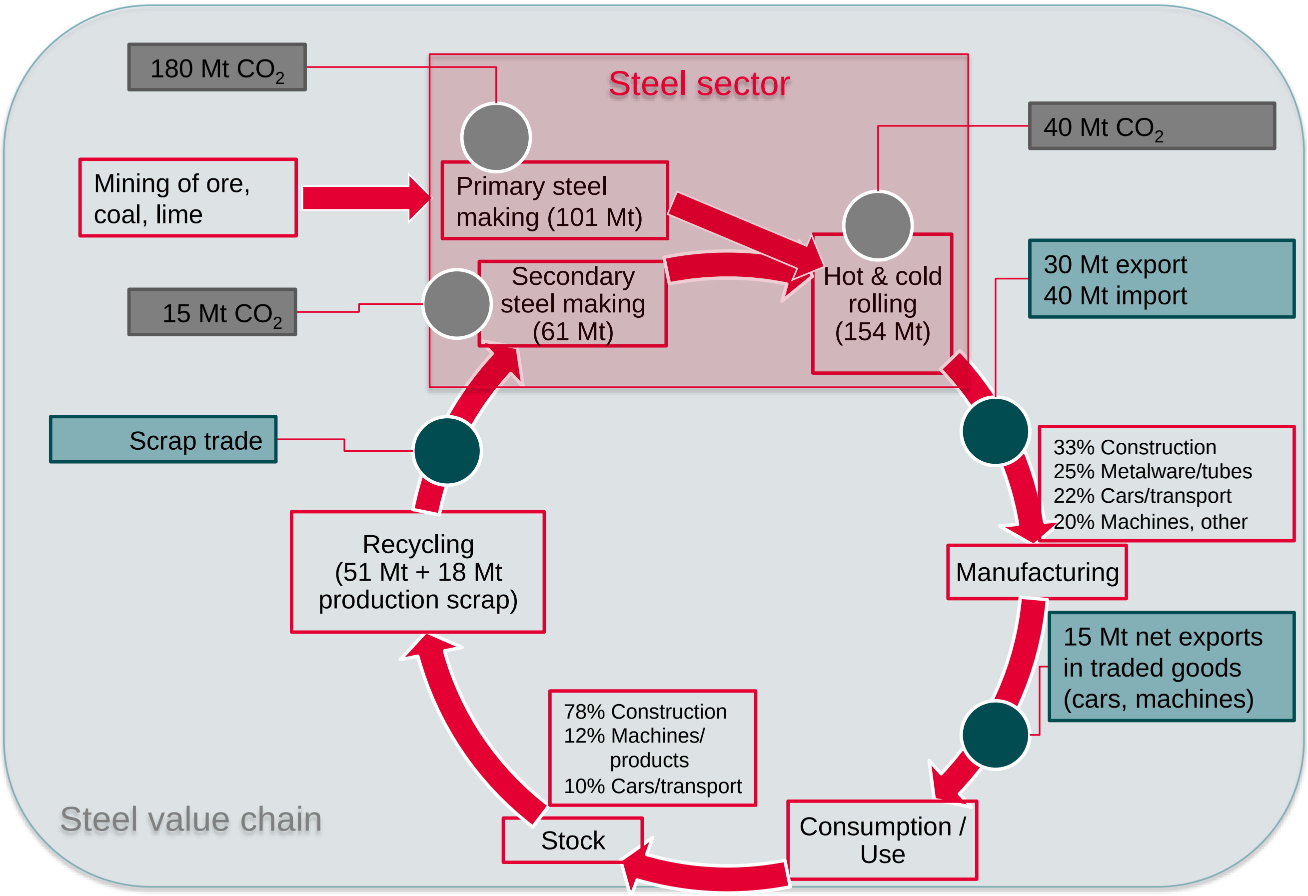

Figure 3-1: Simplified EU steel cycle and CO_2 emissions of steelmaking (Source: Lechtenböhmer & Vogl 2017)

For rolling of steel from both, secondary and primary route, thermal as well as mechanical energy is needed which is responsible for emissions of 40 Mt CO_2 per year in Europe. In the subsequent manufacturing stage, finished steel is processed into end-user products. Together with net imports of 10 Mt of rolled products overall about 154 Mt steel available for fabrication in the EU of which about one third is used for construction. Less than a fifth go into automotive, machines and metal ware (Figure 3-1).

As most of the goods manufactured from steel have rather long lifetimes the steel is estimated to remain for on average 40 years in use (Allwood 2016), which makes up for the so-called steel stock. The EU steel stock is estimated at around 6.5 Gt currently. Due to the long lifespan of buildings and infrastructures, construction makes up for 78% in steel stock and only 10% are vehicles and 12% machines and other goods (own calculation based on Pauliuk et al, 2013)[3]. Of the stock currently around, 50 Mt per year reach the end of their service life and are recycled as input mainly into secondary steelmaking.

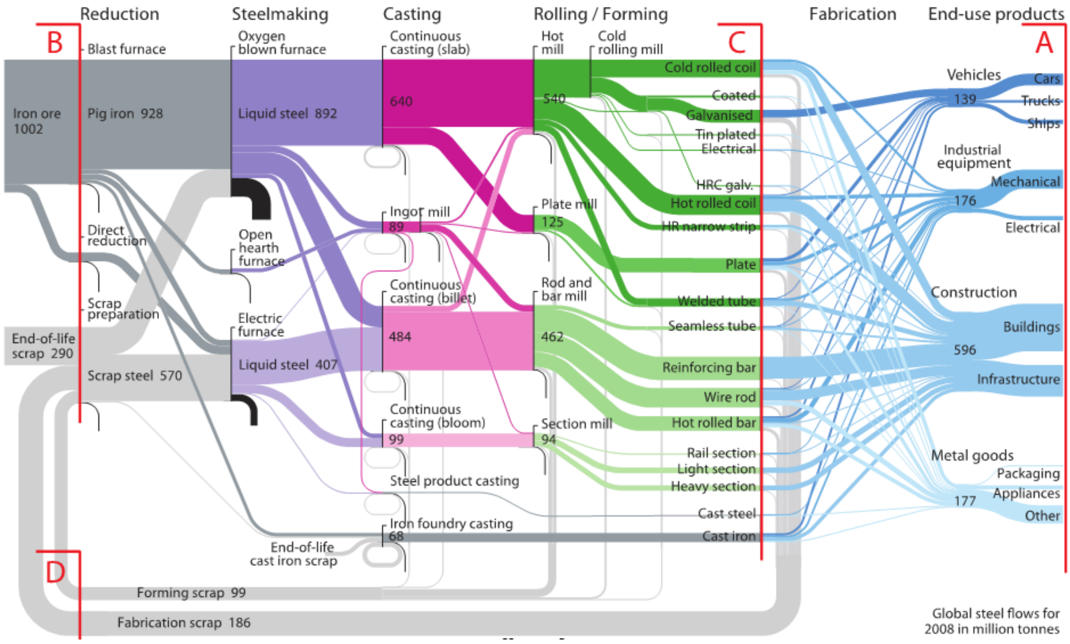

Figure 3-2: Global steel flow chart from 2008 (Cullen et al. 2012). A: steel usage in end-use products.
B: One third of liquid steel is from scrap, 50 % of which is currently occurring during manufacturing. C: Intermediate products. D: 25 % of steel is returned as scrap from manufacturing.

In all steps of the steel value chain international trade is important. Large quantities of steel are either exported directly as finished steel, or indirectly as parts of manufactured goods. In direct exports Europe has high comparative advantages for flat products such as tin plates, hot-rolled sheet and strip, as well as for long products such as pipes and tubes, rails and sections (Sekiguchi 2017). EU exports tend be of higher value-added than its imports, such as for example large amounts of ingots and semi-finished steel coming from Russia and Ukraine into the EU (Sekiguchi 2017).

Globally, 290 Mt end-of-life (or old) scrap and 285 Mt production scrap (186 Mt fabrication scrap and 99 Mt forming scrap) were recycled in 2008. Cullen et al. (2012) have illustrated this is their study of global steel material flows. On the other hand, in the EU end-of-life scrap is dominant over fabrication scrap. This indicates the already huge steel stock in the EU which results in high amounts of old scrap available as well as low growth rates in steel production and use as compared to the

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[3] Allwood (2016) gives roughly comparable values for the UK (buildings and infrastructure: 70%, industrial equipent: 13%, vehicles 12%, metal goods 5%).

global situation, an effect that is further underpinned by net scrap exports from the EU to other countries.

3.2 Production routes from extraction to scrap collection

Figure 3-2 illustrates the diversification and specialisation of the process technologies throughout the value chain. Globally, 93% of the iron ore was reduced with carbon monoxide in blast furnaces to pig iron, while only a fraction was directly reduced to sponge iron by using natural gas (methane) as energy carrier and reduction agent. In primary steelmaking, the pig iron is then liquefied in oxygen blown furnaces together with significant amounts of steel scrap. Most of the scrap is, however, processed in electric furnaces for secondary steelmaking, then making up for one third of the total liquid steel as of 2008. Global production levels were around 892 Mt of steel primary and 407 Mt in secondary steelmaking in 2008.

In the subsequent continuous casting processes, slabs from primary steelmaking and billets from primary as well as secondary steelmaking represent the most relevant casting products preferred over blooms, ingots and cast iron. In rolling, 1,221 Mt of steel were shaped worldwide, mainly in hot mills or rod and bar mills. Cullen et al. (2012) further show that the cast steel from primary steelmaking is mainly formed into hot rolled or hot and cold rolled coils, which are galvanised, plated or tubed, whereas secondary steelmaking steel is preferably formed into reinforced or hot rolled bars and wire rods. The steel used in automotive industry, mainly comes from the primary steelmaking route, whereas for buildings and infrastructure more steel from the secondary steelmaking route is used. Coils, reinforcing bars and wire rods were most common in use for construction, which demanded 596 million tonnes of steel, which is equivalent to 55% of the global steel used.

3.3 Geographical and sectoral interactions

Alfred Weber formulated his “Theory on the location of industries” (1909) based - among others - on the development of the steel industry since the mid of 19th century as the locations of the production sites of the steel industry have historically been determined largely based on minimisation of the transport costs. Today, however, steel industry can be split at least into three main types, with at least partly different locational factors. These are primary steelmaking, secondary steelmaking and rolling as the first step of processing the steel.

In the case of **primary steel**, the raw materials iron ore and coal are many times the weight of steel. Next to some other material like limestone for the production of one tonne of primary steel today around 1.6 tonnes of ore, 0.2 tonnes of scrap and roughly 0.6 tonnes of coal are needed. But with earlier technology the coal demand was significantly higher with more than one tonne of coal per tonne of steel. Therefore the production sites developed during industrialisation were based on existing ore and coal mining and/or cheap waterways to transport resources.

These historical structures can still be detected today in form of concentration of a small number of “old industrialised” steelmaking regions, mainly co-located with (actual or former) coal mining regions like the Rhein-Ruhr region (Germany) or Ostrau (Czech Republic), Wales (UK) and Gijón (Spain). Almost a century later, during the 1960s and 1970s, some new primary steelmaking sites have been developed based on cheap transport due to the access to a port. Examples are Dunkirk, Fos-sur-Mer, Ghent and Ijmuiden (Figure 3-3).

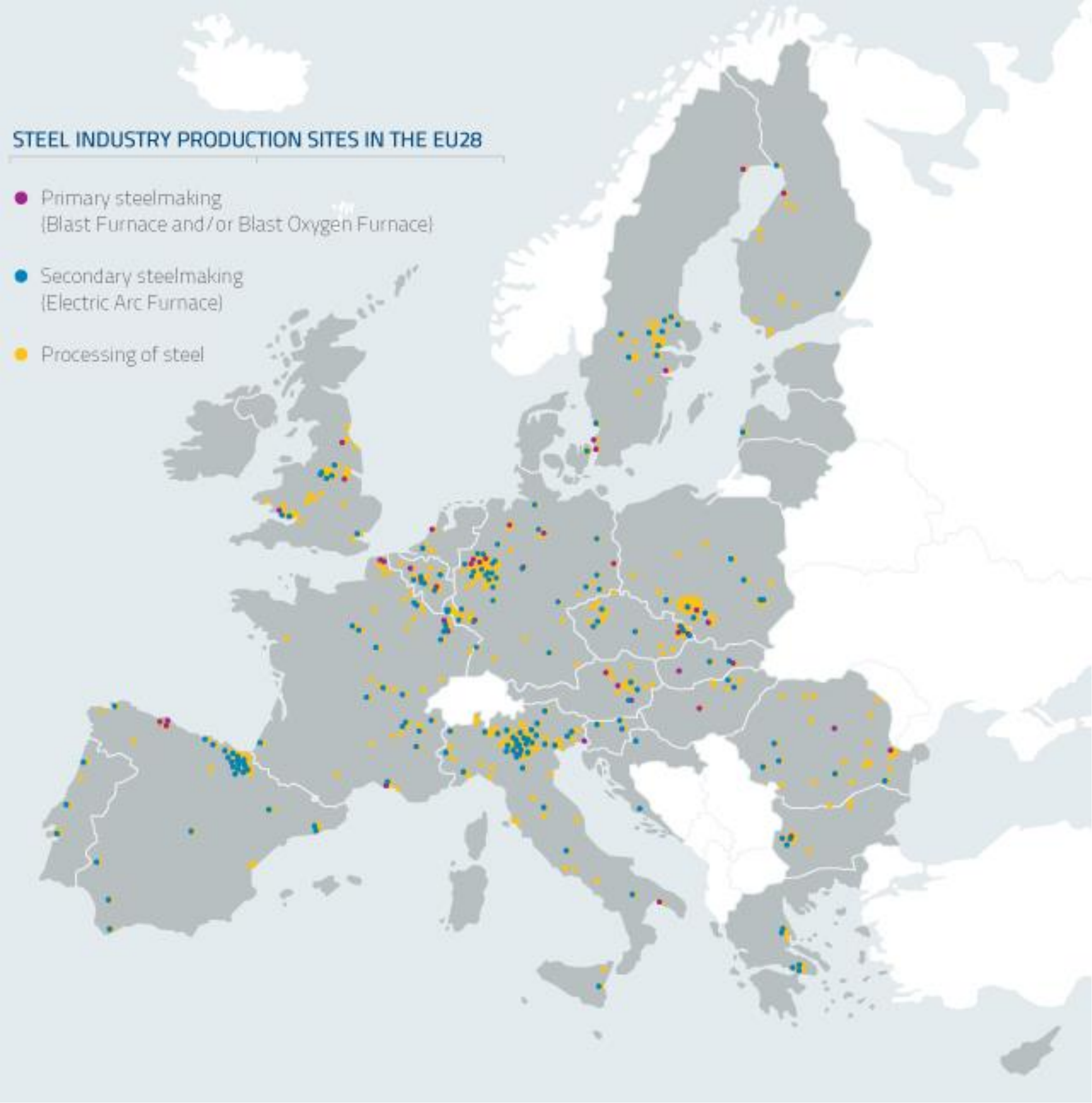

Figure 3-3: Steel industry production sites in the EU28 (Source: Eurofer)

Secondary steelmaking production sites with Electric Arc Furnace are much more widespread within the EU28 yet clustered as well in industrial regions. Secondary steelmaking is based on scrap using around 850 kg of scrap plus around 300 kg of other hot metal as main resource inputs for one tonne of steel produced. This leads to a material index close to one i.e. market orientation is much more important for secondary steel, which means that it is produced in industrial regions as well as other agglomerations where steel demand for construction and manufacturing is high – and typically also scrap is available for the same reasons as steel is demanded.

Steel processing sites can be found in the previously mentioned clustered regions as well. These clusters are partly close to industrial and economic core regions but mainly located in short distance to the demand side, the customers such as the automotive or construction industry as well as near metropolitan regions. This is also due to factors two and three of Weber's theory: (1) cheaper, cost-saving supply with steel for the low value to weight ratio production and (2) the historically grown availability of know-how, access to infrastructure in the regions and closeness to the demand side and to sources of scrap. The largest clusters of solely secondary steelmaking plus processing sites are North-Eastern Spain and Northern Italy.

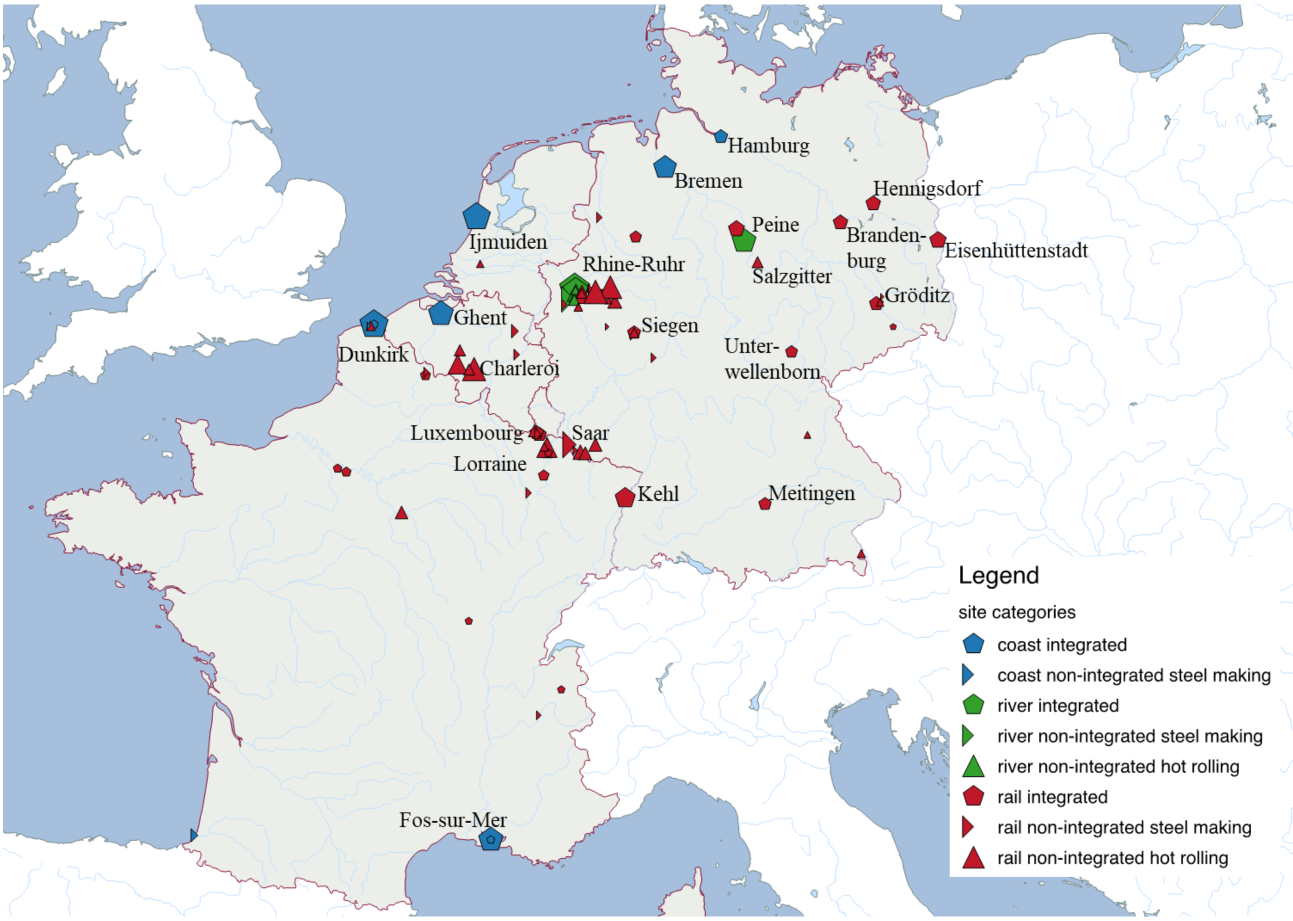

Figure 3-4: Steel production in NWE by site type (Schneider, 2018). coast: supply via sea ship/barge possible; river: supply via inland navigation possible; rail: supply via railway; integrated: primary and or secondary steel mill with hot rolling at the site; non- integrated: either steelmaking or hot rolling separately

A closer look at Germany, France and the BeNeLux in Figure 3-4 provides insight on the structural characteristics of the steel production sites. First vertical integration differs between the sites: there is (1) isolated crude steelmaking, (2) isolated hot rolling sites and (3) vertically integrated sites. Integrated sites are defined here as such sites “where the maximum of crude steelmaking, and hot rolling capacity does not differ by more than 100% from the minimum of both values” (Schneider 2018). The size of icons indicates the site’s capacity in tonnes of product per year.

First, all steel sites require fully developed transport infrastructure to be profitable. In the case of the assessed countries the observation from Figure 3-3 above is confirmed such that the sites are either found at the coast with access to freight ports or along rivers, canals and railway inland. At all coastal steel sites like Dunkirk or Hamburg steelmaking and hot rolling are integrated for reasons of cost efficiency through scale and marine transport. Similarly, river based (wet) inland sites allow for integration and great volumes. Large-sized rail based steel sites, i.e. without seaport or waterway, are mostly non-integrated and do hot rolling only. Many of these are former integrated sites in former mining regions that lost their primary production due to ceasing of coal supply and/or the overall concentration process in industry. Exemptions are integrated secondary steelmaking sites with railway transport near Paris and in southern and eastern part of Germany where they are of significantly smaller capacity compared to primary sites. These descriptions show that steelmaking has not only changed technologically but also locationally – in recent decades mainly due to concentration processes and less do to technology change[4]. In the future, however, changes in steelmaking e.g. due to decarbonisation of steel production by new technologies (see following section) as well as due to higher shares of recycling will probably change locational factors of steel industry and may influence future distribution of steelmaking in the EU.

As mentioned above secondary steel production is typically located close to steel demand in the larger industrial and metropolitan regions while also the traditional primary steelmaking regions are industrial clusters with high demand as well. Within the primary steel production, there are system interactions, mainly with the cement sector and the electricity sector. Blast furnace slag has become an input substituting limestone feedstock for bricks as well as for clinker in cement making, thereby reducing material based emissions from cement making. Further waste gases from primary steelmaking provide heat and electricity. The European steel industry association estimates total effects of these interactions on GHG emissions to around 60 Mt of reduced CO_2 emissions (EUROFER 2013). Rather new are interactions with the plastics sector through, for example, approaches like Carbon2Chem (Thyssenkrupp AG). In this project waste gases from steelmaking are collected and cleaned for the production of chemicals.

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[4] Giarratani et al. (2015) describe how the introduction of electric arc furnace (EAF) and basic oxygen furnace (BOF) as former disruptive technologies has changed the geographical distribution of US steel industry and the emergence of new players in the 1970s and 1980s.

4 Capabilities Review: Innovation system of EU-steel industry

In order to study the past as well as the potential for future innovations in the steel sector, in this section the steel industry is conceptualised as a sociotechnical and innovation (ST&I) system. To this end, the work by Wesseling et al. (2017) is referred to, who identified common characteristics of energy-intensive processing industries (EPIs). The innovation system of EPIs can be described along five core characteristics: Industry structure, innovation strategies, networks including knowledge infrastructure and technology providers, markets and government policy. Figure 4-1 provides an overview of the characteristics for typical processing industries with a focus on this step of the value chain. In many aspects, the steel industry can be seen as a prototype EPI with typical barriers and limits to innovation and change.

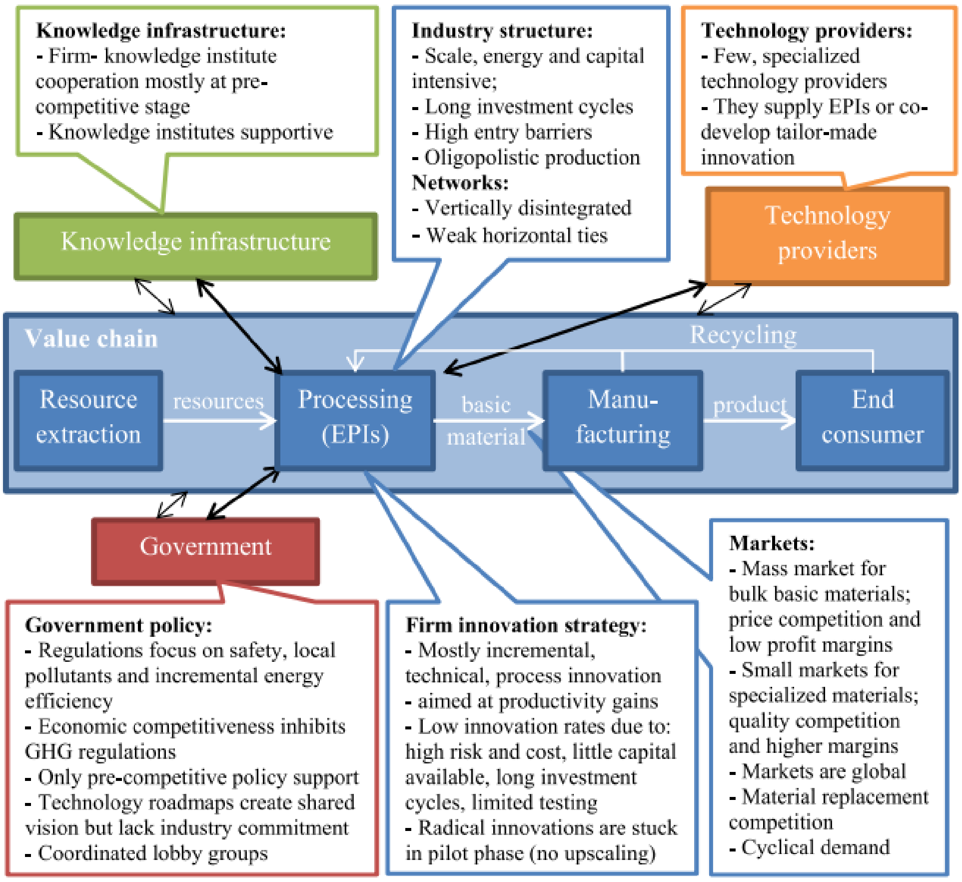

Figure 4-1: Overview of the different structural components of EPIs and their characteristics (Wesseling et al. 2017).

4.1 Industry structure

The steel industry structure features typical characteristics of EPIs as there is intensive production in scale, energy and capital. This is generally due to the very high thermal demand of the primary iron- and steelmaking process steps, and the high economies of scale connected to these. Consequently, fixed costs are often relatively high and can be reduced through efficient energy use with larger production volumes per installation. Integrated steel plants producing steel from ore are typically larger in scale than mini-mills using scrap.

The products of EPIs are further subjected to tough price competition and cyclical market changes, leading to generally low profit margins. This leads to long payback periods and investment cycles. The large investment costs impose high entry barriers to new market entrants, especially for integrated steel plants. In combination with repeated fusions of steelmaking companies in the past the industry is characterised by oligopolistic structures.

4.2 Innovation strategies

In EPIs, new technologies are usually integrated into the existing structures and plants because of the long investment cycles and high-entry barriers for potential new competitors. The investments that were made in the steel sector need to pay off over long periods and therefore the existing structures are highly persistent. Consequently, the probability of novel technologies and processes being implemented is often limited.

Predominantly, incremental innovations with typically smaller and stepwise effects such as productivity increases, energy cost reduction and more efficient material use have entered the markets. The risks and uncertainties of radical innovations on the other hand often require appropriate financial savings to deal with setbacks and failure. This is a challenge in the context of low profit margins and reason for many radical innovations to remain on experimental scale (see also section 6). However, future technological progress in low-temperature-steel-making and possible better economic feasibility of specialised small scale production might offer potential for the market to open to new players.

4.3 Networks

Networks of EPIs tend to play a more important role than in other industries. With its historically strategic relevance which lead to the foundation of the European Community for Coal and Steel the industry has retained a number of specific joint institutions and dedicated (research) funds.

Research and development are often brought forward through collaborations with technology providers and research institutions. At pre-competitive stage, the networks usually include market competitors in publicly funded projects where the high risks are shared leading to the co-development of innovations. An example for this was the ULCOS initiative, where most European steelmakers participated. However, after ULCOS ended and some of the technologies were brought to higher technological maturity, the previously seen broad collaboration between competitors ceased. Instead, a patchwork of different piloting and demonstration projects emerged (see section 6). A reason for this could be that issues of intellectual property gain importance as the technological readiness advances.

The steel industry is represented by a variety of industrial organisations at different scales: national, European Union-wide as well as globally. These organisations often report production data and publish strategic industry documents such as roadmaps. Within the EU, a high-level round table was convened between 2012 and 2013 to advise on the future of the European steel industry. Currently (2018), an updated roadmap by the European association Eurofer is being prepared. Globally, the OECD steel committee as well as the G20 and OECD overcapacity forum bring together governments to address pressing trends in the sector.

4.4 Markets

There are two types of market in the steel industry. On the one hand, the general market for basic material is characterised by strong and global competition at volatile prices with low profit margins, leading to bulk sales. Price premiums for low-CO2 basic materials have not yet become established on the market. On the other hand, there are specialised materials markets, where lower volumes are traded in smaller market segments. Less price-oriented competition allows higher profitability at higher quality. Specialised markets are often based on custom-made products and trust between the cooperation partners. The steel industry typically operates in intermediate business-to-business (B2B) markets and is therefore subject to little pressure from final customers.

4.5 Government policy

Government intervention is characterised by strict regulations focusing on local pollutants and safety rather than GHG emissions. EPIs are often characterised by governmental support of the industry's economic competitiveness in an international context. As a result, regulations tend to be limited to incremental action such as energy efficiency measures. Similarly, the international competition has previously led to the protection of steel industry players through free allocation of emission allowances under the European Emission Trading Scheme (EU ETS). Free allocation is motivated by the fear of carbon leakage, which is the out-migration of industry from the EU due to an international imbalance in regulation, in this case carbon pricing. Therefore, demand-side and consumption-focussed policy instruments have been discussed recently to reform the ETS and alleviate this problem (e.g. Neuhoff et al. 2014). Further research into the use of demand-side policies such as public procurement or quota-certificate schemes could aid to resolve the issue of carbon leakage.

Additional support is provided by funding of pre-competitive innovation stages. Governments are influencing the focus of R&D in the steel industry by offering public funding and the willingness to balance risks. In Europe, Horizon2020 and the upcoming Innovation Fund are examples of such funding schemes. As the time between proof of concept and full scale demonstration of a new process is very long in EPIs, special attention needs to be devoted to demonstration projects. These often require large funding, but outcomes are uncertain as unforeseen events are common due to the increasing scale of operations.

To support research and upscaling, the European Commission drove forth a revision of the Emission Trading System (ETS) in 2015, which included the idea to implement an Innovation Fund with a budget of 450 million Euro to be invested in demonstrational activities for the decarbonisation of EPIs (Jernkontoret 2018b). Experts and representatives of the EPIs were consulted to determine the innovation needs of and potentials for low-carbon pathways in the industry. A summary report with results was published in June 2017. Independent of the EPI type, there was a consensus that such a fund would need to be highly transparent and clearly communicated decision processes. Particular needs for the steel sector were mentioned as well and include emission efficiency strategies like DRI based on hydrogen and the recycling of steel. However, the top-listing of energy efficiency indicates remaining hesitation of the industry's representatives regarding the implementation of radical innovation. (Climate Strategy and Partners 2017).

For the steel industry there have been significant carbon emission targeting research programs and activities over recent decades already, which will be carried on probably with even stronger impetus in the future:

CO_2 Breakthrough program

The World Steel Association started a research initiative in 2003 named ‘CO2 Breakthrough Programme’, targeting coal, hydrogen, electrons, biomass and CCS developments. Research supported in the EU includes ULCOS (Carvalho 2010).

ULCOS

Major decarbonisation R&D has been brought forward in the framework of the Ultra-Low Carbon Steelmaking (ULCOS) programme, which was launched in 2004 (European Commission 2018b). Funded by the EU, know-how has since been channelled and developed in cooperation of the steel and energy industry, manufacturers and research institutes; in total 48 European entities (Climate Strategy and Partners 2017). HISARNA and ULCOWIN are examples for the resulting innovations (Birat 2010). After the end of the ULCOS initiative in 2015, a multitude of research projects developing initial ULOCS ideas further has emerged.

Horizon 2020

Another instrument for innovation support is offered by the European Commission through the Horizon 2020 program. On the one hand, it includes the focus area ‘Building a low-carbon, climate resilient future’, which was budgeted for 3.3 billion Euro until 2020 and aims to support the achievement of targets in the Paris Agreement and the UN Sustainable Development Goals (European Commission 2018c). On the other hand, the European Innovation Council was initiated within the program, endowed with a budget of 2.7 billion Euro for three years until 2020 to support radical innovations from SMEs but multinational companies as well (European Commission 2018d).

Most recently, plans have been proposed by the European Commission for a program by the name of Horizon Europe, succeeding Horizon2020. This includes a budget of 100 billion Euro for a duration of 8 years until 2029. (European Commission 2018a).

SPIRE

The SPIRE (The Sustainable Process Industry through Resource and energy Efficiency) roadmap of the European Commission is an approach to address the capability challenges of EPI’s with networks. Particularly Public Private Partnerships (PPP) are proposed. The project complements the HORIZON programme (A.SPIRE 2013).

HYBRIT

An operating PPP project is the joint venture of the companies SSAB, Vattenfall and LKAB in the forerunner project HYBRIT in 2017 (Jernkontoret 2018). The HYBRIT project is supported by the Swedish Energy Agency by financing 50 % initial feasibility studies and a research programme in cooperation with Swedish academia worth 11.2 million €. The aim here is to build one of the first pilot plants with renewable energy-fueled hydrogen steelmaking by 2020 (Simon 2018).

5 Strategies and Technologies for Decarbonisation

As described in section 4, GHG mitigation options in the steel sector exist along the whole value chain from mining (not included here), through primary steelmaking, manufacturing and consumption to recycling in secondary steelmaking. These options comprise more than pure technological options and can be classified according to the IPCC (Fischedick et al. 2014):

- Emissions efficiency (e.g., from switching to non-fossil fuel electricity supply, or applying CCS to cement kilns);
- Material efficiency
  - Material efficiency in manufacturing (e.g., through reducing yield losses in blanking and stamping sheet metal or re-using old structural steel without melting);
  - Material efficiency in product design (e.g., through extended product life or de-materialisation –product design);
- Product-Service efficiency (e.g., through car sharing, or higher building occupancy);
- Service demand reduction (e.g., less individual mobility switching from private to public transport, sustainable consumption);
- Energy efficiency (e.g., through furnace insulation, process coupling, or increased material recycling).

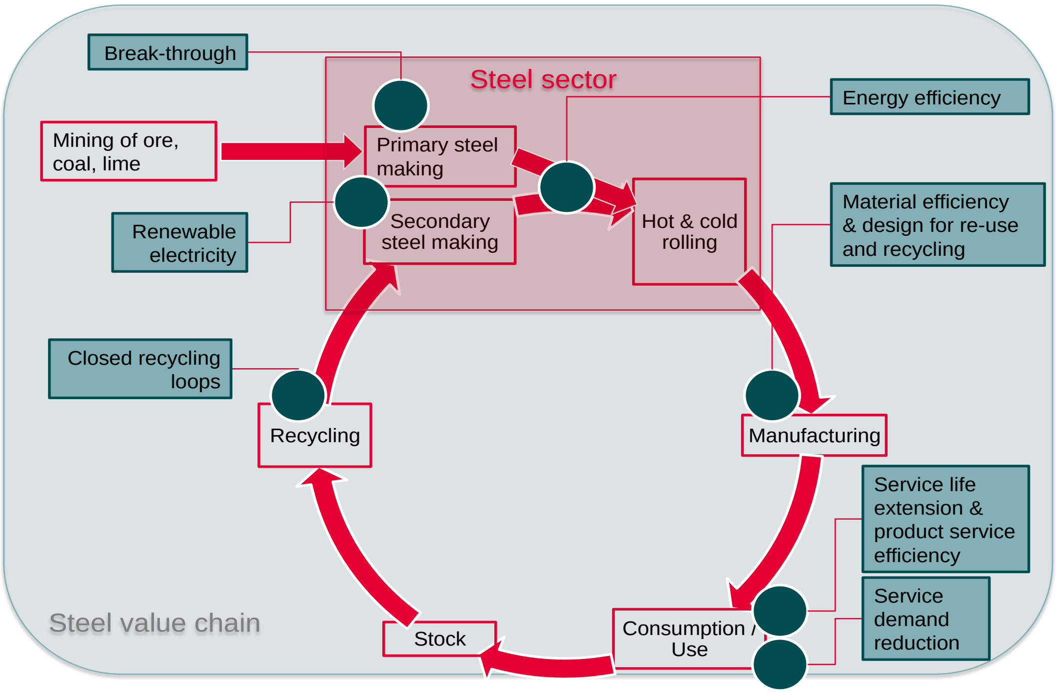

Figure 5-1 GHG mitigation options in steel value chain.

Options and methods for decarbonisation are described along these definitions in this section. Furthermore, Figure 5.1 (GHG mitigation options in steel value chain) provides an overview of the steel value chain with the localisation of the potentials types for decarbonisation. It is used as a base for the following subsections.

5.1 Emission efficiency

In line with the IPCC framework (Fischedick et al. 2014), emission efficiency is understood as shift of energy supply technology towards low-carbon energy along the steel value chain. Today, the steel industry mainly uses fossil fuels to provide energy for chemical reactions as well as heat. In primary steelmaking, coke is the main energy carrier, but also natural gas, coal and sometimes oil are used. In secondary steelmaking, electricity is used to melt scrap, with additional supply of natural gas into the furnace. For downstream metal works such as rolling, high amounts of heat are necessary to bring the product into the desired shapes. In addition, natural gas and electricity are used in all parts of the value chain.

To decarbonise the steel industry fuel switching towards renewable, low-carbon and clean energy sources are relevant along the whole steel value chain. High-temperature heat can be provided with bio-based fuels or electric heating technologies. Furthermore, a low-CO_2 steel sector depends on the decarbonisation of electricity grids. Due to the large amounts of energy required in the steel sector, the widespread use of bio-based energy would require large amounts of biomass and could lead to further environmental problems as well as competition with other sectors with similar intentions. Instead, if heating can be electrified, the focus of bioenergy use could move to sectors such as aviation, where bioenergy is currently without alternative for renewable energies (Energy Transitions Commission 2018).

However, only a small share of GHG emissions from the steel industry can be reduced through switching to renewable fuels. The mechanical strength of coke in the blast furnace is crucial to its operation and coke cannot be substituted by renewable fuels in large installations. As blast furnaces are the main emission source in the steel industry (70%), more radical changes to the process are necessary to reduce GHG emissions to a significant extent. These alternative processes are typically referred to as breakthrough technologies, such as electrowinning, hydrogen direct reduction (H-DR), as well as carbon capture and storage or utilisation (CCSU).

5.1.1 Electrowinning

The direct electrolysis of iron ore fines into iron is called electrowinning. The process was developed under the ULCOS initiative under the name ULCOWIN, and is currently being scaled up under the name SIDERWIN. Electrowinning runs purely on electricity, which means it can be close to CO_2-free when connected to a decarbonised power grid (Weigel et al. 2014). Recent research aims at developing a low-temperature modular process, which can be run flexibly to balance variable power loads.

Electrowinning presents an alternative ironmaking process to the blast furnace. For further processing of iron into steel, a connection to an electric arc furnace plant is required. Thus, existing mini-mills could be upgraded with electrowinning plants to increase the share of virgin iron in the process, or iron from electrowinning could be bought and transported to existing EAF sites. The modularity and low temperature of the process might have the potential for small scale, decentral steel production. However, research has not yet been reported on an alternative steel system based on small-scale, local production.

However, converting the complete EU primary steel production to electrowinning would roughly need 260 TWh of renewable electricity for current levels of primary steelmaking (see Lechtenböhmer et al. 2016). Such an amount (almost double of total current German green electricity production) would need significant investment in generation and transmission.

5.1.2 Hydrogen Direct Reduction

Hydrogen direct reduction (H-DR) refers to the use of green hydrogen in the direct reduction process (Vogl et al. 2018). In today's direct reduction processes, natural gas or coal are used, whereas H-DR uses hydrogen produced from renewable sources. Due to the big scale of hydrogen production necessary, electrolysis is expected to be the main process for hydrogen production. Iron ore pellets are reduced to direct reduced iron (DRI), also known as sponge iron, in a direct reduction plant. Carbon is added to the process either in the pelletising or in the direct reduction process. DRI has to be stored in special vessels, as it tends to re-oxidise quickly under atmospheric conditions. However, DRI can be compacted to hot-briquetted iron (HBI), which allows for longer storage but reduces the porosity of the iron product. DRI or HBI are then transformed to steel in electric arc furnaces, where also scrap can be added to the process (Vogl et al. 2018).

H-DR runs mainly on electricity and can thus be almost CO_2-free (Weigel et al. 2014; Otto et al. 2017). The process offers various options for flexible production and could be used to balance renewable power loads (Vogl et al. 2018). Recent analyses suggested production costs slightly higher than those of current integrated steel plants (HYBRIT 2018). However, low electricity prices and a high carbon price, as well as the increased use of scrap in the process can improve the competitiveness of H-DR significantly.

Several European steelmakers have initiated projects aimed at developing the H-DR process. The Swedish HYBRIT project and the German SALCOS initiative have announced step-by-step plans to replace existing integrated sites with arc furnaces and H-DR plants. The project H2FUTURE aims at developing electrolysis for the use in steel plants.

DR plant and EAF do not necessarily have to be located at the same site. HBI could be produced where access to renewable energy and iron ore pellets is good. The produced HBI could then be transported to existing mini-mills or even integrated sites, reducing the need for iron ore shipping. As an intermediate good it is lighter and easier transported than iron ore. The shift towards trading of HBI rather than ore could offer new conditions and changed location factors. Longer transport distances may become more competitive. From a decarbonisation perspective, this would result in (1) an increased need for decarbonised shipping, but at the same time (2) provide new independency in the location of sites and (3) enable to utilise carbon-free energy where sources are optimal. Another advantage for the trading of HBI would be that global market structures of steel and iron could be used, and value can be added with higher potential profit margins in primary and secondary steelmaking.

Finally, however, hydrogen based steelmaking would need similar amounts of electricity as electrowinning (around 260 TWh for current production levels), or import large amounts of hydrogen via seaports from abroad or via pipelines from ports or EU production hubs e.g. in the North-Sea[5].

5.1.3 Carbon capture and storage or utilisation (CCSU)

In a steel context, Carbon capture and storage (CCS) refers to the capturing of carbon dioxide in the exhaustion air of the industrial steel plants. CO_2 has to be first separated from the off-gas stream, before it can be stored. Options for storage of carbon dioxide are underground storage on land or ocean storage, enhanced oil recovery and as well as the conversion to minerals and subsequent storage of these. Once stored, the integrity of the storage sites must be maintained in order to avoid

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[5] See a discussion on the infrastructure needs for such strategies for North-Rhine-Westphalia in Schneider & Lechtenböhmer (2018).

leakage of CO_2. In some member states public acceptance is low, or CCS is even forbidden (e.g. Austria).

In contrast to electrowinning and H-DR, CCS could be added to existing integrated sites without replacing the blast furnace. However, spatial restrictions and the complexity of integrated steel plants makes this option costly and technically sophisticated. CCS has the potential to reduce emissions from steel plants by 60% at an additional cost of 81 USD per tonne of CO_2 (IEAGHG 2013). For further emissions reductions abatement costs increase as several more exhaust pipes have to be equipped with CO_2 sequestration units (IEA 2017). Thus, CCS probably constitutes a very expensive option for deep decarbonisation.

An emission reduction potential of up to 80% could be achieved to apply CCS on the novel iron- and steelmaking process HIsarna. With its roots in the ULCOS initiative, HIsarna is currently (2018) being demonstrated in the Netherlands. The core feature of the process is the combination of iron- and steelmaking in one process unit, which has only one exhaust pipe, requiring only one unit for CO_2 sequestration. Without CCS, the process emits 20% less GHG than a conventional BF/BOF process. Although HIsarna, such as all CCS applications, is not fit for reaching zero emissions, it can play an important role as a bridging technology.

Compared to electrowinning and H-DR, CCS offers no co-benefits next to emissions reduction. Thus, several current industry projects aim at the utilisation of captured CO_2 (CCU). This would require large amounts of hydrogen, as carbon dioxide is very stable and needs large energy input to react. The basic product from CCU with hydrogen is methane, which can further be processed to many different substances, for example methanol, ethanol or polyurethane.

5.1.4 Increased share of secondary steelmaking

As European steel demand has saturated the availability of scrap increases over time (see section 2). Thus, one decarbonisation option that relies only on known technology is the conversion of BF/BOF sites to scrap-based steelmaking. In this way, current locations and jobs could be preserved, while emissions would reduce significantly. The extent of the achievable GHG emissions reduction increases with the supply of low-carbon electricity, as the main energy carrier for steel recycling is electricity. Another precondition is the availability of clean scrap without impurities such as copper (see below). An advantage of mini-mills is the potential synergies it has with the before mentioned technologies of electrowinning and H-DR. Iron produced in these CO_2-free processes can be added according to the desired steel properties or to dilute copper-contaminated steel scrap.

5.2 Material efficiency

5.2.1 Material efficient production and design

Material efficiency includes the approach to circularity (Fischedick et al. 2014). Its aims are

- to reduce yield losses and minimise scrap in manufacturing and/or
- to achieve extended product life, reduced weight or de-materialisation by product design (Fischedick et al. 2014).
- Furthermore, product re-uses, high-quality recycling and the consideration of links to other sectors are part of material efficiency.

Modular design and single material design can help with achieving these goals. Production and design are strongly influenced by the actors of the wider value chain. However, the low resource costs as opposed to high labour costs remain challenging (Wesseling et al. 2017). Remanufacturing and reuse cycles should preferably dominate over recycling and demand for new products (Energy

Transitions Commission 2018). Milford et al. (2013) developed emission scenarios and found that increases in material efficiency have the potential to reduce emissions in the steel sector significantly by two thirds in combination with optimised energy efficiency improvements.

In commercial buildings, for example, the amount of steel used can be significantly reduced, while at the same time ensuring safety requirements, and to extend the lifetime of buildings from on average 60 to 80 years (Fischedick et al. 2014). This potential emerges from a general overuse of steel in buildings by a factor of two which could be reduced by building in less components, and the implementation of material-efficient-shaped steel structures. However, due to high labour costs in production, low prices for steel and the recyclability, material efficiency has not been focused on in the past (Allwood 2016).

In order to enable high recycling rates and prevent downcycling of steel, it is important to not only reduce steel losses, but to prevent downcycling of scrap steel. Particularly, copper is a problem for material quality that leads to downcycling. Copper is typically not added deliberately as an alloy element, but origins from the un-separated recycling of products containing both steel and copper components (Material Economics 2018b). To date, the state of the art practice in dealing with copper is to dilute the contaminated scrap with high-quality “virgin” scrap and to then produce downgraded lower-values construction steel. Due to the high global demand for construction steel there is a significant market for such lower qualities which to date do the absorb scrap mixed with copper (ETC 2018). It is argued that European steel demand could soon be completely covered by the available amount of scrap within the EU if mixing with copper and other alloys can be avoided. For the European domestic market that could mean that hardly any primary steel would be necessary (Energy Transitions Commission 2018). On a global scale, however, primary steel will be needed for many decades as long as material stocks still grow.

Recycling also needs also to be supported by product design and technology innovations towards tracing the materials and better handling and sorting of scrap, sensitive to contamination for separation of copper in steel (Material Economics 2018b). Furthermore, chemical separation is an option currently under research as well as technologies like Direct Strip Casting (DSC), which aim at increasing tolerances in the steel production (Energy Transitions Commission 2018).

Moreover, some types of steel scrap like underground pipes are often abandoned, adding up to steel losses of about 6 Mt annually worldwide. Similarly, losses accrue from low collection rates of steel in for example consumer goods and although the amount of steel in each product is small it adds up to substantial amounts (69 Mt/year). Therefore, steel losses could be reduced by more systematic efforts to recover all the material (Material Economics 2018b).

The reuse of fully functional steel components can stop losses from re-melting and contamination of up to 5 % or 22 Mt/year. In total, material efficiency is estimated to have the potential to reduce CO_2 equivalent emissions from global steel production by 20% until 2050 and 29 % until 2100 compared to a baseline scenario (Material Economics 2018b).

Another option to achieve less demand for primary steel could be the setup of a structure for steel reuses. Fully functional steel parts should be built into new buildings and thereby saving CO_2 through avoiding redundant recycling through melting (Lechtenböhmer et al. 2018). In combination with material efficiency it is estimated that the CO_2 emissions from global steel production could be reduced by 52% until 2100 compared to a baseline scenario (Material Economics 2018b).

5.2.2 Material substitution

The substitution of steel with aluminum, plastics, carbon fiber or wood is often possible, but the respective pros and cons need to be weighed regarding alternative product durability, functionality, environmental impact, and other aspects. The material mix of the produced goods are also important for its re-usability and recyclability. However, substitution might also occur by the replacement of other materials by steel, e.g. due to its good recyclability. As an example, the automotive industry could generally use plastics for the car bodies or more lightweight aluminum. However, meeting the safety standards for the protection of the passengers in accidents as well as recycling might then become a challenge. Nevertheless, the perspective of autonomous driving in the future offer a wide scope of new opportunities. In total, substitution of materials potentially adds to the decarbonisation potential but the effects of material choice need to be carefully taken into account in the respective (low carbon and circularity oriented) design processes. Therefore no general effects of material substitution can be estimated.

5.3 Product-service efficiency

Product-service efficiency increases with higher amounts of service during the service life of a good produced from steel. To achieve this, ideas include increased sharing systems for cars, tools etc., and the extension of product life-cycles through flexibility, multi-purpose use and modular design. One example for steel is that car-sharing would allow drivers to choose the appropriately-sized car according to the actual needs, potentially saving steel and fuel resources via resulting higher shares of smaller cars in the fleet and fewer cars overall (Fischedick et al. 2014).

5.4 Service demand reduction

Service demand reduction refers to reduced use of steel products. Most of the steel worldwide is stored in buildings. However, over the last decades the occupancy per capita continuously increased and so did the steel demand per person. Reduced service demand would be achieved when the housing needs of people were to be met with lesser occupied space per person. Similarly, car ownerships could become redundant when public transport systems satisfied the needs for mobility. For decarbonisation demand reduction is a potentially very effective strategy, and needs to be further developed. The lower the demand, the lesser production would be necessary, and the more CO_2 emission could be avoided (Material Economics 2018b).

5.5 Energy efficiency

Energy efficiency is the increase of productivity via reduced energy consumption. Due to the productivity aspect, energy efficiency potentially saves costs and increases short term competitiveness. As mentioned before, most ongoing research and innovation is centered around – typically incremental – improvements in technology and operation. Recently discussed major energy efficiency technologies in steelmaking are gas recirculation techniques in the blast furnace like Top Gas Recycling (Otto et al. 2017), which can be combined with CCS, hot charging or insulation improvements in ovens. The reduced use of fossil fuels is energy efficient and saves CO_2 emissions.

In spite of its high benefits, energy efficiency tends to be insufficient as an exclusive strategy to achieve full decarbonisation. Changes through productivity increases in EPIs are mostly ranked in this category: mainly technical, incremental innovations (Wesseling et al. 2017). Continuous information programs, energy audits, subsidies and regulations for the implementation of state-of-the-art technology add to the instruments for improved energy efficiency (Fischedick et al. 2014). In the steel industry, future energy efficiency is estimated to result in limited remaining potential for decarbonisation, a 15% improvement potential in OECD and 20-25% in non-OECD countries is expected to remain by 2050 (Energy Transitions Commission 2018).

6 Current Initiatives

This section provides an overview of recent innovations in the steel sector. They are distinguished between those, which have entered the market already and others which are still under research. The innovations are categorised by their efficiency focus in line with section 5.

6.1 Market-ready and implemented Innovations

Historically, innovations in the steel industry have followed typical EPI industry patterns (see section 4). From the innovations identified within the REINVENT project in this section 20 innovative processes and products are discussed that that have already entered the market, as shown in Figure 6-1. Distinguished by their efficiency type, it can be seen that a large share of innovations target material and energy efficiency gains. Often new steel grades and high value-added products are in focus. There is only one process each but no product that could be identified as emission efficiency and efficiency in demand reduction. Amongst the few product-based innovations found, the majority focuses on increased productivity and cost saving through material efficiency in manufacturing.

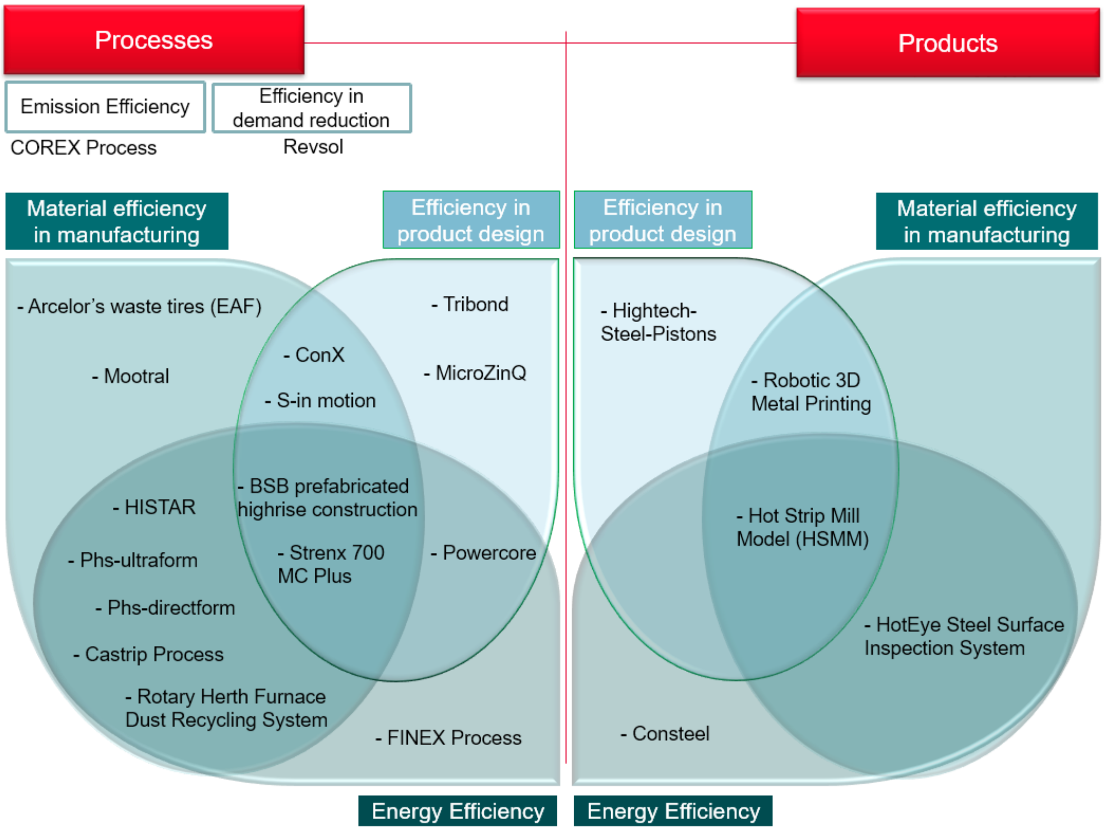

Figure 6-1: Implemented innovations in technological processes and products in steel industry categorised by their efficiency focus. For more details on each of the innovations, visit the Reinvent innovation database: https://www.reinvent-project.eu/documentation/

However, less then half of the innovations identified in the REINVENT database are focused particularly on CO_2 reduction:

- Consteel®
- Mootral
- MicroZinQ
- S-in motion
- BSB prefabricated high-rise construction
- Rotary Hearth Furnace Dust Recycling System
- Arcelor's waste tires in EAF
- phs-directform®
- phs-ultraform®

The following funds and investors are supporting the identified projects in the steel industry, even though a particular emission reduction focus could be identified for only two of them (listed first):

- EIB 25 % Commitment (emission reduction focus)
- Institutional investors group on climate change IIGCC (emission reduction focus)
- World Bank Green Bonds

- Task Force on Climate Related Financial Disclosures
- NYC Pension Fund Divestment
- Ceres Investor Network on climate risk and Sustainability
- Research Fund for Coal and Steel (RFCS)

6.2 Recent innovations under research and development

In spite of the so far strong focus on incremental innovations there is currently a series of ongoing research projects aimed at increasing the emission efficiency of steelmaking as summarised in Table 6-1[6]. All identified initiatives are concerned with technological development and scale-up, except one non-technical initiative by the Swedish steel association Jernkontoret (see below).

A number of these interventions focus on the innovation of carbon-free primary steelmaking technologies, a pathway which has been termed carbon direct avoidance (CDA) by Eurofer. These technologies are: hydrogen direct reduction (H-DR), electrowinning and hydrogen plasma reduction. Several other initiatives work on innovation on the so called smart carbon usage pathway (SCU), which includes technologies that capture and use CO_2. In addition, we identified one technology that aims to improve emission efficiency of integrated steelmaking without separation of CO_2 from the off-gas stream.

A large amount of actors from companies and research is involved in ongoing research projects. While not all, many of the companies operating integrated steel works in Europe are part of at least one of the undertakings. Funding comes both from European programmes such as H2020, SPIRE, RFCS and FCH2-JU, but also from national sources in Sweden, France, Austria and Germany, as well as from the companies' involved. Most projects focus on pilot or demonstration scale today.

Two more trends can be identified from the variety of projects. Firstly, many interventions rely on electrolysis and CO_2-free hydrogen production, or aim at developing this technology. To develop this on the large scale necessary for the decarbonisation of the sector, large amounts of electricity are needed. Next to this, correspondingly large amounts of oxygen will be available as a side-product. Thus, improvement of electrolyser technology is of great importance for these projects. A second

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[6] For recent stocktakes of innovations in the steel sector: Axelson et al. (2018) and the IEA initiative 'Tracking clean energy innovation progress' https://www.iea.org/tcep/innovation/

trend is the increasing connection of steel industry to the chemicals sector, with projects investigating the production of methane, ethanol, methanol, polyurethane, ammonia and ethyl acetate (Carbon2Chem, Steelanol, FreSme, VALORCO, Carbon4PUR, i3upgrade).

The outlier to the identified ongoing initiatives is the effort for societal value creation by the Swedish steel association Jernkontoret together with Stockholm Environment Institute. The objective of this project is the development of a toolbox for the assessment of societal value within the Swedish steel industry. The project is a follow-up to a first part that used explorative scenarios to study the role of the national industry in a global context (Hallding et al. 2015). The result was a 10 point action plan for societal value creation (Hallding & Blixt 2017). The second project maps out the UN sustainable development goals (SDGs) to study their interactions and the effect Swedish steelmaking has on them to create a societal value compass. Initiated by the progress in the projects, the Swedish steel industry has adapted a long-term vision for 2050 in which it aims that all products and by-products from the steel industry shall have societal value.

Table 6 - 1: Current European R&D projects on Emission Efficiency Innovation

Innovation Technology	Companies	Research institutes	Reduction potential	Main R&D subject	Funding	Planned progression
DRI (Hydrogen)						
HYBRIT	SSAB, LKAB, Vattenfall, Sandvik)	Lund University, SEI, KTH, Swerea MEFOS, SP, Luleå Tekniska Universitet	fossil-free	Fossil-free value chain (2045)	Swedish Energy Agency, companies	End of demo 2035
SALCOS	Salzgitter AG	Fraunhofer	up to 85%	H2-enriched DRI		Full implementation 2040
GrInHy	Salzgitter, Boeing, sunfire	VTT (Finland), Politecnico de Torina, ipm (CZ)		High-temperature reversible electrolyser	EU H2020 FCH2-JU	
H2FUTURE	voestalpine, Verbund, Siemens, Austrian Power Grid	K1-MET, Energy Research Centre of the Netherlands	min. 80%	PEM electrolyser	EU H2020 FCH2-JU	6 MW PEM electrolyser by 2021
SuSteel	voestalpine	K1-MET, Montanuniversität Leoben		Hydrogen plasma reduction		reaching demo scale 2019
Electrowinning						
SIDERWIN	ArcelorMittal, Cockeril, Electricite de France, CFD Numerics,	Funacion Tecnalia Research & Innovation, Universidade de	87% of direct emissions	Low-temperature direct electrolysis of iron ore	EU H2020 SPIRE	TRL 6 by 2022

	Quantis, Mytilineos Anonimi Etairia, N-Side, Dynergie	Aveiro, NTUA, NTNU			2017	
CCS/CCU						
Carbon2Chem	ThyssenKrupp, Clariant, Siemens, BASF, AkzoNobel, Evonik, Covestro, Linde	Max Planck Institute for Chemical Energy Conversion (MPI-CEC), Fraunhofer UMSICHT,	20 Mt CO_2/y; 50% of emissions from process gases	Ammonia and methanol production from steel gases; catalyst development	GER - BMBF	Large-scale before 2030
HIsarna	Tata (ULCOS), RioTinto, ArcelorMittal, ThyssenKrupp, voestalpine, Paul Wurth		Up to 80%	Up-scaling of smelting reduction process	Tata Ijmuiden	Demo starting 2020
Steelanol	ArcelorMittal, Primetals, Lanzatech, E4Tech		LCA needed	Fermentation of steel off-gases to produce Ethanol	H2020 Low Carbon Energy	production of 65,000 t/y of ethanol in 2019
STEPWISE	SSAB, Kisuma Chemicals, Johnson Matthey, Amec Foster Wheeler, Tata Steel Consulting	Energy research center of the Netherlands (ECN), Politecnico Milano, Swerea Mefos, Universitatea Babes-Bolyai	Steelmaking CO_2 intensity below 0.5 t CO_2/t steel	Demonstrate sorption enhanced water-gas shift reaction for CCS from steel off-gases	H2020 Low Carbon Energy	
FreSme	SSAB, Tata Steel, Carbon Recycling International, i-deals, Stena Rederi, Kisuma Chemicals, Array Industries	ECN, Swerea Mefos, Kemijski Institut, Politecnico Milano	80% of BF emissions	Use of methanol produced from steel off-gases to fuel a ship	H2020-LCE-2016-RES-CCS-RIA	End user demo 2020
VALORCO	ArcelorMittal			CO_2 separation in amine process CCU to Ethylacetate (fermentation), methanol	ADEME	move to demonstration phase in 2020

Carbon4PUR	Covestro, ArcelorMittal, Recticel N.V., South Pole Carbon Asset Management, Grand Port of Marseille, PNO Consultants, Megara Resins S.A.	Dechema, TU Berlin, Ghent University, Leiden University, RTWH Aachen, Imperial College London, French Atomic Energy and Alternative Energies Commission	20-60% CO_2 reduction in PU production	Polyurethane production from steel off-gases	H2020-SPIRE-2017	
i3upgrade	voestalpine, Air Liquide	Universität Erlangen-Nürnberg, Central Mining Institute (Polen), Montanuniversität Leoben, K1-MET, Centre for Research and Technology Hellas, Scuola Superiore Sant'Anna		Enrichment of steel off-gases with hydrogen from electrolysis to produce methane.	Research Fund for Coal and Steel	2021 proof of concept on laboratory scale
Process Optimisation						
IGAR	ArcelorMittal		0.1 – 0.3 t $_{CO_2}$/t steel	plasma torch technology to reform steel plant gases and inject them in the blast furnace, replacing coke by electricity.		Full size system 2022

7 Pathways to Decarbonisation

Drivers and barriers of a low-carbon transition of the steel sector are highlighted in this section through looking at the steel industry as a socio-technical system, focussing on agency, and power, geographical and material aspects (Figure 7-1). Rather than looking at the transition of the industry from a typical production focus, this systems approach can yield new insights into the dynamics between inertia and innovation.

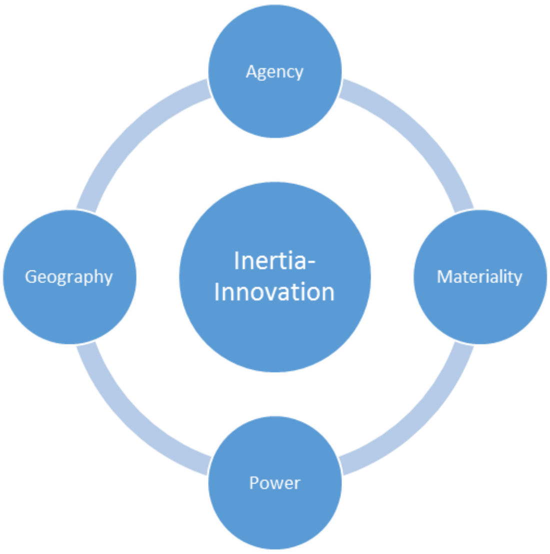

Figure 7-1: REINVENT conceptional framework of low-carbon transitions (D 1.3)

Section 4 identified steel as a prototype energy-intensive process industry (EPI), capital-intensive with economies of scale. Consequentially, the incumbents are few (and declining, due to mergers and concentration) and barriers for new entrants are very high, so that the transition most likely has to involve today's incumbents. Scale, energy and capital intensity in combination with low profit margins, long investment cycles and uncertain prices in a mass market have led to high barriers for radical changes, high risks and limited testing.

While the position of the European steel industry towards decarbonisation has changed since their last roadmap in 2013, only few forerunners have announced clear step-by-step transition plans for decarbonisation until 2050 (Eggert 2018, EUROFER 2013b). However, new cross-sectoral coalitions have formed and engaged in relatively large technology development projects within Europe (see previous section). There are still large uncertainties concerning the systemic implications of scaling up proposed breakthrough technologies. Although initial efforts have been made, no common or overall target for decarbonisation has been accepted in the European steel industry. This complicates policymaking, as new technologies are not sufficiently assessed to be able to formulate clear targets and policies to support a low-carbon transition. Besides missing targets, new sectorial couplings as well as the issue of how to define green steel present challenges for policymaking.

A low-carbon transition in the steel industry could follow different pathways, which all require fundamental changes to existing production facilities, especially to the blast furnace and basic oxygen furnace route which is currently the dominant (primary) steelmaking route.

- Carbon capture and storage (CCS) offers the possibility to modify existing production without having to replace the main elements of production. It might act as a bridge to lower-carbon production technologies, but is not enough for achieving zero carbon emissions.

- In contrast, electrification of primary steelmaking can be a long-term solution, but requires fundamental changes to existing production facilities. However, it has strong synergies with steel recycling. The conversion of integrated sites to scrap-based production could be a first step towards later electrification of primary production (or purchasing of "green" iron). The fundamental changes required could entail large potentials for industrial symbiosis through, for example, using excess oxygen and heat.
- In order to create a sustainable steel value chain from a societal perspective both production side technological pathways, CCS and electrification, need to be complemented by measures of material and energy efficiency, as well as product-service and service-demand efficiency. If less material and energy are lost in the value chain and primary steel production could be decreased at the same time, emissions can be reduced. Rebound effects might limit this potential and have to be treated carefully. As part of the strategy mix a switch towards more scrap-based steelmaking could reduce emissions significantly, especially if it co-evolves with decarbonised power grids. Therefore, improving material efficiency and recycling and in particular keeping scrap clean from impurities such as copper is crucial in all pathways. From a business perspective the last strategy has particular challenges, since markets for primary steel would need to decline. Compensation for that might come from extending business cases around throughout other parts of the value chain.

Depending on the pathway pursued different implications on geography, materiality and the agents involved can be identified.

- Using CCS and the use of carbon dioxide will shape new connections between the steel and the chemicals sector. The CCS path relies on the availability of CO_2 transport and storage infrastructure.
- Going for electrification instead could tie the industry closer to the energy sector, as large possibilities of flexibility and grid balancing could be used.

Both pathways depend strongly on developments and expertise in electrolyser technology, as well as on a high carbon price and a solution for handling the carbon leakage problem.

The high demand for renewable electricity and hydrogen in both pathways will have to be met by large installations of renewables capacity, but offers spill-overs due to the potential use of hydrogen in other parts of the economy. Current European production sites are not unequally suitable for electrification options (including CCU), as some are faced with good renewables conditions while others are highly concentrated in areas with limited renewable energy potentials. A conversion of some of the disadvantaged sites to scrap-based steelmaking and the outsourcing of primary steelmaking to more advantaged places is one of the systemic pathways that could ease this discrepancy.

Inertia-Innovation dynamics will be crucial in determining the timing and speed of the transition. Many technologies are still under development, and it is not yet clear which will make it to commercialisation and when. Industry and politics both share a large interest in keeping current production sites intact. Public concerns about the safety of CCS or hydrogen have to be dealt with when choosing a technological path. Public and NGO pressure on steel companies using coal has not been witnessed yet, although it appears to be increasing in the coal power sector. The steel industry is operating mainly in business-to-business markets and so far there is very little end consumer pressure for greener steel. Although in principle well established, there has not been significant progress in the fields of recycling and material efficiency in recent years.

Market introduction of breakthrough technologies requires large investments in scale-up and demonstration. Despite un-successful experiences in attempting to support CCS under the NER300 scheme (e.g., halting the planned CCS project at the Florange steel plant in France) (Friedrichsen et al. 2018, Duwe and Ostwald 2018), public support will be required in the transition, not only for technology R&D and deployment but also for the necessary infrastructures for CCS or electrification, which would both be significant if primary production is converted.

Further, “green” primary steel produced without fossil carbon emission would most probably be more expensive – as long as carbon costs remain low or non-existent for steel industries globally – than conventional steel from competitors or abroad, while possibly having little or no benefits over conventional steel. Therefore markets need to be ready to take up low carbon products at higher prices. Here, for example, potential demand-side polices to create niche markets for CO_2-free steel and need to be explored further (Åhman et al. 2018). The establishment criteria and labels for “green steel” could be one of the instruments to increase the impact of customer choice and public procurement. It further helps to raise awareness amongst the customers for differences in not only steel quality but production and carbon footprint as well. Public procurement for low carbon steel or emission quotas for steel in products (e.g. cars) would be other policy instruments to foster markets. Design for material efficiency and product service efficiency could also help, as they would reduce the amount of steel used in a product or for service and by this might compensate for higher costs of material input.

8 Conclusion

The characteristic barriers of innovation in EPI's such as e.g. steelmaking are most importantly high capital costs, low profit margins at uncertain price levels, and consequently long investment cycles with low risk-taking and incremental innovations. Despite these, research and development for low-carbon technologies is continuing to grow, mainly through public support programs such as Horizon 2020, the Innovation Fund, the Research Fund for Coal and Steel or SPIRE, as well as national funding bodies. Some co-operations with a focus on decarbonisation and support from research institutes already exist. However, extending these to all levels along the value chain is essential for the deep decarbonisation of the industry.

While the steel sector has been implementing energy-saving and therefore cost-reducing innovation over the last decades, emission efficiency potentials in the primary steelmaking – which accounts for almost 90% of GHG emissions from crude steel production in the EU – are far from exhaustion.

- DRI with hydrogen from electrolysis, electrowinning and CCS are amongst the discussed and presented technology options for emission efficiency.
- Strategically promoting and increasing scrap-based steelmaking has the potential to reduce sectorial emissions as scrap availability is set to increase in Europe. This includes better recycling strategies in order to avoid downgrading of the steel.
- Material and energy efficiency, as well as using fewer products more intensively, must be at the heart of decarbonisation. This offers high potentials for GHG mitigation but needs to be complemented with new business strategies by steelmakers (e.g. with stronger integration along the value chain) in order not to be perceived as harmful to their businesses.

Deep decarbonisation of the steel industry cannot successfully take place without a systemic, holistic approach, which regards the industry as a system that expands the perspective from traditional steel industry to a comprehensive value chain perspective.

The available pathways entail systemic consequences beyond steel industry's traditional borders if really implemented.

- Pursuing CCS can create new cross-sectoral interdependencies, but pose challenges in the long-term to reach decarbonisation targets.
- The electrification options offer the potential for energy storage and large-scale balancing of variable power and could build upon existing scrap-based production sites.
- Other side effects for the sector could be the independence from coal imports and, or, the growth of new markets, for example for HBI and oxygen.
- However, large expansions of renewables capacity as well as the related infrastructures will be needed to meet the additional power demand when converting the industry from coal to electricity.

Finally, most major changes towards non-fossil technologies require large investments and involve considerable risks. International competition, technology risks, and the need for new infrastructure means that a strong innovation pathway towards a decarbonised European steel system will need major public engagement. Steel industry has signalled more openness for such pathways in recent years and the number of research and development projects around deep decarbonisation is increasing.

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