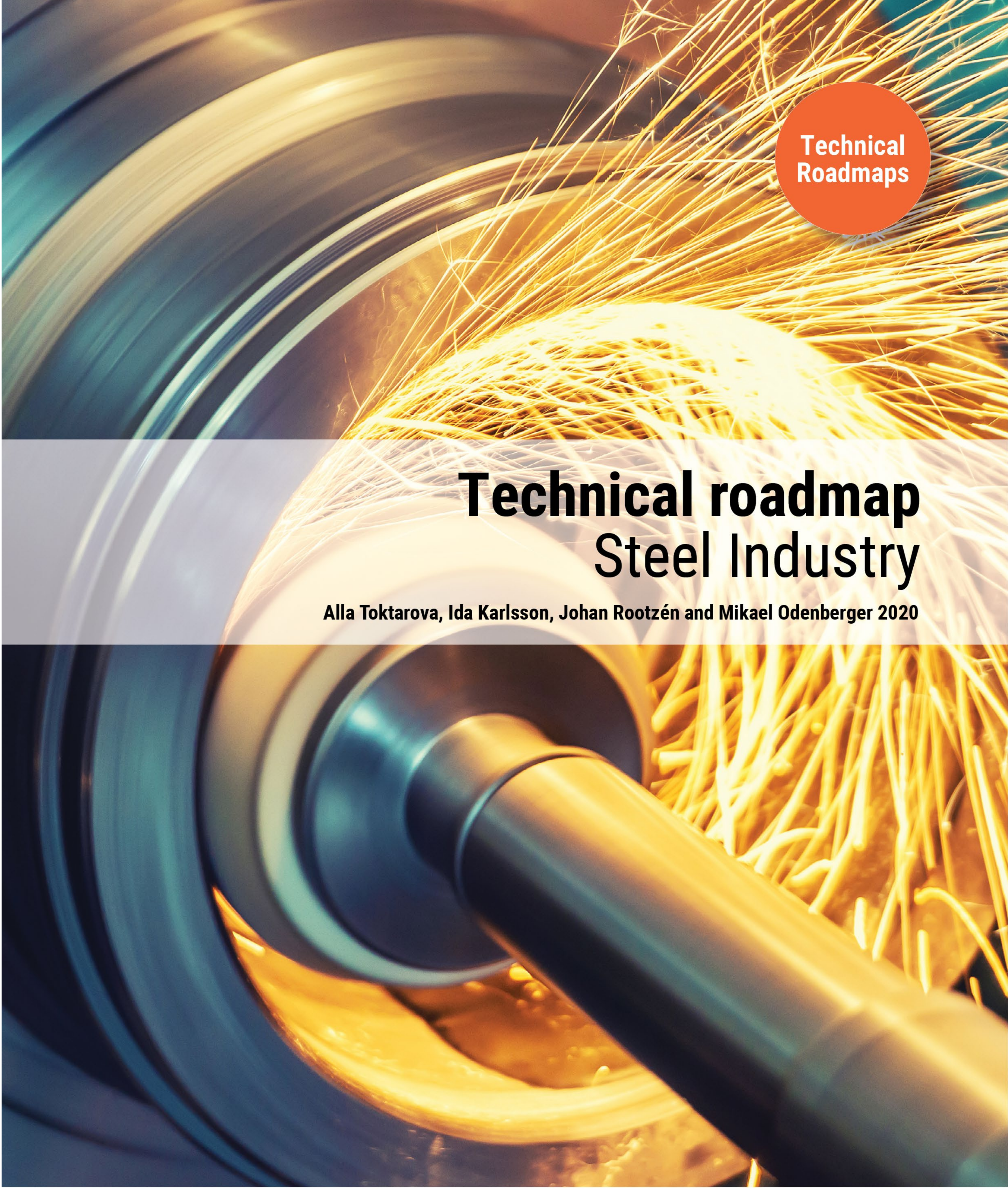

Technical Roadmaps

Technical roadmap
Steel Industry

Alla Toktarova, Ida Karlsson, Johan Rootzén and Mikael Odenberger 2020

MISTRA CARBON EXIT

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Abstract

This report explores different possible trajectories of technological developments in the primary production of steel. By linking short-term and long-term goals with specific technology options, the Mistra Carbon Exit roadmaps describe key decision points and potential synergies, competing goals and lock-in effects. The analysis combines quantitative analytical methods, i.e. scenarios and stylized models, with participatory processes involving relevant stakeholders in the roadmap assessment process. The roadmaps outline material and energy flows along with costs associated with different technical and strategical choices and explore interlinkages and interactions across sectors. The results show how strategic choices with respect to process technologies, energy carriers and the availability of biofuels, carbon capture, transport and storage (CCS) and carbon neutral electricity may have very different implications on energy use and CO_2 emissions over time.

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The three reports: Technical roadmap Steel Industry, Technical roadmap Cement Industry and Technical roadmap Buildings and transport infrastructure.

Mistra Carbon Exit – Technical roadmaps

Introduction

Sweden has, in line with the Paris agreement, committed to reducing GHG emissions to net-zero by 2045 and to pursue negative emissions thereafter. The overarching goal of the Mistra Carbon Exit (MCE) research program is to identify and analyse the technical, economic and political opportunities and challenges involved in this undertaking.

With a time horizon of several decades, any notions as to the future development of the complex economic, social, and technical dynamics that govern demand for energy and materials, and the associated greenhouse gas emissions, are likely to be speculative. Nevertheless, decisions as to how to best manage the transition must be made taking the future into account.

In Mistra Carbon Exit we work with a set of Scenarios and Roadmaps as tools to assess interlinkages and interactions across sectors and to communicate internally between the project partners and externally to inform and engage relevant stakeholders. The MCE Roadmaps are aimed at exploring different future trajectories of technological developments in the supply chains for buildings and transportation infrastructure. By matching short-term and long-term goals with specific technology solutions, the MCE Roadmaps make it possible to identify key decision points and potential synergies, competing goals and lock-in effects.

Mistra Carbon Exit research investigates External scenarios (described in WP1, related to global development in "Shared Socioeconomic Pathways", SSPs), Internal scenarios (described in WP1, referring to the development of the Swedish energy system meeting national targets) and Roadmaps that explore different technological pathways for the supply chains for buildings and transportation infrastructure (*cf.* Figure 1). The latter, i.e. the Roadmaps, will be used in an iterative approach to be included in the narratives for the internal scenarios, which means that there for example should be consistency between the development of the Swedish demand for electricity and the development of transforming Swedish steel industry to using hydrogen as reduction agent in the reduction of iron ore. Thus, Roadmaps are an important part of describing drivers that give rise to new demand that need to be included in the Internal scenarios. The aim is to find clear timelines for scenarios and roadmaps and finding combinations of roadmaps that fit a certain scenario narrative. Thus, it may take iterations to find both coherence in terms of timing of measures and which measures that fit what scenario.

Roadmap description

This report describes the initial work with the Mistra Carbon Exit roadmap for the Steel industry. The following subsections are described for each of the Mistra Carbon Exit roadmaps:

- Technological options
- Alternative pathways (Key decision points and investments, technological specifications, assumed activity levels, energy carriers)
- Timeline (Describing production mix/ market shares, resulting energy mix and CO_2-emissions)
- Description of risks, barriers and enablers linked to the respective roadmap

To find all the roadmap reports, please visit www.mistracarbonexit.com.

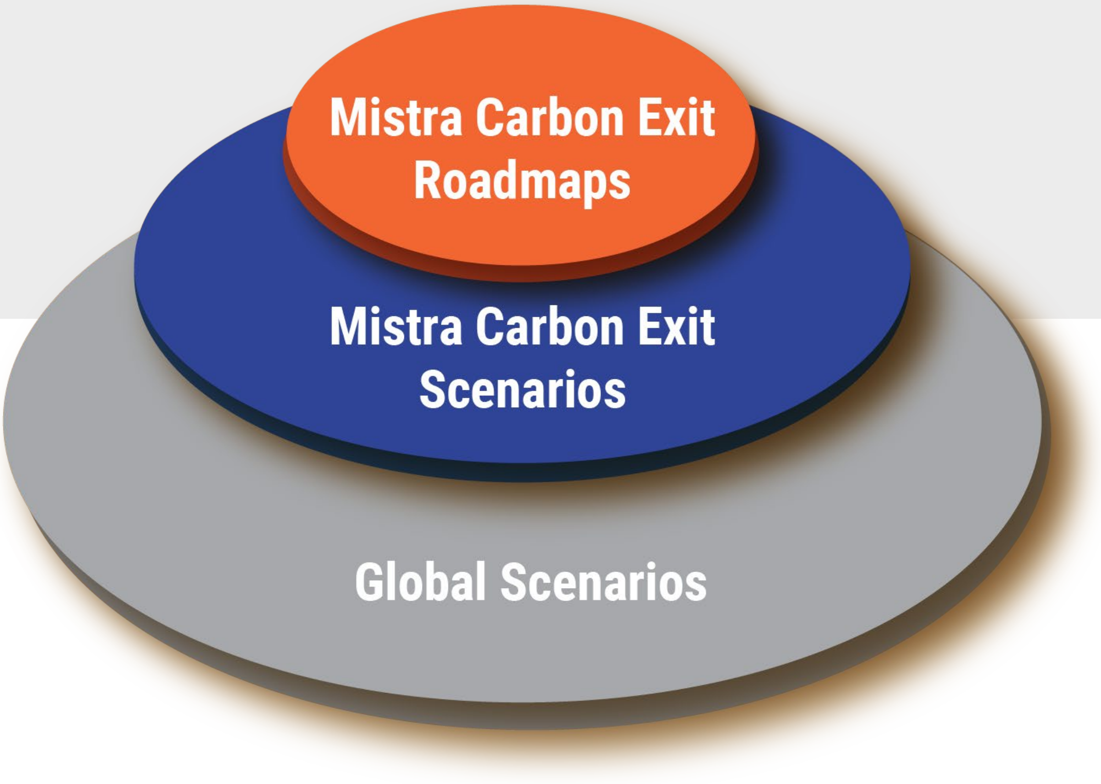

Figure 1. Mistra Carbon Exit use External scenarios to describe global development to meet a low carbon future, Internal scenarios to describe the development of that Swedish energy system and Roadmaps to describe how different technology options may impact the Internal scenarios.

Mistra Carbon Exit Roadmap

Steel Industry

Current status

The steel industry is the largest emitting industrial sector in Sweden, accounting for more than a third of the total industrial CO_2 emissions in 2017 (including direct and indirect emissions, i.e. Scope 1 and 2 emissions). The average annual production of crude steel from 2007 to 2017 in Sweden was around 4.5 Mt. Two-thirds of the current steel production comes from iron ore-based steel production, which takes place in two plants, in Luleå and in Oxelösund, owned by the company SSAB. Secondary steelmaking, where scrap metal, direct reduced iron, and cast iron are processed in electrical arc furnaces (EAF) to produce crude steel, accounts for one-third of the Swedish steel production.

In Sweden, iron ore is mostly mined in the mining district of Norrbotten, where LKAB, a state-owned mining company, has been operating since the end of the 19th century. The ore from the LKAB mines is mainly turned into pellets, accounting for 83% of LKAB’s deliveries of iron ore. LKAB is the world’s second-largest producer in the seaborne pellet market. 77% of LKAB's iron ore products are exported, with exports of around 17 Mt of iron ore pellets annually.

Technological options

The main technology used in Sweden today for reducing iron ore to iron is the blast furnace (BF). The blast furnace is fed with iron ore, limestone and coke, where the latter functions as both fuel and reducing agent. The produced liquid iron is transformed into steel in a basic oxygen converter (BOF) and subsequently treated in secondary metallurgy. The primary steel route generates over 90% of the carbon dioxide emissions of steel production, and about 80% of these emissions come from the reduction of iron ore into iron. In scrap-based steel production, steel is produced by steel scraps that are melted in electric arc furnaces. These mainly use electricity but are also fuelled by natural gas (25-30%) and a smaller share of coal (<5%). Refurbishments and upgrades of current electric arc furnaces provide potential for decreased electricity consumption, and there is also potential for biomass to substitute fossil process energy in EAFs, both as a reducing agent and as fuel in reheating furnaces.

The main options that currently can be defined for deep emission reduction in the iron and steel industry are the use of carbon capture and storage (CCS), the use of biomass to replace coke as fuel and reducing agent, and electrification with renewable electricity (either via hydrogen direct reduction or through electrowinning).

Partial CO_2 capture is a mature and low-cost technology that can be implemented in the coming 10-15 years without major changes to the existing process and which can be combined with biomass substitution. There are different ways of introducing biomass in the BF/BOF route, such as substituting pulverized coal with biocoal in the blast furnace; replacing coke/oil with biofuel for sintering/pelletizing of iron ore; partly replacing top-fed coke into the BF with biocoke; partly or fully replacing nut coke with biocoke. The biomass substitution technologies are at different stages of development, with substitution of pulverized coal with biocoal being the most feasible and promising in the near term. Depending on the pulverized coal injection (PCI) rate of a blast furnace, this would imply an emissions reduction potential of between 18 and 40%, where higher PCI rates provide for larger CO_2 reductions (Feliciano-Bruzual, 2014).

In the case of Sweden, the vision for complete decarbonisation of the iron and steel industries are shifting towards the electrification option. The Swedish steel maker SSAB, the mining company LKAB and energy company Vattenfall have, with governmental support established the Hydrogen Breakthrough Iron-making Technology (HYBRIT) project. The main target is for the iron and steel industry to have zero emissions by the year 2045. According to the HYBRIT concept, iron ore is reduced directly in a solid state by adding hydrogen as a reduction agent in a shaft furnace. Details on the emissions and costs associated with the different technological decarbonisation options for the steel industry are found in Table 1.

Table 1. Specifications of current commercially available and new transformative low CO_2 production processes for steel production in greenfield production facilities

Process/Technology	GHG emission	Costs	Reference
Ore based steel making			
Conventional Blast Furnace – Basic Oxygen Furnace (BF/BOF)	1.6 - 2.2 tCO_2/t steel	Investment costs: 386-442 €/t OPEX: 429 €/t	(Eurofer, 2013; Fischedick et al., 2014; HYBRIT, 2018b)
Top gas recycling Blast Furnace – Basic Oxygen Furnace with carbon capture and storage (TGRBF/BOF + CCS)	0.77 - 1.36 tCO_2/t steel	Investment costs: 566 €/t - year	(IEAGHG, 2013; Fischedick et al., 2014; Rootzén, 2015; Otto et al., 2017)
Smelting reduction (SR/BOF)	1.2 - 2.25 tCO_2/t steel	Investment costs: 393 €/t OPEX: 440 €/t	(Kuramochi et al., 2012; Eurofer, 2013)
Direct reduction with natural gas (DR/EAF)	0.63 - 1.15 tCO_2/t steel	Investment costs: 414 €/t OPEX: 572 €/t	(Kirschen, Badr and Pfeifer, 2011; Eurofer, 2013)
Hydrogen direct reduction (H-DR/EAF)	0.025 tCO2/t steel	Investment costs 550-900 €/t steel. Total production costs: 361-640 €/t steel	(HYBRIT, 2018a; Vogl, Åhman and Nilsson, 2018)
Electrowinning (EW)	0.2 - 0.29 tCO_2/t steel	Investment costs: 639 €/t	(Fischedick et al., 2014; SIDERWIN, 2017)
Scrap based steel making			
Conventional Electric Arc furnace (EAF)	0.6 tCO_2/t steel	Investment costs: 169 - 184 €/t OPEX: 489 €/t	(Eurofer, 2013; Otto *et al.*, 2017; Xylia *et al.*, 2018)
Improved EAF with biomass (I-EAF)	0.005 tCO_2/t steel	Investment costs: 169 - 184 €/t OPEX: 489 €/t	(Bianco, Baracchini and Cirilli, 2013; HYBRIT, 2018a; Vogl, Åhman and Nilsson, 2018)
Downstream metallurgy			
Casting steel		Investment costs: 80 €/t	(Xylia *et al.*, 2018)
Finishing steel		Investment costs: 85 €/t	(Xylia *et al.*, 2018)

Alternative steel production pathways

Four pathways were developed for the steel roadmap. Pathway 0 is based on the conventional primary steel production route with blast furnace and basic oxygen converter (BF/BOF) combined with conventional electric arc furnaces (EAF) for scrap-based steel production. The production processes in Pathway 1 are similar to Pathway 0, but with CO_2 emissions from primary steel production addressed by means of biomass usage and process modification enabling top gas recycling combined with carbon capture and storage. Pathway 1 thus adopts CO_2 absorption in amines from blast furnace gases and substitution of pulverized coal in the blast furnace with biomass.

Pathways 2 and 3 are based on a hydrogen direct reduction (H-DR/EAF) steelmaking process. For Pathway 3, it is assumed that the demand for the direct reduced iron (DRI) pellets increase, leading to a reduction of CO2 emissions from iron-making outside of Sweden. Parts of the current export of iron ore pellets are thus replaced by export of direct reduced iron (DRI) pellets. By the year 2045 the export of DRI pellets reaches 6 Mt which since the iron content in DRI pellets is higher than in iron ore pellets corresponds to approximately 50% of LKAB:s iron ore pellets export in 2017.

For all three decarbonisation pathways, current electric arc furnaces for scrap-based secondary steel production are being refurbished and upgraded at a continuous rate, alongside partial bioenergy substitution.

As a baseline, steel production is assumed to be unchanged between 2020 and 2045, where increased demand is compensated by resource and efficient production of steel, intelligent use of steel in structures and user-friendly utilisation of scrap metal and waste products. A sensitivity analysis is used to explore the sensitivity of this assumption.

Details of the timelines for the pathways are described in Figure 2.

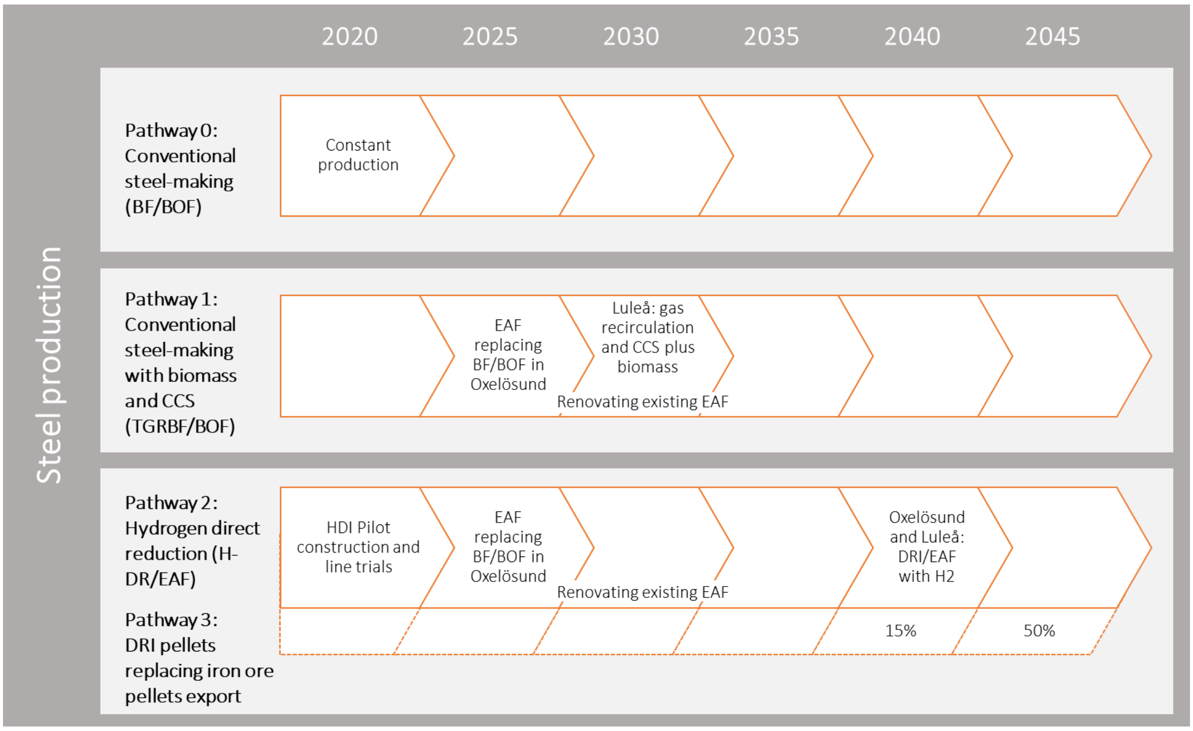

Figure 2. Key time-line decision points and investments for the steel industry roadmap pathways

Results

The distribution in production technology mix, energy carriers and the resulting reduction in carbon emissions over time for the four pathways are presented in Figures 3, 4, and 5, respectively.

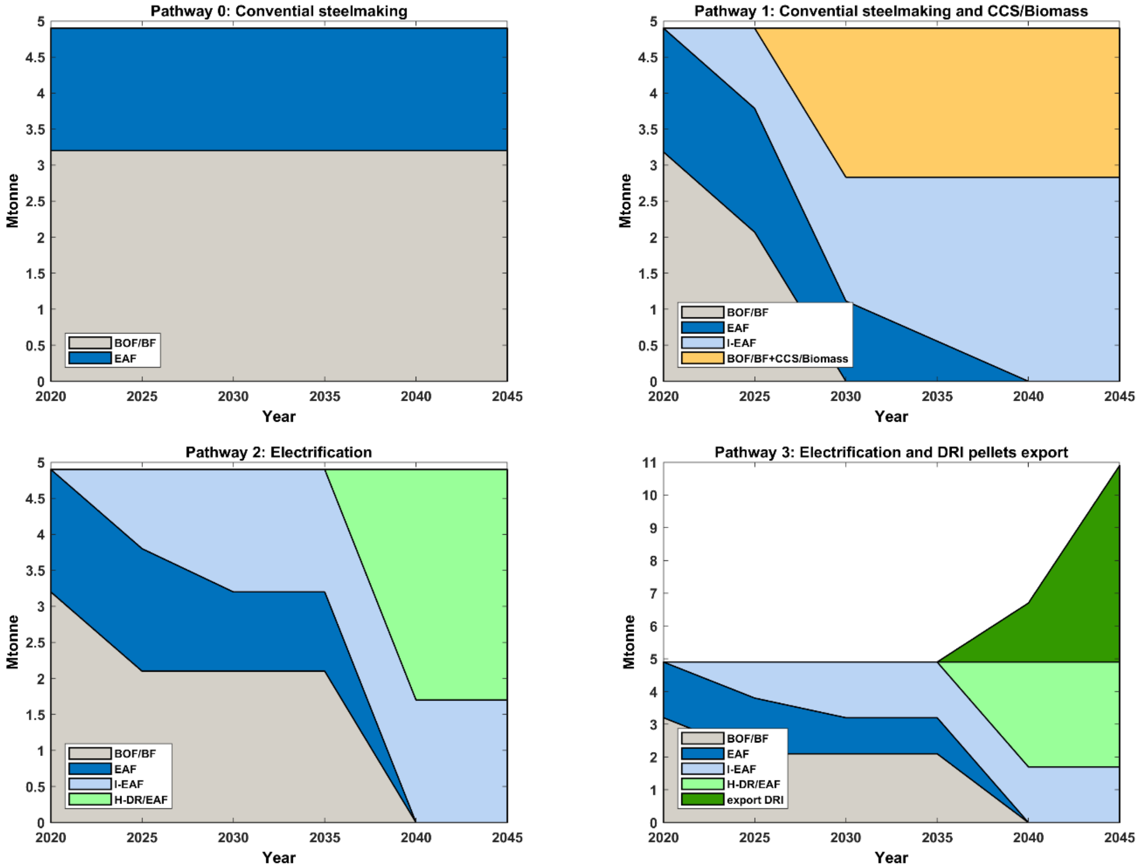

Figure 3. Production mix/ market shares for the Swedish steel industry pathways by process from 2020 to 2045

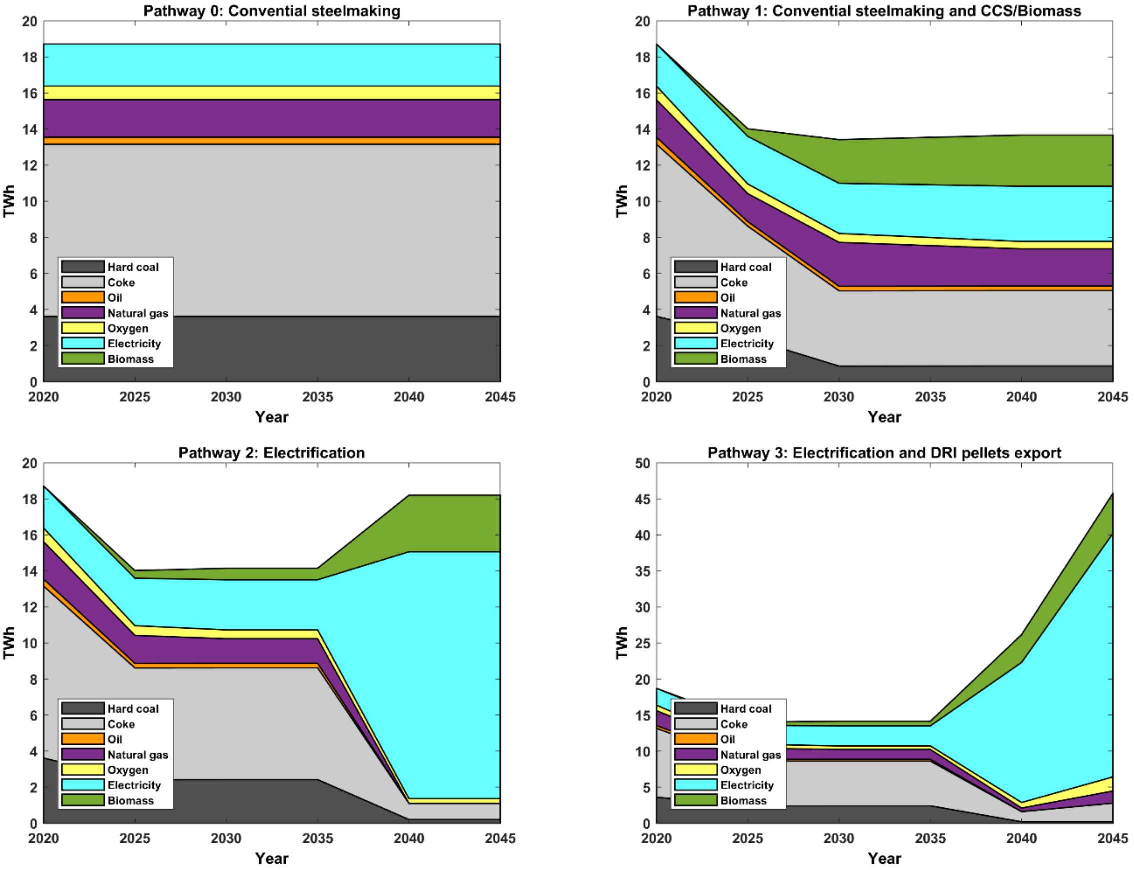

Figure 4. Energy use per energy carrier for the Swedish steel industry pathways from 2020 to 2045

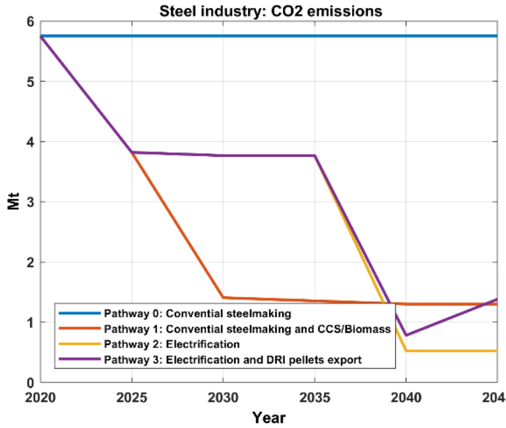

Figure 5. Development of total CO2 emissions for the Swedish steel industry pathways from 2020 to 2045

In Pathway 2, the electricity use increases significantly, implying electricity needs of around 14 TWh per year in 2045. Biomass usage correspond to around 3 TWh in 2045 in both Pathway 1 and 2, reaching close to 6 TWh in Pathway 3. In the medium term, however the biomass usage is larger in in the bio/CCS pathway. Similarly, the use of coke and coal reduces more in the medium term in the bio/CCS pathway, while it is lower in the electrification pathways in 2045.

While electrification leads to a potential for close to zero carbon emissions by 2045, we can see from Figure 5 that the emissions do not reach zero due to process emissions caused in the production of lime and adding carbon, which is an essential component in steel.

From 2040, there is a slight increase in CO_2 emissions for Pathway 3 resulting from the large growth in DRI pellets production for export, aiming to support international emissions reduction efforts. The principal market for DRI pellets is electric arc furnace (EAF) steelmaking, but DRI also finds application as a feedstock in basic oxygen furnace (BOF) steelmaking. DRI pellets produced via the hydrogen direct reduction (H-DR) steelmaking process decreases CO_2 emissions from ironmaking by 90% compared with iron production in a blast furnace, and by 80% compared with a direct reduction of iron using natural gas as a reducing agent. The main drawback of this pathway is the dramatic increase in electricity consumption, which would amount to around 33 TWh in the year 2045.

The potential CO_2 emission reduction from CCS in combination with biomass substitution in the blast furnace is limited to about 78%, as the small and diffuse emission sources in the various steps of the BF/BOF steel production makes larger emissions reduction less economically feasible. However, as Figure 5 demonstrates, this pathway constitutes an important medium-term option for CO_2 reduction from primary steel production. While the electrification pathway has lower emissions in 2045, when comparing the pathways from a carbon budget standpoint, the biomass and CCS pathway has 34% lower cumulative emissions compared to the electrification pathway from 2025 to 2045.

Economic analysis

Nearly 60% of current steel production costs consist of raw materials (i.e. iron ore, ferro-alloys, scrap and fluxes), fuels and reductant, while CAPEX only contributes around 20% of the total cost. Future steel production costs are influenced by different market drivers, mainly the cost of iron ore, biomass and electricity. Although the cost estimates presented here are rather exact (as obtained from the calculations) it should be noted that they are associated with uncertainty. The analysis assumes emission-free electricity and EAFs only being charged with direct reduced iron.

Conventional steelmaking with biomass and CCS

In this study, the deployment of post-combustion capture technology involves the capture of CO_2 from flue gases of hot stoves and steam generation plant. Using the overall energy consumption for the conventional BF/BOF route as a basis, post-combustion capture corresponds to an increase in energy consumption of 3.37 GJ/ t steel (IEAGHG, 2013; Otto *et al.*, 2017). This capture technology can achieve about 50% CO_2 emissions reduction, assuming a 90% capture rate.

The production cost of steel produced with post combustion capture technology increases by approximately 13% compared to the conventional production route, while noting that the CO_2 avoidance cost is very specific to the assumptions made in various studies. The estimated cost of CO_2 avoidance of blast furnace gases capture can vary and from €54/t CO_2 to €72/t CO_2. If also capturing CO_2 from other sources (i.e. coke ovens, sinter plant lime kiln), there is an increase in avoidance costs up to €60-100/t CO2 (Biermann *et al.*, 2019). These estimates do not include the cost of CO_2 transport and storage.

Introduction of biofuel in the process would further increase the steel production cost, as the cost for charcoal ranges between €240-510/t (Feliciano-Bruzual, 2014), while the cost for coal is in the range between €100-120/t. The CO_2 avoidance cost of emissions due to the deployment of CCS with biomass is estimated to €80/t CO_2 on average, being a matter of high uncertainty as it depends on biomass substitution level, costs of CCS deployment and the biomass price (Mandova *et al.*, 2019).

Electrification

The steel production cost C_{prod} is evaluated by summing the contributions of the annualized CAPEX, C_{cap}, the resource costs C_R, the electricity cost C_{el}, and other operating and maintenance cost $C_{O\&M}$, all expressed per ton of steel produced (i.e., as €/t).

$$C_{prod} = C_{cap} + C_R + C_{el} + C_{O\&M} \qquad (1)$$

The production cost for the steelmaking process with hydrogen reduction is approximately 20 to 30% higher than for the conventional primary steelmaking process (BF/BOF). Figure 6 (left) shows the steel production cost the H-DR/EAF plant as a function of the electricity cost, illustrating how the electricity price is the main factor affecting the production cost of the H-DR/EAF route.

Figure 6 (right) indicates the impact of the carbon cost on the steel production cost for conventional BF/BOF plant compared to the production cost of the H-DR/EAF plant when the electricity price is assumed at €38/MWh. This graph demonstrates that a carbon price of €45/t CO_2 makes the H-DR/EAF route competitive to the conventional BF/BOF process.

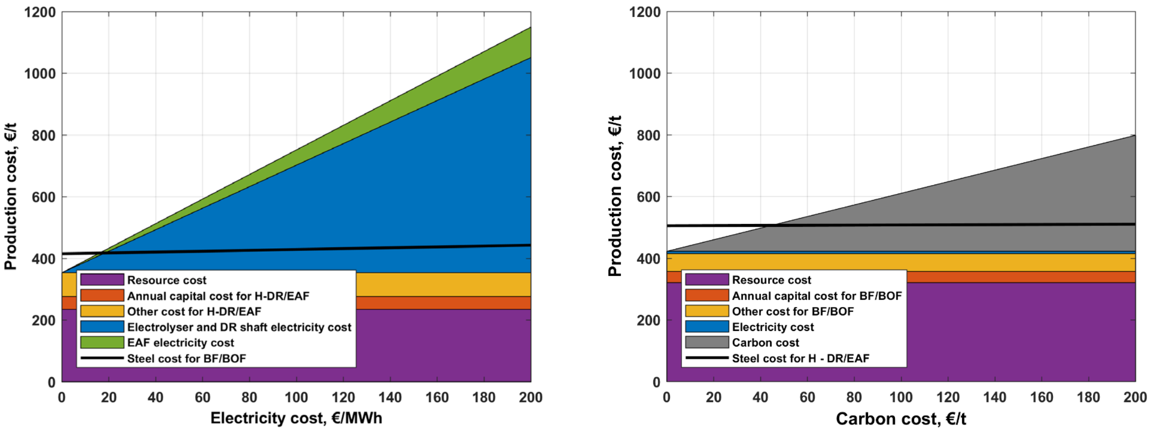

Figure 6. Steel production cost for BF/BOF and H-DR/EAF routes as a function of the electricity cost (left) and as a function of carbon pricing (right)

Vogl et al (2018) determined that an H-DR/EAF plant can be competitive with traditional BF/BOF route at a carbon price of €52/t CO_2 and an electricity cost of €40/MWh if greenfield investments are compared.

Sensitivity analysis

Steel is a global commodity and it is extremely difficult to predict how changes in steel demand internationally would affect demand and activity levels in the Swedish steel industry. However, as future demand and production levels obviously will have major impacts on energy use and CO_2 emissions, a sensitivity analysis was conducted to examine the effect changing demand on the modelling results.

The high end of the sensitivity analysis is based on projections that EU steel demand will grow by 0.6% annually up until 2050 (Material Economics, 2019). On the lower end, it is estimated that demand-side measures, including increased scrap use, prolonged lifetime of final products and changed consumption patterns, can decrease the steel demand by 25% to 2045 (Allwood and Cullen, 2012; Moynihan, Allwood and Allwood, 2014; Energy Transition Commission, 2018; Fleiter et al., 2019; Material Economics, 2019).

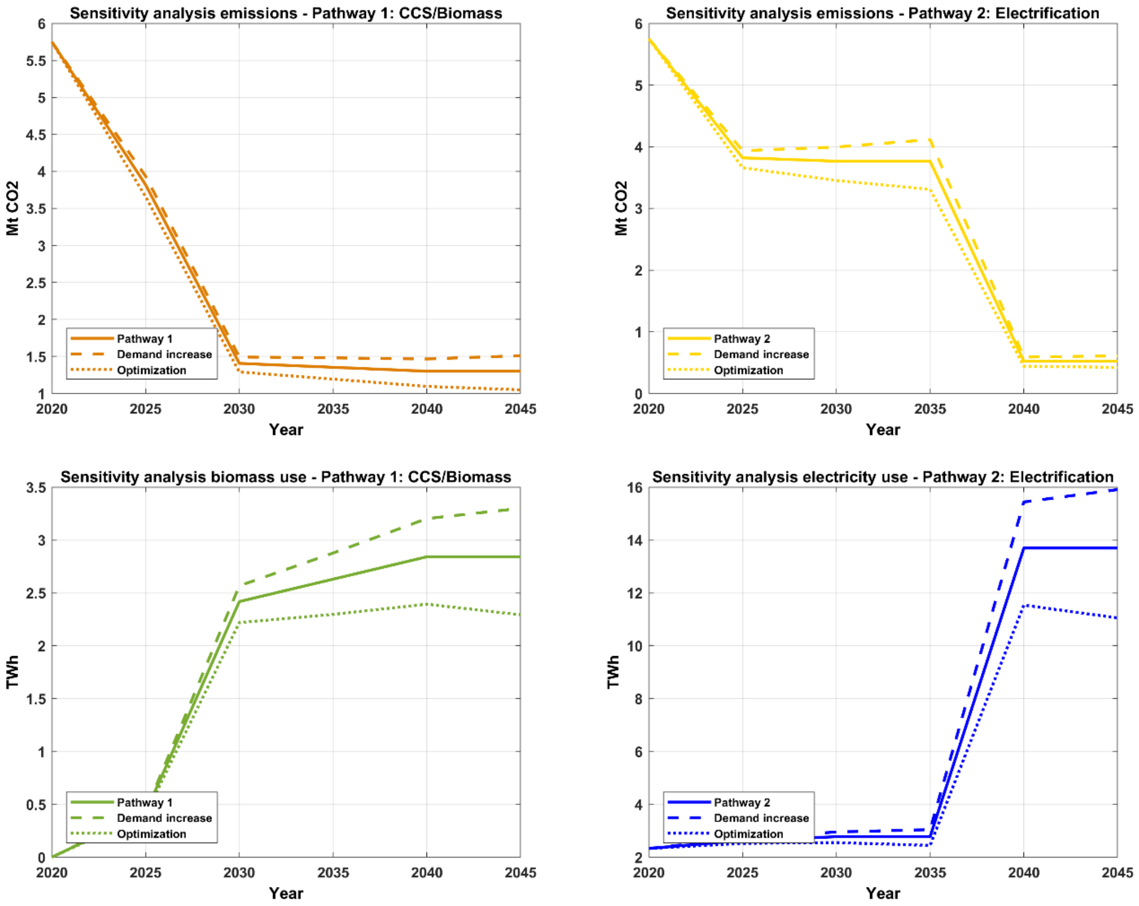

Figure 7. Production level sensitivity analysis for the bio/CCS and electrification pathways detailing emissions (top graphs), biomass use (bottom left), and electricity use (bottom right) for consumption increase versus optimisation

As can be seen in Figure 7, variations in steel production levels do not imply notable changes in CO_2 emissions reduction in the long term due to the low-carbon intensity of the adopted production processes. The main divergence occurs for the electrification pathway in the medium term, where optimization has the potential of reducing emissions by around 0.5 Mt CO_2 in 2035 compared to constant production, while demand growth may result in an increase in emissions of around 0.3 Mt CO_2 in the same year.

In terms of biomass use, we see a slight variation with optimization having potential to reduce biomass usage for the CCS and biomass pathway by 0.6 TWh in 2045, while demand growth on the other hand may increase biomass needs by 0.5 TWh. As expected however, there is a significant difference in electricity use for the electrification pathway. The gap between the optimization and demand growth equal 5.8 TWh, which corresponds to 5% of total Swedish electricity demand in 2017.

Risks, enablers & barriers

Details of some of the key risks and uncertainties together with potential enablers to realise the different technological pathways are described in Table 2. The input is drawn from the industries' own roadmaps developed within the "Fossil Free Sweden" initiative, stakeholder input and feedback gathered from workshops and conferences within Mistra Carbon Exit together with inspiration from other relevant national and international literature (see Appendix 1).

Table 2. Risks, enablers and potential barriers for low carbon steel production

Technological development and diffusion	Risks and uncertainties	Enablers
Biomass	Biomass availability and competition between sectors; Consequences for other sustainability targets; Focus on biomass as carbon storage and provider of biodiversity - limiting biomass use to certain sectors; Requires specific biofuels adapted for each process; Additional costs for pre-treatment	Develop a national bioenergy strategy and action plan for access to and distribution of sustainable biofuels; Establish a regulatory cross-sectoral framework for biomass use; Develop tightly defined sustainability standards for biofuels; Establish and secure a well-functioning market for biofuels
Carbon capture and storage	Availability of CO2 storage and transport infrastructure; Public acceptance for CCS; Risk of lock-in effect in fossil fuel infrastructure Large upfront investments; Public acceptance	Flexible fuel and raw material input; Potential to reach close to zero emissions sooner - Requires only small process changes; Commission an authority with responsibility for developing and implementing a national CCS strategy; Strategic planning for cooperation around CO2 transportation and storage infrastructure Supplementary and supportive instruments to the EU emissions trading scheme;
Electrification	Large upfront investments; Lack of coordinated electrification strategy allowing for increased electrification in both industry and transport - Energy/effect supply/demand balance crucial; Transmission and distribution - Capacity concern, public acceptance of grid expansion, cost and lead times; Lengthy and uncertain permitting processes; Stability of grids and flexibility of energy system; Electricity price uncertainty	Develop a national electrification strategy and action plan for access to and distribution of low/zero CO2 electricity; Create conditions for transformation of the basic industry through financing, risk sharing, innovation support and policy instruments; Active and continuous public policy coordination; Secure continued government support for initiatives such as 'Industriklivet' - the "industrial leap"; Political engagement to secure grid stability, access to and availability of zero-carbon electricity; Establish and implement plans for demand integration in line with expansion of supply from renewables; Efficient and predictable permitting processes (e.g. by using learnings from the development of wind power permitting processes); Support system for continued fast deployment renewable energy generation capacity; Secure a well-functioning electricity market focusing on energy system flexibility to minimise system cost

Summary and discussions – Steel

The ambition with this Roadmap is to explore how different choices, with respect to technological development in the Swedish steel industry, affect material flows, energy use, CO_2 emissions and cost over time. However, it is important to note that the steel production pathways assessed in this roadmap are explorative and not intended as projections. The scenario analysis effectively illustrates how different technological choices (i.e. hydrogen direct reduction, CCS, biocoke) will have very different impacts on the surrounding energy system. The results also give an indication of the rate and scale at which support infrastructure would need to be rolled out (renewable electricity supply, electricity grid expansion, hydrogen storage, CCS infrastructure, sustainable biofuel supply).

Only a relatively small share of the steel produced in Sweden have a domestic end use, i.e. most (>85%) of the steel produced in Sweden is exported. Still, even though mitigating CO_2 emission by using less steel has a limited potential on national basis efforts, material efficiency and circularity measures will be important to reduce CO_2 emissions related to steel production and to achieve the long term emission reduction goals. These include measures to:

- use less steel for same function;
- maximize upgrading, recycling and reuse of steel already in use; and
- switch to lower-CO_2 materials.

Here end-users in for example the construction sector or in the vehicle manufacturing industry will have an important role to play. In addition, it will also be important to prioritize innovation and technological development related to delivering high quality steel from recycled scrap-based steel (see e.g. Allwood *et al.* 2019).

Whereas many challenges still remain to be resolved, the announcement in 2016 by the largest Swedish steel producer SSAB of their plans to switch from coal to renewable hydrogen (HYBRIT, 2018b), has attracted significant attention and support. Several other steel producers (e.g. Voerstalpine, Salzgitter, ArcelorMittal, Thyssenkrupp) have since followed suite and initiated their own research and development projects to explore options to replace coal and coke with hydrogen as reductant and energy source. In 2019, the partners in the HYBRIT consortia (which includes SSAB, the iron ore producer LKAB and the energy company Vattenfall) initiated the construction of a pilot plant and have announced plans to construct and run trials with a hydrogen storage facility between 2022-2024 with the aim to deliver the first low-CO_2 steel to the market already in 2026.

Irrespective of the exact configuration of steel production processes the development from pilot to demonstration and subsequently commercial scale, will involve large up-front investments and significant financial risks. SSAB like any other firm seeking to invest in high-cost high-risk (but low-CO_2) technology faces a dilemma. On the one hand, it is difficult to motivate and find a business case for investments away from traditional and established technologies, especially in the currently uncertain policy regime. On the other hand, a failure to invest in a shift to less carbon-intensive technology is incompatible with the Paris Agreement. Thus, it is worth pointing out, which is also done in other work (see e.g. Bataille *et al.*, 2018; Neuhoff *et al.*, 2019), that the current policy mix targeting the basic material industry will need to be strengthened with complementary policy interventions and/or private initiatives to secure financing and lower the financial risk in investments for decarbonisation up to 2045.

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Appendices

Appendix 1: Overview of relevant roadmap studies and reports

	Description	Geographical scope	Reference(s)
Basic industry			
The "Fossil Free Sweden" initiative development of "Roadmaps for fossil free competitiveness"	Initiative in which Swedish business sectors (including cement, concrete, steel and building and construction) have developed roadmaps towards zero GHG emissions. Roadmaps have been developed for: the Aggregates Industry, the Aviation Industry, the Cement Industry, the Concrete Industry, the Construction and Civil Engineering Sector, the Digitalisation Consultancy Industry, the Food Retail Sector, the Forest Sector, the Heating Sector, the Heavy Haulage Industry, the Maritime Industry, the Mining and Minerals Industry, and the Steel Industry.	Sweden	(Fossil Free Sweden Initiative 2018)
Klimatneutral konkurrenskraft - Kvantifiering av åtgärder i klimatfärdplan	Quantifies the increased requirements for electricity and bioenergy in 2045 resulting from the combined measures of the industry roadmaps developed within the Fossilfree Sweden initiative, together with other parts of the Transport sector and the Chemical industry.	Sweden	(SWECO 2019)
Så klarar svensk industri klimatmålen	Survey of technological and process abatement options in the Swedish industry sector up until 2045. Coverage: Iron and steel, Cement, Petrochemicals/Chemicals, Non-Ferrous metals, Forestry, Oil Refining, Mining and minerals.	Sweden	(Kungliga IngenjörsVetenskaps Akademien 2019a)
Hinder för klimatomställning i processindustrin	A report within the government assignment *Innovation-promoting efforts to reduce greenhouse gas emissions in the process industry*. Details technical, market, regulatory, resource and infrastructure barrier to a low-carbon transition for the Swedish process industries: Iron and steel, non-ferrous metal, Cement, Petrochemicals/Chemicals and Oil Refining.	Sweden	(Swedish Energy Agency 2019)
Statens roll för klimatomställning i processindustrin	Provides an overview of the role of the government and other public and private actors in facilitating a climate transition in the Swedish process industry. Coverage: Iron and steel, Cement, Petrochemicals/Chemicals and Oil Refining	Sweden	(Karltorp et al. 2019)
A Steel Roadmap for a Low Carbon Europe	Industry association assessment of abatement options for the steel industry and conditions required for its realisation. Also details the role of steel for low carbon solutions in other societal sectors.	Europe	(Eurofer 2013)
Cements for a low-carbon Europe	Industry association report focusing on the diverse solutions applied by the cement industry across Europe to reduce the carbon footprint of its products through the production of low clinker cements.	Europe	(Cembureau 2013)
A sustainable future for the European cement and concrete industry	Summarises the practices and technologies that can be implemented to significantly reduce CO2 emissions from the cement and concrete sector in Europe by 2050. Details the potential and need for reduction efforts along the complete value chain.	Europe	(Favier et al. 2018)
Towards A Flemish Industrial	Puts forth a proposal on the possible scope and blueprint of a future facilitative framework towards a Flemish low-carbon economy taking into account the	Flanders and Belgium	(Wyns et al. 2019)

Transition Framework	interactions and possible synergies between energy intensive industries and the rest of the economy.		
Decarbonising Europe’s energy intensive industries	Sketches the blueprint of an industrial strategy towards climate neutrality in the EU. The study provides an integrated structure that scrutinizes a broad set of policy instruments and provides ideas for making the whole policy set as tangible as possible.	Europe	(Wyns et al. 2019; Wyns and Axelson 2016)
Building Blocks for a Climate-Neutral European Industrial Sector	Outline an integrated industrial climate strategy for the EU and describes five policy options to facilitate decarbonisation of the basic materials industry by 2050.	Europe	(Neuhoff et al. 2019)
Industrial Innovation: Pathways to deep decarbonisation of Industry	Investigates the extent to which key EU industrial sectors can benefit and contribute to a climate-neutral future. The project takes a perspective to 2050 and beyond and analyses the technologies, pathways to 2050 and the policy mix needed for implementation.	Europe	(Fleiter et al. 2019; Chan et al. 2019)
Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry	Characterises how net zero emissions can be achieved by 2050 from the largest sources of ‘hard to abate’ emissions: Steel, Plastics, Ammonia, and Cement. Starts from a broad mapping of options to eliminate fossil CO2-emissions from production and integrates these with the potential for a more circular economy.	Europe	(Material Economics 2019)
Mission Possible - Reaching Net Zero Carbon Emissions from Harder-to-abate sectors by Mid-century	Outlines the possible routes to fully decarbonize Cement, Steel, Plastics, Trucking, Shipping and Aviation. Combines technical abatement options with materials efficiency, recycling, logistics efficiency and modal shifts.	World	(Energy Transition Commission 2018)
Construction			
Roadmap for a carbon neutral and competitive construction and civil engineering sector	Ongoing initiative, with the ambition to increase the awareness of the building sector’s climate impact and highlight trends, motivations, barriers and business opportunities; and ultimately establishing a common view of responsibilities and actions required to achieve a carbon neutral and competitive building sector.	Sweden	(Fossilfritt Sverige 2018)
The Property Sector’s Roadmap Towards 2050	Recommendation to Norwegian owners and commercial building managers regarding their short and long-term choices in ensuring that the property sector contributes to a sustainable society by 2050.	Norway	(Grønn Byggallianse and Norsk Eiendom 2016)
Finnish Ministry of Environment’s Low Carbon Construction Roadmap	Plan for how to reduce GHG emissions related to building materials and the construction industry in general, with the goal of regulating buildings’ emissions via legislation by mid 2020s.	Finland	(Finnish Ministry of Environment 2019; WGBC 2019)
Low Carbon Routemap for the UK Built Environment	A project exploring options to reduce GHG emissions from the user phase, supply chain and construction activities for the UK built environment. Covers operational as well as embodied carbon emission from both the buildings and infrastructure sectors.	UK	(Green Construction Board 2013; Steele, Hurst, and Giesekam 2015)
Bringing embodied carbon upfront	Call for coordinated action for the building and construction sector to tackle embodied carbon.	World	(WGBC 2019)

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