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Review

Towards Deep Decarbonisation of Energy-Intensive Industries: A Review of Current Status, Technologies and Policies

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Abstract: Industries account for about 30% of total final energy consumption worldwide and about 20% of global CO_2 emissions. While transitions towards renewable energy have occurred in many parts of the world in the energy sectors, the industrial sectors have been lagging behind. Decarbonising the energy-intensive industrial sectors is however important for mitigating emissions leading to climate change. This paper analyses various technological trajectories and key policies for decarbonising energy-intensive industries: steel, mining and minerals, cement, pulp and paper and refinery. Electrification, fuel switching to low carbon fuels together with technological breakthroughs such as fossil-free steel production and CCS are required to bring emissions from energy-intensive industry down to net-zero. A long-term credible carbon price, support for technological development in various parts of the innovation chain, policies for creating markets for low-carbon materials and the right condition for electrification and increased use of biofuels will be essential for a successful transition towards carbon neutrality. The study focuses on Sweden as a reference case, as it is one of the most advanced countries in the decarbonisation of industries. The paper concludes that it may be technically feasible to deep decarbonise energy-intensive industries by 2045, given financial and political support.

Keywords: energy-intensive industry; emission; decarbonisation; low carbon technology; policy

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1. Introduction

1.1. Background

A substantial reduction of greenhouse gas (GHG) emissions must be achieved to limit the global temperature rise well below 2 °C, as stipulated in the Paris Agreement climate target [1]. This reduction requires fundamental, rapid and large-scale systemic transformations to fully decarbonise the global energy system [2]. However, global decarbonisation is complex and highly uncertain [3], in which managing it presents new risks and opportunities for societies across the world. All countries have a role to play in decarbonising entire sectors towards climate neutral targets. Nevertheless, timing and speed of emission reduction differ according to each country's circumstances such as their dependence on fossil fuels, ambitions in its energy transition, socio-economic, political context, and capacities to reduce GHG emissions.

Over the past decades, decarbonisation pathways have emerged in the buildings, heat and power and transport sectors. These have been driven by technological breakthroughs, cost reduction and market growth of decarbonisation technology, for instance, in hydropower, wind and solar energy, electric vehicles, low-energy buildings and biofuels [4,5]. However, for industrial sector, decarbonisation pathways are less well-defined.

Energy-intensive industries (EIIs) constitute a significant part of the economy and responsible for a large amount of energy use, resource consumption and emissions. The industries produce basic materials such as steel, metallurgy, cement, paper and chemicals [6].

Globally, EIIs contribute around 30% of total GHG emissions [7,8]. Emission reduction in the EIIs is more challenging than other sectors, so-called 'hard to abate' sectors due to its heterogeneity, GHG intensity, trade and cost sensitivity, and long facility life [9]. As a consequence, less has been done to date in this sector. Decarbonising the EII sectors is however important for mitigating emissions leading to climate change.

1.2. Overview of Industrial Decarbonisation Worldwide

Worldwide use of basic materials has increased steadily since 1990 in parallel to the growing world economy [10]. In 2018, the industrial sectors accounted for about 20% of global CO_2 emissions, corresponding to 6.2 Gigatonne of CO_2, where around 60–80% of this emission mainly comes from EIIs that produce basic materials [9,11]. Direct industrial emissions have continued to increase globally, and this was mainly driven by industrialisation in the developing country, whereas emissions in developed countries have decreased slightly [7]. In the past two decades, the growth in emissions from increased production has been partly offset by substantial improvements in energy efficiency and large investments in new low-carbon energy technologies such as in China, Europe and the United States (US) [12].

The increasing awareness of sustainability has transformed the energy and climate change policy landscape and entailed an increased level of regulation and political commitment globally. The European Union (EU) has been leading in successfully decoupling carbon emissions from economic growth. The EU has engaged in a proactive climate policy and prioritised the decarbonisation of the energy system by setting the long-term goal of a climate neutral economy by 2050 [13]. Individual EU countries set their own national targets to reach the EU's target. Among the member states, the Nordic countries are pioneers of green energy transitions [14], and Sweden has been acknowledged as one of the leading EU member countries in the energy transition with a well-performing low carbon energy system [15].

Industrial decarbonisation will play out differently in different countries depending on local characteristics. For instance, feasibility of decarbonisation options can be strongly influenced by the price and availability of biomass, renewable electricity, and carbon storage locations. Therefore, different strategies and paths to reduce emissions in all countries and sector should be explored [16]. Currently, there is growing literature exploring pathways and opportunities for industrial decarbonisation at the global, regional and national level. A main focus has been on developing long-term low carbon pathway scenarios that outline the possible routes to fully decarbonise global industry sectors, such as reported in the "Energy Technology Perspectives" report from the International Energy Agency (IEA) [17], and the "Mission Possible" report by the Energy Transitions Commission (ETC) [18]. These reports state that it is technically and economically feasible to achieve full decarbonisation of hard-to-abate sectors of the economy by 2050.

Radical technology innovations are required to achieve the necessary emissions reductions [19]. Industrial decarbonisation is likely to imply a substantial increase in product prices, yet limited impacts on end consumer prices are estimated [19,20]. For globally-traded commodities such as steel, an uneven transition on a global scale could cause competitiveness issues. Therefore, designing cost-effective climate policy instruments is important for future climate policies.

The use of renewables for energy and feedstocks is crucial to reach zero emissions across EIIs and transport sectors, as highlighted in the IRENA report "Reaching zero with renewables" [21]. In all pathways to a net-zero-carbon economy, electricity's share of total final energy demand will increase from 20% to over 60% by 2060. This implies that variable renewable energy (VRE) sources such as wind and solar PV must be integrated into existing power systems at a large scale.

Due to stringent reduction targets to achieve net zero GHG emission, the momentum for CCS from industrial facilities has accelerated globally over the past years [22,23]. Today, 20 large-scale CCS applications at industrial facilities have entered operation, while some

24 future large-scale applications are currently at various development stages [24]. Despite an increase of CCS capacity globally over the past years, the deployment was far too slow to meet global climate targets [24].

The majority of technologies outlined in the decarbonisation pathways reports have not yet reached commercial due to many uncertainties remain about their potential and optimum use, as well as various deployment barriers. For EIIs, technological, institutional, infrastructural, market and policy barriers are deeply intertwined. Thus, innovative solutions integrating innovations in enabling technologies, business models, market design, and system operation are required to overcome various barriers across the value chain [21].

Many studies on decarbonisation pathways have focused much on the technological pathways and less on the supportive enabling reforms that would facilitate their uptake. Thus, pathways analysis coupled with the enabling environment discussion is required to make decarbonization technically, economically and politically feasible. Bataille et al. [25] reviewed technology and policy to deep decarbonise energy-intensive industry. They developed a preliminary integrated strategy for managing the transition, which takes into account global perspectives. Rissman et al. [5] also extensively reviewed technologies and policy interventions as well as sociological consideration to fully decarbonise global industry. This study identifies both supply-side mitigation measures (e.g., energy efficiency, CCS, electrification, fuel switching) and demand-side measures (e.g., material efficiency, substitution etc.). The inventory of technology options is not discussed specifically for each industrial sector, except for steel and cement industry.

1.3. The Issues Considered

In exploring industrial transformation towards deep decarbonisation, Sweden serves as an interesting case study. Sweden has had a long-term active climate and energy policy, including significant changes in carbon and energy taxes over the last few decades. Moreover, Sweden has almost fully decarbonised its electricity and heat production through major investment in hydropower, nuclear, and other renewable energies, as well as energy efficiency improvements. As a result of the low carbon energy mix, Sweden is the country with the lowest proportion of fossil fuels in its primary energy supply among the IEA member countries [15].

The study focuses on Sweden as a reference case, as it is one of the most advanced countries in the decarbonisation of industries. Sweden could arguably be regarded as a significant case for understanding the characteristics of industrial transformations towards deep decarbonisation. Moreover, the lessons learned are applicable across much of the industrialised world, even though the mix of policies, strategies and energy sources needed to solve the problem will differ among countries.

Sweden has set the ambitious target of a net zero carbon economy by 2045 in the Climate Policy Framework that entered into force in 2018 [26]. However, despite impressive progress in the energy transition and cutting GHG emissions, Sweden's current emission trajectory is insufficient to reach the 2045 vision of zero net emissions [15,27]. To meet the ambitious Swedish long-term vision, the pace of transformation should be accelerated through deep decarbonisation of entire sectors, particularly energy-intensive industries and transportation [9]. This paper, therefore, analyses various technological trajectories for decarbonisation of energy-intensive industries such as steel, mining and minerals, cement, pulp and paper and refineries.

There have been several works that studied decarbonisation of Swedish industries. Gode et al. [28] reported modelling and scenario development for developing Sweden's long-term low-carbon pathway strategies. Moreover, at the sectoral level, potential decarbonisation trajectories have been investigated by several authors, for instance in the iron and steel sector [29–32], cement sector [33], chemicals sector [34], the mining and mineral sector [26,27], and other works that covered industrial sectors from a more aggregated perspective [35,36]. Several industrial sectors, such as steel, cement and mining and mineral also launched their own roadmaps for decarbonisation [37]. However, some of this literature is dated and not up-to-date, and it is spread out across a range of different sources including scientific papers, grey literature and industry reports. An up-to-date overview paper that critically analyses the technological trajectories and policies for decarbonisation of energy-intensive industries, using Sweden as a case study, is absent from the current academic literature. Therefore, focusing on the Swedish case, this paper explores the latest cutting-edge status of industrial decarbonisation, a way forward until 2050 and the key policies required for implementation. Opportunities and barriers to the decarbonisation of industrial sectors are also critically discussed here. This study aims to provide insights both into technology and policy strategies in governing a long-term transition for a decarbonised industry.

The discussion in this paper focuses in particular on five EII sectors: (1) iron and steel, (2) mining, (3) cement, (4) refinery and (5) pulp paper. The chemical sector is excluded in this paper. This is because of the heterogeneous nature of the chemicals sector that is made up of many different processes, each producing a wide range of products.

Section 3 analyses the Swedish energy and emission profile. This is followed by an overview of industrial sectors along with their CO_2 emissions, alternative decarbonisation pathways and a way forward for Swedish EIIs (Section 4). Section 5 and 6 discuss drivers together with opportunities and barriers for Swedish industry to become climate neutral. Section 7 provides conclusions and recommendations.

2. Materials and Methods

This paper is based on a review study of industrial decarbonisation using Sweden as a case study, considering the significance of the case, its representativeness and applicability of Sweden's approaches to climate action to other regions. We use Robert Yin's approaches to exploratory case study research [38]. The approach aligns with the explorative nature of our research question and our objectives to gain an extensive and in-depth description of a contemporary phenomenon by providing real-world examples and findings [38]. The explorative research design involves both qualitative and quantitative data collection through desk research. Combining qualitative and quantitative data can help create unique insight into a complex social phenomenon that is not available from either types of data alone, and thus, it is often highly desirable [39]. In terms of quantitative data, we draw on databases such as from the International Energy Agency (IEA), the Swedish Energy Agency (SEA), the Swedish Environmental Protection Agency (SEPA) and the Statistics Sweden. Emissions by sector only consider the direct CO_2 emissions from the industry. Downstream emissions from use and end-of-life of the products are excluded.

Qualitative data is based on a systematic literature review of scientific papers, high-quality grey literature, industry reports and policy papers related to industrial decarbonisation. We used keywords such as "industrial decarbonisation", "energy-intensive industries", "energy transitions" AND "industry", "climate change mitigation" AND "industry" as well as a combination of these in relation to decarbonisation of the (1) iron and steel industry, (2) mining, (3) cement, (4) refinery and (5) pulp paper in Sweden and world-wide. For those with relevant titles, we read the abstract, and for those with relevant abstracts, we read the full paper to extract relevant information.

3. Characteristics of the Swedish Energy System and Basic Industries

3.1. Energy Portfolio

In 2018, the total primary energy supply (TPES) in Sweden amounted to 552 TWh [40]. High proportions of nuclear power, hydropower and bioenergy characterise Sweden's energy supply, which together accounted for around 70% of the TPES in 2018, as shown in Figure 1 [41]. Sweden's energy mix has significantly changed within the past decades. The proportion of fossil fuel use has been reduced considerably, mainly due to the transition from oil to other low carbon energy sources [42]. The industrial sector has contributed to the shift of final energy consumption away from oil products towards more electricity, as shown in Figure 2. In addition, there was an increasing supply of biofuels where they become increasingly important in the EIIs, such as for the pulp and paper industry.

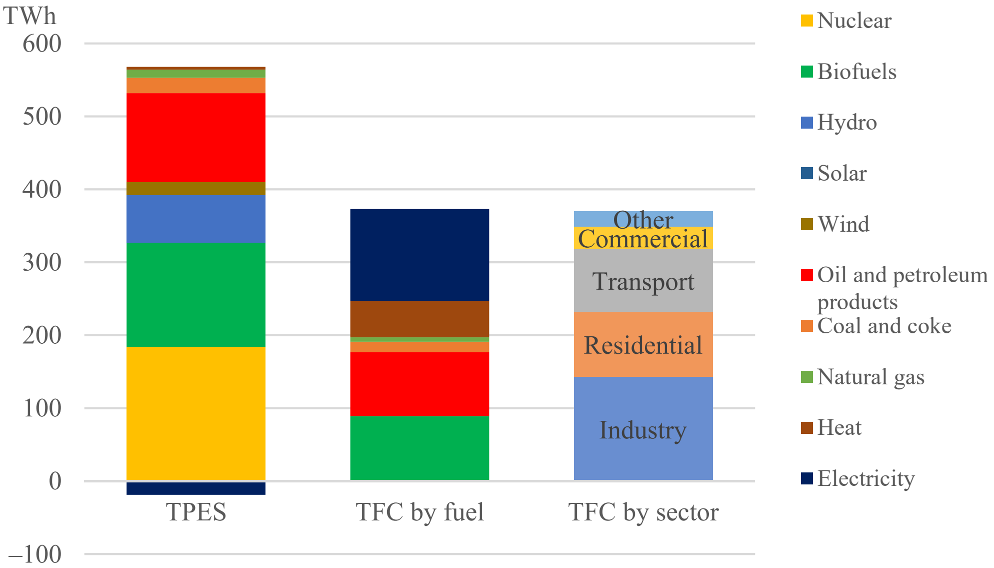

Figure 1. Overview of TPES and TFC by fuel and sector in 2018. Source: Swedish Energy Agency [40].

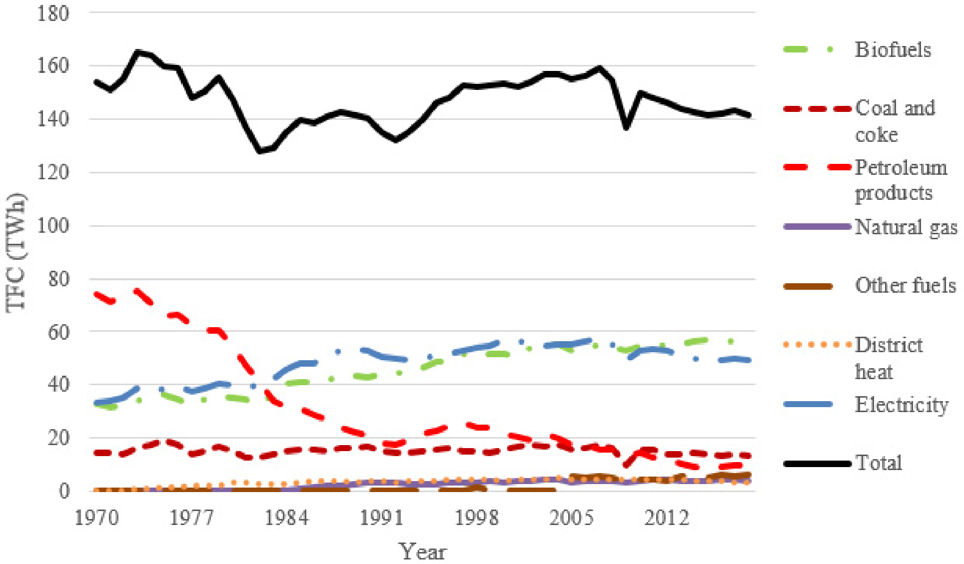

Figure 2. TFC in industrial sectors by energy type. Source: Swedish Energy Agency [41].

Electricity production throughout Sweden was approximately 160 TWh in 2018 and is almost emissions-free, due to the large production from hydropower and nuclear power, together with wind and bioenergy and waste. In 2017, the Swedish parliament set a new target for renewable electricity generation in which the production of renewable electricity should be increased by further 18 TWh by 2030 [36]. The expansion of renewable energy such as wind and solar PV has been promoted through energy policies such as Electricity Certificate System. The expansion of wind and solar PV are pushed by the government in order to reach the target of 100% renewable energy by 2040.

3.2. Emissions Profile: History, Present and Future Outlook

Since the end of the 19th century, rapid productivity growth and expansion of EIIs have boosted the Swedish economy. The use of new technologies and fossil fuels to support industrialisation has led to an increase in emissions. However, the emissions trends were reversed in the 1970s due to the global oil crises and also driven by motives to achieve energy security and competitiveness [43]. In addition, structural changes in the Swedish economy, from the dominance of energy-intensive basic industries to a greater presence of knowledge-based industries with lower energy intensity, have significantly impacted the development of Sweden's energy systems and the reduction of GHG emissions [44]. These shifts made CO_2 emissions drop by a total of approximately 40% between 1976 and 1983 [43].

The total GHG emissions have fallen by more than 25% from over 70 Mt CO_2-eq in 1990, as can be seen from Figure 3. This decline was possible due to an improvement in industrial energy efficiency, a reduction in the use of fossil fuels, and an increasing share of renewable energy sources. The CO_2 emissions in 2018 were 41.8 Mt CO_2, of which industries accounted for about 39% of the CO_2 emission [40]. To meet the EU's climate target for 2030, Sweden's decarbonisation rate should accelerate by a factor of one-and-a-half over the next decade compared with the past three decades. From 2030 to 2050, efforts would need to improve by at least an additional factor of two to achieve net zero emissions goal. However, it should be noted that the emissions reduction trajectory may not follow a linear path, considering the deployment of breakthrough technologies in the long-term can result in rapid emissions reduction.

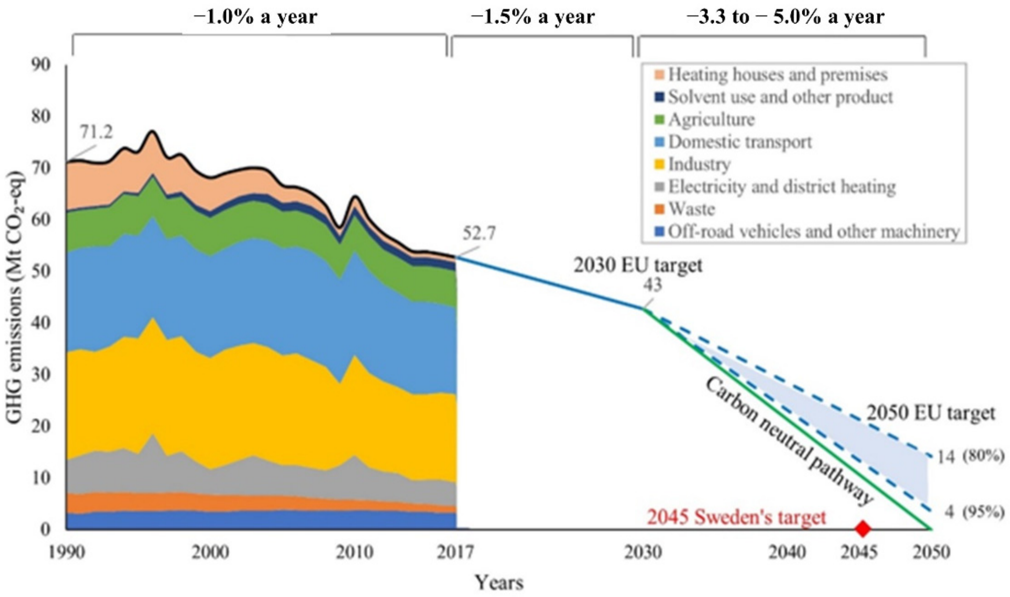

Figure 3. Historical greenhouse gas emissions by sector and the target of net-zero emissions. Source (historical data): Swedish Environmental Protection Agency [45].

3.3. *Swedish Energy-Intensive Industries (EIIs)*

Energy-intensive industries constitute a significant part of the economy and responsible for a large amount of energy use, resource consumption and emissions. This mainly includes the mining industry, iron and steel, aluminium, pulp and paper, chemicals, petrochemicals, cement and glass industries. In 2018, the industry sector used 141 TWh energy, of which around 75% is used in EIIs. Subsectors contributing most emissions are iron and steel, mineral, chemical, pulp and paper and refinery industries, as presented in Figure 4.

Phasing out GHG emissions in the EIIs is challenging from both innovation and technical perspectives. This is due to their substantial carbon emissions, highly capital-intensive companies with long-term investment cycles, dependencies on international markets and limited market incentives [46]. Moreover, EIIs are located early in the value chain, distant from end-consumers: therefore, it is difficult to push forward higher costs generated by improved environmental performance. The best available technologies (BATs) can only lower emissions by 15–30% in these sectors, even if they are applied on a bigger scale [9]. The most effective GHG mitigation strategy is, therefore, to switch to low carbon energy sources. Interestingly, the total energy consumption from the pulp and paper industry is the highest of all industrial sub-sectors in Sweden [40], however the pulp and paper industry has very low emissions compared to other sub-sectors, as most of the energy it uses comes from biofuels and low carbon electricity.

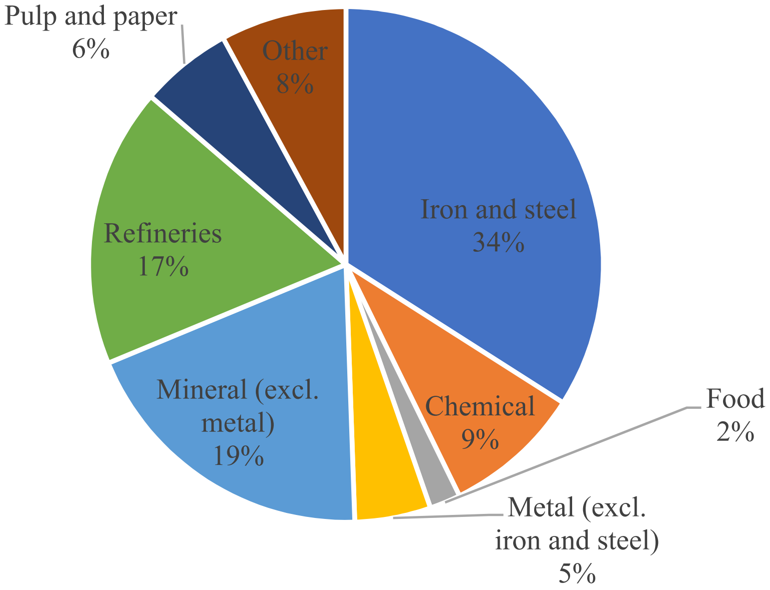

Figure 4. Greenhouse gas emissions from Swedish industry in 2018, as a percentage of total industrial emissions. Source: Swedish Environmental Protection Agency [45].

4. Industrial Decarbonisation

4.1. Technological Options

The GHG emissions from the industrial sector originate from energy use (including those indirectly emitted from electricity use), production processes and fugitive emissions. There are mainly six decarbonisation options to reduce industrial emissions: (1) demand-side measures, (2) energy efficiency improvement, (3) replacing fossil fuels and feedstocks with low carbon sources (e.g., biomass and renewable hydrogen), (4) electrification of the process based on low carbon energy sources, (5) the use of Carbon Capture Utilisation and Storage (CCUS), and (6) the use of negative emission technologies such as Bioenergy Carbon Capture and Storage (BECCS). Demand-side measures cover material intensity reduction through improved product design, product reuse, high-quality recycling, and different business models. These measures are effective for decarbonisation but not a focus of this section.

Decarbonisation of EII sector cannot be solved by one type of solution. For several decades, the main focus has been on short- to medium-term improvements through energy efficiency measures [46]. To a great extent, energy efficiency measures have already been made within the Swedish industries. Yet, to reach the net zero emissions goals by 2045, more ground-breaking technological changes are required.

Replacement of fossil fuels by electrification based on low carbon energy sources, biomass, renewable hydrogen or the use of CCUS and BECCS could bring substantial emission reductions. Nevertheless, these options are not necessarily straightforward since they require fundamental technological changes, including developing and introducing new core processes technologies and infrastructures. CCS is commercially and technically viable option for most large combustion industrial plants to keep their existing production processes [47,48]. However, CCS imposes additional costs on industries that prevent its wider implementation without substantial economic incentives. The other alternative measures such as electrification or fuel switching, could be more cost-competitive through further innovation. BECCS is a negative emission technology that can be used to abate, or offset, emissions from sectors where low-carbon options are lacking.

Each subsector within the EIIs has its specific technical challenges to producing basic materials with zero emissions. In the following subsections, the current decarbonisation status and decarbonisation pathways for different Swedish industries, alongside their emission reduction potential are further discussed.

4.2. Decarbonising The Iron and Steel Industry

4.2.1. Current State

Iron and steel are produced at thirteen plants in Sweden: two integrated iron and steel productions with blast furnaces (BF), one ore-based direct reduction plant (DRI) and ten scrap-based steel production plants. The average annual crude steel production in 2019 was 4.7 million tonnes. The main processes currently used in Sweden for reducing iron ore to iron is the BF process. The BF is fed with iron ore, limestone and coke to firstly produce liquid iron. The liquid iron is then converted into steel in a basic oxygen converter (BOF) and subsequently processed in secondary metallurgy. In scrap-based steel production, steel scraps are melted in electric arc furnaces (EAF) to produce molten steel. Electricity is mainly used for this process, but natural gas and a smaller share of coal are also used as fuels.

The iron and steel industry emitted 5.7 Mt CO_2-eq of emissions or accounted for around 11% of total GHG emissions in 2018 [45]. About 80% of the CO_2 emissions from primary steel production mainly originate from the reduction of iron ore into iron in the BF by using coke, both as fuel and reducing agent. Considering this, finding new reduction agents is the key focus towards deep decarbonising the steel industry. The remaining part of CO_2 emissions that come from fuel use can potentially be replaced by biofuels or electrification.

4.2.2. Decarbonisation Pathways

A shift to state-of-the-art technologies has provided an enhancement in energy efficiency, but transformative technologies are still required to achieve deep decarbonisation in the iron and steel industry. There are four main options for deep emission reduction in this sector, focusing on the iron reduction process: the use of biochar to replace fossil coal, the use of hydrogen as a reduction agent, the reduction of iron ore through electrowinning and the implementation of CCS/CCUS. The alternative technologies to decarbonise iron and steel production, along with their emissions and technology readiness levels (TRLs) are listed in Table 1. The concept of Technology Readiness Level (TRL 1–9) is used for grading the level of technical maturity [49], from basic idea to full commercialisation which is established by means of a literature review.

The use of biochar has the potential to decrease fossil CO_2 emission but do not offer fully carbon-neutral steel production. Currently, biochar can only potentially replace metallurgical coke up to 10% in the conventional BF [36]. Hence, this technology needs to be combined with CCS. Beside potential use in the BF, biochar could also replace coal in other heating processes and heat treatment furnaces.

Hydrogen, natural gas, syngas and biogas could be used as the reducing agent in DRI process that enables nearly emission-free steel production. The natural gas-based DRI processes have been demonstrated in commercial scale (e.g., Midrex process), yet the H_2-based DRI process is currently at the pilot–scale trial in Sweden. The other alternative for low carbon steelmaking is smelting reduction (SR) technology. Some of SRs have been commercially proven while others are still under demonstration [50]. Unlike the BF, smelting furnaces operations use coal instead of cokes; thus, it allows full utilisation of biomass substitutes and avoids the need for CCS. The other full decarbonisation option is through electrolytic steel production or electrowinning. However, this technology is still at an early stage of development [51].

Table 1. Technical options for decarbonisation of iron and steel industry including CO_2 reduction potential and technology readiness levels (TRLs). See [49] for a description of the TRLs.

Technology	Description	Example	CO_2 Intensity or Reduction Potential	Technology Readiness Level (TRL) [1]	References
Reference Steelmaking Technology					
Blast Furnace	The blast furnace (BF) is fed with iron ore, limestone and coke to produce liquid iron. The liquid iron is then converted into steel in a basic oxygen furnace (BOF). The BF partly re-uses the BF gas as fuel, but send most of the gas for use in other processes. Biochars have the potential to replace metallurgical coke, but only up to 10%.		1.5–2.2 t CO_2/t steel	Commercial (TRL 9)	[52–54]
Electric Arc Furnace (EAF)	Steel scrap is heated and melted by heat of electric arcs. More than 40% of energy comes from chemical sources by fossil fuels: natural and coal. The fossil fuels could potentially be replaced by biofuels.		0.6 t CO_2/t steel	Commercial (TRL 9)	[55,56]
Alternative Low-Carbon Technologies					
Top-gas recycling blast furnace (without CCUS)	The BF gas is conditioned and recycled in the process, thus re-introducing carbon monoxide and hydrogen (H_2) in the process, which acts as reducing agents.	ULCOS-BF, IGAR	up to 25%; with CCUS can be up to 60%	TRL 7	[54,57,58]
Smelting reduction (without CCUS)	Ores are partly reduced in the pre-reduction unit by using off gas from the smelting unit. Thereafter, final reduction and melting takes place in the smelting unit. The raw iron is then processed in a BOF to produce steel. Unlike the BF, smelting furnaces operations allows for full utilisation of biomass substitutes.	HIsarna	up to 35%, with CCUS can be up to 80%	Commercial (TRL 9)	[58–60]
Direct reduction using electrical arc furnaces	In the process, the reducing agents (natural gas) reacts with the iron ore without melting the iron. The product is a solid iron product called as sponge iron which must be melted afterwards for alloying purposes.	Midrex, HYL	40–60%	Commercial (TRL 9)	[54,60,61]
Hydrogen direct reduction	Instead of natural gas, this process utilises H_2 as the reducing agent. The produced sponge iron is then heated and melted in EAF.	HYBRIT, GrINHy, H2Future, SuSteel, SALCOS	Up to 95%	TRL 5–7	[62–64]
Electrowinning	The electrolysis process transform iron ore into steel plate. With this technology, carbon is replaced by electricity. The BF would be an electric plant, with oxygen being the only gas emitted.	SIDERWIN, ULCOWIN	Up to 95%	TRL 5–6	[9,64,65]
Carbon capture utilisation and storage	CO_2 is captured either before or after combustion. The concept of partial capture is being explored to reduce the cost for CO_2 capture in the industrial sector. The CO_2 can also be used as a feedstock for chemical or material production.	Carbon2Chem, Steelanol	Typical capture rate: 90%	TRL 6–9	[54]

[1] Current Technology Readiness Level with respect to steel production.

Currently, the main priority for decarbonisation in the steel industry in Sweden is to develop H_2-based DRI processes to replace coking coal. In 2016, the main Swedish steel producer, SSAB, together with the state-owned energy company, Vattenfall and the main Swedish iron ore extractor, LKAB has developed a project called HYBRIT (Hydrogen Breakthrough Ironmaking Technology) for a direct reduction of iron ore with H_2 as a reducing agent [66]. The collaborative project covers the entire value chain from pelletising the ore to finished steel. The project also includes the development of large-scale technology for the production of renewable H_2 and storage of H_2. The demonstration facility is planned to begin in 2022. According to the HYBRIT project's target, the process will be ready to be implemented commercially at a large scale at the earliest year 2035 and expected to potentially reduce Sweden's CO_2 emissions by 10% [66].

A study by Vogl et al. [30] found that H_2-based DRI processes would be cost competitive at a carbon price of 34–68 EUR/tCO_2, assuming electricity costs of 0.04 EUR/kWh. The electricity price will highly influence the production costs. Sweden's main advantages in this case is the high share of fossil-free in the electricity mix in combination with a stable grid and relatively cheap electricity. Additionally, with low levelised generation costs for utility-scale solar PV and onshore wind, and it is expected to decline even further, production of H_2-based steel may be achieved at a lower cost [5].

Other projects in the decarbonisation of iron and steel industry focus on electrification and biomass utilisation, such as PLATIS (plasmateknik I stålindustrins ugnar) and ProbioStål. The PLATIS project investigates thermal plasma generated by electricity power to make the kiln processes fossil-free [67]. In the plasma generator, electric arc occurs, which in turn heat up the carrier gas (e.g., air) so that plasma is formed, and could be used for high-temperature processes. ProbioStål project focused on the possibilities of producing renewable energy on a commercial scale from biomass for use in the steel industry, specifically in metal powder production [68,69]. Swedish universities and research institutes also closely collaborate with the steel industry in various projects.

4.3. Decarbonising the Mining Industry

4.3.1. Current State

Currently, there are fourteen iron ore and non-iron ore mines in production in Sweden [70]. The mining and mineral industry is responsible for about 8% of Swedish total CO_2 emissions [71]. Emissions can be broken down as follow: 1% from iron ore production, less than 1% from metal production and around 6% from lime and cement production, as a percentage of Sweden's total emissions. This section focuses on mining and ore industries, while the cement industry is presented in the following section (see Section 4.4).

Carbon emissions are generated across the mining industry value chain. Emissions come from the use of fuels in transportation, mining operations (e.g., grinding, crushing, enriching, etc.), heat for ventilation and processing of iron and metal ores. In the production of ore pellets, carbon emissions originate from fossil oil burners used to heat the ore.

4.3.2. Decarbonisation Pathways

There are several options the mining industry can take to reduce their emissions, including adding renewables to their electricity supply, improving the mining processes, fuel switching to renewable sources and optimising transportation.

A substantial share of the mining industry emissions is driven by electricity supply. Therefore, renewable electricity generation is a crucial carbon mitigation pathway for the mining industry. Electrifying mining equipment offers environmental benefit and more emissions-efficient processes if based on low carbon energy sources. Compared to diesel-powered machinery, electric equipment does not emit diesel fumes or particulate matter, and they generate less heat which means that less energy is needed for ventilation. In addition, the mining industry can also reduce their emissions through process and technology improvements aimed at more efficient operations.

The Swedish mining industry aims at having the world's first fossil-free mine before 2035 [71]. There has been remarkable progress in replacing diesel-powered machines by electric-powered machines that reduce the total energy and fuel consumption. Moreover, electrified truck and conveyor belts have been introduced to replace conventional mining trucks. Ongoing electrification projects in the Swedish mining industry, for example, are at the Aitik mine near Galliväre, Sweden's largest open-pit mine, and at the mine in Kiruna. In addition to electrification, digitalisation and automation transform the mining industry to drive efficiency and optimisation [72,73].

For the burning and refining processes, the progress towards a fossil-free process is still under development. The most apparent way of reducing CO_2 emissions from heat generation is to replace fossil energy with biomass. Within the HYBRIT framework, the industry is exploring the possibility of using biofuels, fossil-free electricity, hydrogen and plasma as a heat source to produce fossil-free pellets [74].

4.4. Decarbonising the Cement Industry

4.4.1. Current State

Among non-metallic mineral industries, cement production accounts for the significant part of the emissions. The Swedish cement industry accounted for about 2.5 Mt CO_2-eq. emission in 2018, corresponding to 4.8% of total GHG emissions [45]. Two cement plants in Sweden are owned by Cementa, producing about 3 Mt/y of cement in total [75]. The major emission originates from process emissions and fuel combustion.

The process emissions come from the clinker production, an intermediate product in the cement production, that occur during the calcination of limestone in the rotary kiln. This contributes to around 60% of the total CO_2 emission while the remaining 40% of emissions stem from kilns' fuels [33]. The amount of biomass in the fuel mix has been continuously increased to reduce emissions from fossil fuel combustion. The plant in Slite, for example, currently has 23% of biomass in its fuel mix [76].

4.4.2. Decarbonisation Pathways

There are four main options to decarbonise the entire cement industry: fuel switching, electrification, clinker substitution and CCS. The Swedish cement industry uses an energy-efficient dry kiln process and estimates that only 2–3% of emission reductions can be achieved through energy efficiency improvements [76]. Fuel switching from fossil fuels to biofuels or via electrification can potentially cut the GHG emissions by approximately 30% [36,75]. In the CemZero project, Cementa and Vattenfall have conducted a pilot study on electrified cement production [77]. This project aims for large scale implementation by 2030. Considering that fuel switching to biofuels still generates biogenic CO_2 and other emissions, electrification offers more advantages since the CO_2 stream will be pure, which eases CO_2 capture. This can significantly lower the cost associated with CCS. The summary of technical options for low-CO_2 cement production can be seen in Table 2.

The process-related emissions cannot be eliminated by electrification or fuel switching since it is released from the raw materials. There are two main pathways to reduce process-related emissions: by substituting clinker with other materials or implementing CCS. The Swedish cement has an average clinker content of 83%. By replacing parts of the clinker with other materials, such as fly ash and slag, the clinker content can be lowered, reducing CO_2 emissions from cement production [78]. A blast furnace slag, a byproduct of steel production, is one of promising clinker substitutes that could potentially reduce emissions by around 15–60% [36]. However, this will no longer be an option if the steel making adopted new direct reduction processes, as described in the previous section. Here, CCS will still be required for the remaining emissions to achieve the carbon neutral target.

Table 2. Technical options for decarbonisation of cement industry including CO_2 reduction potential and technology readiness levels (TRLs). See [49] for a description of the TRLs.

Technology	Brief Description	CO_2 Intensity or Reduction Potential	Technology Readiness Level (TRL) [1]	References
Cement Manufacturing Process				
Dry kilns	The raw materials are ground and dried to raw meal, and then fed to the precalciner kiln. This process is more thermally efficient than the conventional wet process.	0.85 t CO_2/t clinker	Commercial (TRL 9)	[75,79]
Carbon Capture and Storage (CCS)				
Chemical absorption	CO_2 is captured after being generated in the cement kiln via chemical absorption.	Typical capture rate > 90%	TRL 7	[75,80–82]
Oxy-fuel technology	Using pure oxygen instead of air to provide a high CO_2 concentration exhaust gas stream for further capture.	Typical capture rate Full oxy-fuel > 90% Partial oxy-fuel~65%	TRL 7	[59,78,82,83]
Calcium looping	Flue gas containing CO_2 is reacted with CaO-based sorbent to form $CaCO_3$. The $CaCO_3$ is passed to the calciner to produce CaO that is passed back to the carbonator while leaving a pure CO_2 stream behind.	Typical capture rate > 90%	TRL 7	[59,80–82]
Electrification + CCS	Electrification of cement production combined with CCS	Potential = 0 t CO_2/t clinker (if fossil free electricity is used)	TRL 2–4	[75,82,84]
Fuel Switching		Depend on the fuel mix percentage		[85]
Biomass	Combusting biomass as a fuel to provide the necessary process heat.		TRL 9	
Hydrogen	Combusting hydrogen as a fuel to provide the high temperatures required in the cement manufacturing process.		TRL 2	
Alternative binders	Substitution of clinker with lower GHG cementious materials	Average 20–30% CO_2 reduction.		
Fly ash BF slag Limestone and calcined clays		Theoretical potential 60% reduction for substitution levels of over 70%.	TRL 9 TRL 7 TRL 5–7	[86] [82,86] [82,86]
Alternative cement chemistries Calcium sulfone aluminate, geopolymer, magnesium silicate, etc.	All these chemistries have potential to replace limestone, but require extensive piloting and commercialisation.	Depends on the chemistries	TRL 2–4	[87]

[1] Current Technology Readiness Level with respect to cement production.

Two options have been at the centre of interest for CO_2 capture in the European cement industry: post-combustion and oxyfuel combustion [88]. In post-combustion processes, CO_2 is captured after being generated in the cement kiln while in the oxyfuel combustion process, CO_2 is purified from kiln flue gases by applying combustion with pure oxygen instead of air [89]. The post-combustion process is a relatively mature technology and does not involve any modifications to the existing plant if there is enough space available on the site [90]. This technology is mainly based on chemical absorption/desorption using liquid sorbent such as amine solutions or capturing CO_2 via a calcium looping process [48].

Oxyfuel combustion requires process modifications and additional air separation units for the production of oxygen. The development of oxyfuel technology for application in the cement industry is still at the early development stage, but it is expected to be more cost-effective than post-combustion capture [88]. Another promising technology under demonstration is chemical looping [91].

The cost of CO_2 avoided vary among the carbon capture technologies and sensitive to a carbon price. It lies between 42 EUR/tCO_2 (oxyfuel process), which is around halved compared to conventional monoethanolamine-based solvent (MEA), and 84 EUR/tCO_2 (membrane-assisted CO_2 liquefaction process), which is on the same level as MEA [92]. Furthermore, the cost of clinker will increase by 49–92% compared with the reference case without capture [92]. The cost reduction is hence crucial in reducing the investment risk, especially for early adopters and during the maturation of the carbon markets.

4.5. Decarbonising the Pulp and Paper Industry

4.5.1. Current State

Pulp and paper is the largest industrial subsector in Sweden that used around 50% of the total industrial energy consumption in 2017 [41]. This sector uses around 21 TWh of electricity per year, equal to about 15% of all electricity consumption in Sweden. By fully utilising the residual materials from pulp production, the industry can self-generate part of the electricity used in the processes and reduce its dependence on fossil fuels. Currently, the processes in the paper and pulp industry are 96% free of fossil energy sources, so the major emission is biogenic CO_2 [93]. Two-thirds of energy use comes from biofuels (primarily wood fuels and black liquor), and the remaining is mostly electricity [41]. The minor portion of fossil fuels is used for heating purpose in the lime kilns for start-up purposes in the mill's boilers and paper production [93]. Several mills have started to replace fossil oil use in the lime kilns with biofuels in the past years.

4.5.2. Decarbonisation Pathways

Mitigation options to decarbonise further this sector are mainly fuel switching and electrification. The energy efficiency improvement measure is continuously ongoing in the industry, and carbon intensity has been vastly reduced for decades. The fuel switching to biomass is ongoing, especially in the heating process in boilers and the lime kilns. Electricity can replace steam and fuels for heating purposes enabling decarbonisation of this sector. Moreover, the use of plasma generators to replace the fuel in lime kilns is currently being explored.

Since a large share of biogenic emissions characterises the Swedish pulp and paper industry, the future role of this sector in meeting climate goals is as a supplier of renewable fuels, chemicals, electricity and carbon negative emissions [35]. The integration of biorefineries with pulp and paper mills has been proposed in Sweden [94,95]. It will enable the production of high-value chemical products together with conventional outputs such as transport fuels, lignin, textile fibres and bio-composites.

A shift in perspective is currently taking place within the pulp and paper industry towards greater product diversification in a bioeconomy context. Sweden has unique knowledge, state-of-the-art advanced infrastructure and interdisciplinary research in these areas. Emerging biorefinery technologies enable this product diversification. Several biorefinery technologies can be integrated into an existing pulp and paper mill, including hemicellulose extraction, lignin extraction, conversion of cellulose to alternative products via several technologies, black liquor (or wood waste) gasification, and separation-refining of extractives from bark or black liquor [96].

As an alternative to the recovery boiler used in pulp and paper mill, black liquor gasification (BLG) converts most of the organic content in the black liquor to syngas while recovering the pulping chemicals [97]. Black liquor gasification has potential advantages over standard recovery boiler such as higher process efficiency, greater end-use flexibility offered by gaseous fuel, reduced air pollutant content and safer [98,99]. In spite of these potential advantages, BLG technologies are still at a demonstration stage and need further development [100]. Black liquor gasification has been researched for the production of dimethyl ether (DME), methanol, Fischer-Tropsch (FT) diesel, synthetic natural gas (SNG), hydrogen and ammonia, constituting a number of possible pathways in various potential biorefinery designs. The most advanced BLG technology is the Chemrec process developed by a Swedish-based technology company and was employed at the BioDME pilot plant [101].

An alternative to BLG is to extract the lignin and hemicellulose from the black liquor. Lignin is renewable organic material that can be used as a solid fuel or raw material for production of various chemicals and materials. The Swedish patented separation process, LignoBoost, enables lignin to be extracted from the black liquor in Kraft pulping mills [102]. Extracted lignin can be upgraded into specialty chemicals, for instance, binder, carbon fibre, lignin-based plastics, dispersants and other chemicals in a wide range of industries. Extracted hemicelluloses can be used as raw material for the production of ethanol and fibre additives. By removing lignin and hemicellulose in the black liquor, the boiler capacity can be increased to allow more pulp production.

Other than pulp for paper, cellulose can be processed into a wide range of products such as textile fibres, ethanol and biocomposites. Ethanol can be produced from cellulose via acid or enzymatic hydrolysis followed by fermentation [97]. In biocomposites production, cellulose can serve as fibre sources formed by fibres reinforced by a matrix of bio-based polymers. However, both biofuels production via BLG and materials and chemical production from extracted lignin or hemicelluloses are not commercialised yet [97].

Various extractives can also be extracted from black liquor or bark and wood chips [96]. The crude tall oil, for instance, can be processed into biofuels, and a range of chemical intermediates for production of adhesives, coatings etc. The processing of crude tall oil for renewable diesel production has increased over the past few years and a number of new production capacity is planned, mainly in the Nordic region [103]. SunPine is a Swedish company that has patented a renewable diesel process technology using crude tall oil as feedstock [96]. The company is an excellent example of how Sweden can develop new low carbon technology and pursue commercial production.

Breakthrough technologies for the pulp and paper industry are also being explored. For example, deep eutectic solvents technology enables pulp production at low temperatures and atmospheric pressure leading to minimal energy, emissions and residues [104]. This technology can replace some of the most energy-intensive parts of the existing process, yet currently still at the early stage of development.

The pulp and paper industry also can act as a site for negative emissions by coupling to CCS facilities. Depending on the plant size, pulping technology and location, the opportunity for adopting CCS vary between different mills [96]. A BECCS project in pulp and paper mill has recently been initiated as a collaboration between Swedish university and industry partner. Currently, there are two CCS pilot projects operated in Sweden: BECCS pilot plant at Värtan biomass-fired combined heat and power (CHP) plant in Stockholm and pilot test facility for CO_2 capture at Preem's oil refinery in Lysekil. Globally, in the power sector, CO_2 capture has only recently been commercially deployed at two coal-fired power plant facilities [22]. In other sectors like the iron and steel and cement industry, CO_2 capture has been proven at commercial scale but not yet widely implemented [22].

4.6. Decarbonising the Refinery Sector

4.6.1. Current State

The refinery industry is the third highest emitting industrial sector accounting for about 3 Mt CO_2-eq. emission in 2018 or 5.8% of Swedish total GHG emissions [45]. There are five crude oil refineries in Sweden with a total refining capacity of around 526,000 barrels per day. The refinery converts crude oil into products such as gas oil, diesel oils, gasoline, aviation fuel, lubricating oil and heating oils for both the Swedish market and export. A majority of the production (>60%) is exported to the international market.

The refinery process results in direct emissions associated with processes, such as fuel combusted at a refinery and downstream emissions at the end-of-life for the products (e.g., transport fuels). The emissions from fuel combusted for producing heat and electricity can be reduced with CCS. However, the majority of the carbon from fossil feedstock remains in the products. The transition from fossil fuels to biofuels in the transport sector has started. In 2017, biofuels accounted for 20.8% of all fuels supplied to vehicles operating in Sweden, based on energy content [103]. Recently, the rapid increase in biofuels is mainly due to the increased use of hydrotreated vegetable oil-based (HVO) diesel and biomethane [105].

4.6.2. Decarbonisation Pathways

Besides process improvements, the refinery industry can decarbonise its production plant by fuel switching to low carbon feedstock (biomass and hydrogen), electrification, and CCS. The first option implies a transition from petroleum refinery to biorefinery or as an integrated industry. A summary of technical options for decarbonisation of the refinery industry can be seen in Table 3.

Refinery products used for heating, such as fuel oils, refinery gases and liquid petroleum gas (LPG) can be replaced by solid biofuels or electric power [36]. However, the replacement of refinery products for combustion engines, such as gasoline, diesel oil, aircraft kerosene, marine gas oil, light and heavy fuel oil is less straightforward due to the required specific quality. Currently, the Swedish refinery industry has developed and introduced a renewable diesel to the fuel market. It is a product from co-processing of bio-oil (tall oil) and light gasoil in conventional oil refineries. Moreover, the development of sustainable aviation fuel is also being explored and planned at the refinery.

Preem, the largest oil refining company in Sweden, has set goals to become the world's first climate-neutral petroleum and biofuels company, with net zero emissions in its entire value chain before 2045 [106]. They have been involved in several research projects related to biofuels, renewable hydrogen, a renewable raw material supply chain and carbon capture [106]. A test facility for CO_2 capture has been operated at Preem's refinery in Lysekil as a basis for a full-scale CCS plant that is planned to be implemented by 2025 [106]. However, considering the CO_2 emissions in a refinery is distributed across several different points with varying flows and concentrations, it is harder to fully capture the emission, which in turn lead to a higher abatement cost.

Table 3. Technical options for decarbonisation of refinery industry including CO_2 reduction potential and technology readiness levels (TRLs). See [49] for a description of the TRLs.

Technology	Description	CO_2 Reduction Potential	Technology Readiness Level (TRL)	Reference
Waste heat recovery	Optimise heat usage and recover waste heat for new purposes	10%	TRL 7	[58]
Electrification	Increased use of low-carbon electricity Use of electricity for general operations and some heating processes. Production of hydrogen with electrolysers	25%	TRL 4–8	[107]
Carbon capture and storage	Partial capture of CO_2 emission, for instance at steam reforming plants (SMR) to produce a low-carbon intensity hydrogen.	25% for partial capture; up to >90% for full capture	TRL 6–7	[107]
Low carbon feedstocks	Integration of bio-based feedstocks, power to-fuels (renewable hydrogen) into the refinery. Negative emissions could potentially be achieved when combined with CCS.	Depending on pathways to produce renewable feedstocks	TRL 3–7	[107]

4.7. A Way Forward for Swedish EIIs

According to the Swedish Environmental Protection Agency's long-term reference scenarios, Table 4 presents the historical emission reductions and scenarios for future emissions reduction in several Swedish EIIs. In this reference scenario, it is assumed that no new technology shifts take place [108]. It can be seen that pulp and paper is one of the sectors that has undergone deep decarbonisation for the past 30 years. The emission in cement and pulp and paper is expected to be lower in 2045 than in 1990, primarily due to the increasing use of electricity and biofuels. On the other hand, it is expected that the emissions from iron and steel and refinery industries will be higher in 2045, mainly due to the increase in production. The total emissions from industry are estimated to decrease by only 20% by 2050 compared to 1990. This implies that achieving the net zero emissions target entails implementing various decarbonisation pathways for various sectors, including negative emissions technology such as BECCS.

Table 4. The characteristics of several Swedish EIIs along with their historical and future CO_2 emissions reductions.

Industry	Capacity in 2018		Total GHG Emissions	Historical GHGs Emission Reduction Rate (% Change)	Future Scenario of CO_2-Emission Reduction [c] (% Change)		Ref.
	Value	**Unit**	**MtCO$_2$, 2018**	**1990–2018**	**1990–2030**	**1990–2045**	
Iron and steel	4.6	Mt crude steel/year	5.7	−1.3%	6%	7%	[45,108,109]
Mining	81.4	Mt ore/year	0.8	49.2%	Not specified	Not specified	[45,70,108]
Cement	3.0	Mt cement/year	2.5	2.8%	−12%	−15%	[45,75,108]
Refinery [a]	21.8	Mt crude oil/year	3.0	33.2%	46%	49%	[45,108,110]
Pulp and paper [b]	6.2	Mt paper and packaging/year	0.8	−58.8%	−64%	−72%	[45,108,111]
Total industry [d]			16.8	−17%	−18%	−20%	

[a] The two Swedish refineries that produce specialty products are not included. [b] The capacity includes paper, packaging paperboard, graphic paper, book and journal paper. [c] According to the report 'Scenarier över utsläpp och upptag av växthusgaser 2019' (Scenarios of emissions and uptake of greenhouse gases 2019, where it is assumed that no new technology shifts take place [108]. [d] Total industry also includes metal, chemical, pharmaceutical and other industries that are not mentioned in detail in this study.

Several industry sectors have voluntarily developed their own roadmap to become fossil free within the framework of the Government's Fossil-Free Sweden initiative. Based on the compilation of these industrial climate roadmaps, it is estimated that around 60–80% of industrial emissions could be reduced by 2045, compared to 2016 by implementing several decarbonisation measures. Electrification and fossil fuels switching to low carbon fuels are two pathways that have been identified as potential solutions for EIIs. However, although considerable emission reduction potential by transition to biomass and electricity is possible, new technological breakthrough is required to achieve deep decarbonisation targets [112]. For instance, fossil free steel production and CCS in the mineral industry are considered important technological shifts. Once new technology is implemented, it can lead to a significant reduction of GHG emissions. Table 5 compiles the industry climate plan towards achieving a fossil free industry and summarises several projects underway in Swedish industries that, in the long run, can lead to major technological shifts and large-scale emission reductions.

Recent work by Sweco [113] reported that the industries' combined measures outlined in the industries' climate roadmaps could lead up to a 78% reduction in total Swedish industrial emissions. The iron and steel industry accounts for the highest CO_2 emission reduction, followed by the overall reductions in chemical, aluminium, refinery and other industrial sectors. Moreover, the report shows that around 37 TWh of additional electricity will be required to cover the new electricity demand from these measures. This corresponds to an increase of 30% of electricity use in Sweden, which will require a large expansion of energy generation capacity over the next couple of decades. Also, if all measures where bioenergy replaces fossil fuel were implemented, this could lead to an increase of 86% bioenergy use compared with Swedish bioenergy use in 2016, corresponding to 75 TWh [113]. The right conditions should be in place to achieve climate neutrality through decarbonisation pathways outlined in the industries' climate roadmaps. This includes sufficient and long-term reliable access to fossil-free electricity and sustainable bioenergy at competitive costs.

Table 5. Compilation of industrial climate action plans within the framework of the Fossil-Free Sweden initiative for decarbonising energy-intensive industries (compiled from: [68,77,93,113,114]).

Industry	Total CO_2 Emission in 2018 (Mt CO_2-eq)	Decarbonisation Pathways		Status in Sweden	Example Projects	Potential Reduction of Annual CO_2 Emission (Mt CO_2-eq/y)
Steel	5.7	Hydrogen	Hydrogen direct reduction of iron ore	Demonstration project	HYBRIT	4–5
		Electrification	Electrification of heat treatment process (<1000 °C) Electrification of heating process (>1000 °C)	Initiated process, R&D	PLATIS	0.3–0.4
		Fuel switching	Switching to biomass-based gas Switching to biochar	R&D	Probiostål	0.5–0.6 0.1–0.2
Mining, mineral and metal	2.2	Electrification	Electrification of processes Electrification of work machines	R&D Test project	Electrified Mine Truck Operation	0.2–0.3 0.5–1
		Fuel switching	Switching to biofuels	R&D	HYBRIT	0.5–0.6
		CCS/CCU	CO_2 capture for reuse or storage in geological formation	Demo and test facilities required		0.4–0.5
Cement	2.5	Electrification	Electrification of heating processes	R&D, test project	Cemzero	0.4–0.6
		Fuel switching	Switching to biofuels in heating process	Currently, 20% biofuels and 50% waste fuel		0.4–0.6
		CCS/CCU	CO_2 capture for reuse or storage in geological formation	Pilot project in Norway		1–1.1
		New products	CO_2 uptake in cement-containing products and new cement varieties	R&D		0.3–0.4
Pulp & paper	0.8	Electrification	Electrification of heating process	R&D		Not specified
		Fuel switching	Replace fossil oil in the lime kilns with biofuels	Ongoing		Not specified
Refinery	2.8	Hydrogen	Replace fossil-based hydrogen with renewable H_2	Test project	Preem-Vattenfall	Not specified
		CCS/CCU	CO_2 capture for reuse or storage in geological formation	Test project, under development	Preem CCS, CinfraCap	Not specified
		New products	Production of renewable fuels	Ongoing process, R&D		Not specified

The uncertainties in sustainable biomass supply and the presence of many sectors competing for biomass resources will be a challenge in decarbonisation planning. A large demand and intense biomass competition are likely to substantially increase future biomass prices compared to current levels [115]. A study by Börjesson et al. [115] showed that under high CO_2 reduction scenarios (Sweden's ambitious climate target) without the fossil-fuel phase-out policy applied, biomass prices increase more than triples, from 19 EUR/MWh in model year 2010 to 43 EUR/MWh in 2030 and, further, to 66 EUR/MWh in 2050. Availability of biomass and the dynamics in demand should therefore be monitored while considering sustainability constraints. Additionally, policy measures for increasing biomass supply and efficient utilisation will be vital to achieving ambitious climate targets in a cost-efficient manner.

It is possible to achieve a 100% renewable power system with an increasingly higher shares of VRE sources in Sweden by 2040, according to the recent report by IRENA [21]. However, access to future renewable electricity will become a much more strategic issue for EIIs due to several uncertainties related to when and how the electricity demand will increase [35]. Good communication and collaboration between different actors are hence essential to avoid power and capacity shortages. The long lead times in permit processes and line capacity expansion also makes it important to plan well in advance. Additionally, challenges related to increasing power system flexibility to accommodate larger VRE shares for a 100% renewable-powered future by 2040 demand an adequate policy environment and solid coordination at local, national and European levels [21].

The IEA analysed the carbon-neutral scenario for the Nordic region and estimated the electricity price in 2050 when the nuclear power in Sweden is replaced with wind power [116]. The estimated electricity price is around 67 USD/MWh, which is higher than the current electricity cost at 55 USD/MWh. However, optimal transmission expansion can provide more flexibility to the European electricity network, which in turn deals with the intermittency of VRE supply and reduces the system-wide cost [117].

A recent study exploring investment needs for deep decarbonising EIIs (steel, petrochemicals, cement and oil refining plants) in Sweden shows that the costs for decarbonising this sector are manageable [118]. The total capital needs of 66 billion SEK in production processes are required to decarbonise these industries, which equals approximately 10% of the total Swedish state transport infrastructure budget for 2018–2029 [118]. In that study, each sector's finance and capital challenges are highlighted to differ considerably, relying heavily on the extent of transformation that will take place. Moreover, it is highlighted that increasing direct public support throughout the next decade could have a substantial impact in speeding up decarbonisation efforts.

5. Drivers of Industrial Decarbonisation

5.1. Proactive Measures to Address the Climate and Energy Challenges

The transition to a low carbon economy within the next decade is imperative. IEA estimates that each year the world delays taking action on climate change, there is an additional $500 billion to the total mitigation cost [119]. This suggests that early, strong action on climate change is much less costly than inaction. As a result, the internationally agreed targets of the Paris Agreement are set, and countries are increasingly taking on stringent national targets. In the Swedish context, the government has set ambitious goals to achieve net zero emissions by 2045 and 100% renewable energy by 2040 [26,27].

5.2. Policy Support

5.2.1. Relevant Policies at International, European and National Level

The Paris Agreement offers a political framework for global climate action and enables countries to set their own commitments for climate change through voluntary Nationally Determined Contributions (NDCs) that are being reviewed every five years [1]. When implemented effectively, it could drive behavioral change in countries by providing infrastructure, strong signal and clear direction to ramp up national commitments to decarbonisation [120]. As a part of the NDC to the Paris Agreement, the EU has adopted a target to reduce GHG emissions by 40% by 2030 against 1990 levels [121].

The EU Emissions Trading System (EU ETS) was launched in 2005 as a central pillar of climate policy to achieve the EU targets. This cap-and-trade system sets a cap on the total emissions that can be emitted by all participants but, within that limit, allows participants in the system to buy and sell allowances as they require. Beside EU ETS, there are policies and measures of relevance to EIIs as follow:

- Regulations reducing emissions of industrial gases
- Energy efficiency directive (EED)
- Renewable energy directive (RED)
- Funding for demonstration of innovative low-carbon technology and investment instruments that can provide capital to energy-intensive industries.

The 2030 target is distributed between two sub-targets, where 43% of the reduction effort shall be covered by the EU Emissions Trading System (EU ETS), regulated by the EU ETS Directive and 30% to non-EU ETS sectors (such as buildings, agriculture, waste and transport) regulated by the Effort Sharing Regulation (ESR) [121]. Recently, the EU Commission has proposed a more ambitious goal by increasing its GHGs reduction target to at least 55% by 2030 [122]. These targets are proposed to achieve the EU long-term target of being climate neutral by 2050.

Sweden's climate policy has progressively developed since the 1980s and continues to evolve towards better integration of EU policy and international cooperation. In 2017, the Swedish government adopted a climate policy framework with a climate act that defines Sweden' implementation of the Paris Agreement [26]. In the long-term target, Sweden aims at net zero emissions of GHG into the atmosphere by 2045, and thereafter negative emissions. There are also milestone targets (2020, 2030 and 2040 targets) towards the long-term goal. In the milestone target, the domestic transport sector should reduce its emissions by 70% by 2030. Moreover, since the EU 2030 target for the Non-EU ETS sectors has been broken down to individual member states level, the climate change act covers in more detail how Sweden can meet the Non-EU ETS target by 2030.

The policies and measures that mainly affect emissions from Swedish industry are the EU ETS, energy and CO_2 taxes, the electricity certificates system, the Program for Energy Efficiency in Energy Intensive Industry (PFE) and the Environmental Code [123]. The overview of these policies is presented in Table 6. The following subsections will further discuss carbon pricing, including EU ETS and other targeted instruments directly related to Swedish EIIs.

5.2.2. Carbon Pricing

There are two types of carbon pricing in Sweden: ETS and carbon taxes, together they form the basis of the cross-sectoral economic instruments of Swedish climate policy. The CO_2 tax was introduced in 1991 and has been the primary instrument for Sweden to reduce fossil fuel consumption in sectors outside the EU ETS and contribute to reaching targets for increasing the share of renewable energy and energy efficiency. The tax has gradually been increased from SEK 0.25/kg CO_2 (1991) to SEK 1.19/kg CO_2 (2020) to achieve cost-effective emission reductions while providing time for households and companies to adapt [124]. In 2005, the EU ETS, with a fixed emissions cap that decreases every year, was launched as the cornerstone of the EU's strategy to reduce emissions. Consequently, most of the Swedish EIIs are regulated by the EU ETS and no CO_2 tax on fuels for these industrial installations.

Since the EU ETS Phase 3 almost all industrial process emissions fall within the EU ETS scope. The ETS covers energy-intensive installations including power stations and other combustion plants, oil refineries, coke ovens, iron and steel plants, the aluminium industry, production and processing of non-ferrous metals, factories making cement, glass, lime, bricks, ceramics, pulp, paper, board, parts of the chemical industry and aviation [125]. The Swedish emissions covered by the EU ETS equal around 38% of total emissions in 2017, where around 80% of these emissions came from industrial plants and 20% from power and district heating installations [123,126]. Sweden requires no additional policies to reach the 2030 emission reduction target of 43% within the EU ETS sectors due to the gradual reduction of the amount of emission permits regulated from the EU. The level of ambition of the emissions reduction in the EU ETS sectors is determined on a joint EU basis, under the trading system regulation.

Several studies have evaluated the quantitative impact of EU ETS Phase 1 to 3 on reduction emission within Europe [127–129]. Several studies find that the EU ETS accelerates the trend of decoupling economic growth from emissions in Europe [130,131]. On the other hand, the EU ETS has also been criticised for not being stringent enough and not resulting in any significant abatement measures since the EU ETS's current performance is characterised by a large allowance surplus and a low carbon price [132,133]. Large allowance surplus has resulted in large profits for the EIIs from a system that is designed to make polluters pay [128]. Consequently, there are calls for more restrictive allocations, mechanisms to address the allowance surplus, and comprehensive carbon pricing to strengthen the abatement performance of the EU ETS in Phase 4.

Carbon leakage (i.e., transfer of industrial production to countries with less stringent or absent carbon pricing resulting in an increase of emissions in those countries) is much discussed in carbon pricing policy. It has been researched both theoretically and empirically yet arrived at mixed conclusions. On the one hand, most ex-post empirical studies have found no statistically significant effects of carbon pricing in the EU ETS on carbon leakage [134–136]. For instance, an ex-post analysis of the steel and cement industries under the EU ETS found no evidence of carbon leakage for the past two ETS periods (2005–2007 and 2008–2012) [136]. On the other hand, the theoretical literature tends to predict significant leakage rates for EIIs (e.g., 5–10% of cement or steel emissions [137]) in the absence of free allocation of allowances or other carbon leakage policies [138]. In term of competitiveness, a review of empirical studies by Arlinghaus finds that no effect of carbon pricing on the competitiveness of companies subjected to the policy [139]. However, it should be emphasized that estimating leakage risk accurately is challenging, and future carbon pricing may affect industrial competitiveness.

Based on the modelling of the aggregate effects of economic instruments in the energy sector at the Swedish level, the EU ETS is the most important climate instrument for limiting emission in the industry sector. However, another study argues that the introduction of the EU ETS does not seem to have had a significant effect on Swedish firm investment decisions in CO_2 reducing measures due to a low carbon price [140]. The current allowance price is just around one-fourth of the current Swedish carbon dioxide tax. Thus, facilities within the EU ETS have a significantly weaker financial incentive to reduce emissions than sectors subject to carbon tax and full energy tax. Here, the price of emission allowances will be of significance for the future impact of this instrument. A robust carbon price can be a strong driver for immediate change, and a clear signal for investment in clean, low-carbon technologies.

5.2.3. Energy Efficiency Measures

The EU has adopted an amended Energy Efficiency Directive (EED) in 2008 that includes a target of at least 32.5% improved energy efficiency by 2030. To adapt Swedish regulations to the Directive, in the 2030 Framework target, Sweden's energy use is to be 50% more efficient by 2030 compared to 2005 [141]. Under the EU EED, Sweden has introduced policy instruments to achieve increased industrial efficiency listed in Table 6.

A broad range of energy efficiency policy instruments such as carbon taxes and EU ETS, energy performance requirements and actions for increased awareness has been introduced. One of the instruments, the voluntary agreement PFE (Program for Improving Energy Efficiency), was introduced in 2004 that focused on EIIs. The PFE offered exemption from energy tax on electricity to EIIs in exchange for the obligation to perform an audit, introduce a certified energy management system, and implement electricity saving measures. However, EIIs would require a more ambitious and clearly defined instrument with a long-term horizon to achieve significant energy saving through substantial investments in core processes' energy efficiency improvement.

Table 6. Key policies related to industrial decarbonisation in Sweden.

Policy Type	Policy	Short Description	Effective Date/Year
Price-based system	Carbon dioxide (CO_2) tax	Most fossil fuel use, as well as low blends of biofuels in gasoline and diesel are subject to CO_2 tax. Emitters to pay a fee per ton of CO_2 they emit, at a nominal rate of SEK 1190 per tonne of CO_2. Industries covered by the EU ETS generally do not pay the CO_2 Tax.	1991
	Energy tax	Most fossil fuels as well as a low blends of biofuels in gasoline and diesel used in the industry are subject to the energy tax. The manufacturing industry pays 30% of the general energy tax.	1924
	EU ETS	Under the 'cap and trade' principle, a cap is set on the total emissions that can be emitted by all participants but, within that limit, allows participants in the system to buy and sell allowances as they require. Includes emissions from major industries, incineration plants and civil aviation within EU.	1 January 2005
Technology support policies	Climate leap	The program aims to reduce emissions by providing local and regional investments in all sectors, except those included in the EU ETS.	2015
	Industrial leap	The program aims to support the development of technologies and processes to significantly reduce process emissions in Swedish industry. Feasibility studies and full-scale investments can be granted.	2018
	Investment support for renewables	The program aims to support solar power and initiatives for wind power through investment support, dissemination of knowledge and information.	2009
Quota system	Electricity certificate system	The system aims to increase the production of renewable electricity. Producers of electricity are allocated a certificate unit for every MWh of electricity generated, which can then be sold in an open market. The purchasers are mainly electricity suppliers having quota obligations.	2003
Command and control regulations	Environmental code	The code contains general rules for consideration to be observed in all activities and measures that affect the environment including GHG emissions.	1 January 1999
Information and voluntary approaches	Energy audit	Large companies are required to conduct an energy audit at least every fourth year except they have implemented an environment or energy management system.	2010
	Energy step	Energy efficiency program where companies can get support for projecting energy efficiency actions or investing in energy efficiency measures identified in the audit.	2018
	Grants energy audit	Financial support to small and medium-sized enterprises (SME) to conduct an energy audit.	2010
	Energy and climate coaches	A national initiative that combines coaching and knowledge transfer between participating companies to improve energy efficiency.	2016
	Energy efficiency network	A network project for SMEs that supporting them to introduce energy management principles. The networks has regional coordinators and energy experts.	2015
	Information	Provides useful knowledge and tools on how to mitigate climate change and adapt to climate change.	

5.2.4. RD&D and Technology Support

The risk of carbon leakage accentuates the challenge of forcing future emission reduction at a higher price. In this sense, the long-term policy to promote low carbon technologies will play a pivotal role in substantially reducing GHG emissions while avoiding carbon leakage and maintaining EU industrial competitiveness. Depending only on carbon pricing for driving long-term global decarbonisation is inadequate for achieving cost-effective mitigation, as believed by many economists [142–144]. In the EU level, various funding such as "Innovation Fund" is intended to help EII and the power sectors meet the low carbon innovation and investment challenges. This program uses the EU ETS revenues to fund highly innovative technologies and flagship projects that could lead to substantial emission reductions [145].

Public research, development, and deployment (RD&D) can foster the deployment of innovative technologies necessary for decarbonisation and signal the government's commitment to the low carbon transition. At the national level, the Swedish Government has launched The Industrial Leap as a long-term initiative to prepare the Swedish industry for the future. This program aims to support the industrial sector's transition to zero emissions, from studies to large scale investment, through technological development. The program was funded with 300 million SEK in 2018 and 2019, and is currently being proposed to be doubled (600 million SEK) from 2020 to 2040. A project of interest is HYBRIT, an innovation program to develop a process for hydrogen-based direct reduction for steel production. The Swedish Energy Agency (SEA) also supports different research projects regarding CCS. Recently, the government has an interest in further investigating and proposing ways forward for negative emissions, such as BECCS and CCS, which may be required over the long term to reduce some of the process emissions that are unavoidable in some sectors.

Enacting the right policies can make an investment in cleaner industrial processes more profitable and significantly accelerate emissions reductions. Moreover, the targeted technologies support policy for EIIs, including funding for RD&D up to market development, is necessary. Public-private collaboration on RD&D will also be essential to accelerate innovation and technological solutions through knowledge, cost and risk-sharing.

Policies on renewable electricity generation and reduction obligation also have a significant impact on current industrial decarbonisation. Sweden has increased the share of renewables with the range of policies and measures such as electricity certificate system, tax relief, tax reduction and support for solar and wind power. In Sweden, a reduction obligation quota has been introduced to promote the switch from fossil to renewable transport fuels, which means that fuel suppliers must reduce GHG emissions from petrol and diesel by blending sustainable biofuels. The increasing biofuel requirements have created a window of opportunity for the refinery sector to engage more in biofuel production and reduce their carbon footprint.

5.3. Cooperation

The Swedish government's ambition towards the net zero emission target requires mobilisation of the whole society. For that purpose, the Swedish government initiated Fossil Free Sweden, which acts as a platform for dialogue, knowledge exchange, and collaboration between the actors and the government [37]. Through the initiative, thirteen industry sectors have set up their own roadmaps containing commitments for the stakeholders and political solutions [37]. Moreover, these roadmaps include a climate target plan, detailed plans for possible technologies and pathways for fossil-free, RD&D priorities, investment issues, policy pathways and obstacles. This shows how the business sector is also driving the transition in Sweden.

The government also support the transition through funding research and innovation spending on low carbon technologies. For instance, industrial decarbonisation projects such as HYBRIT, CemZero, Preem CCS are partially funded through the SEA. The SEA is involved at every stage of the chain, from research to development, demonstration and commercialisation.

Successful deployment of industrial decarbonisation is more likely to occur when the entire supply chain actors highly engage in creating solutions [25]. For example, The HYBRIT project that encompasses the entire value chain from mining to steel production is one attempt to enable sustainable transition through cooperation across the value chain [146]. The Swedish refinery sector has initiated strategic partnerships with the forestry-based industry and biorefinery to efficiently produce biofuels and also with the potential customer to develop the renewable fuels market (e.g., aviation sector) further. Effective collaboration is crucial throughout the technological development process until technology can be successfully implemented.

Collaboration is also the best way forward to accelerate the process toward achieving carbon neutrality. Another unique collaboration is CinfraCap (Carbon Infrastructure Capture) project that involves various industries in western Sweden. The project aims to identify an optimised joint infrastructure to transport liquefied carbon dioxide and aspires to share the experience and the business model with the rest of Sweden and the world.

5.4. Technological Capabilities

Sweden is prominent in several areas of research and innovation, including in low carbon technologies. Investments in environmental R&D have made Sweden an innovation leader for several clean energy technologies such as biofuels. Through decarbonisation measures discussed in Section 4, Sweden targets EIIs to become more energy and resource-efficient and free of CO_2 emissions. Despite the high cost of current clean technologies, as the technology R&D progresses, learning curves and economies of scale will decrease costs, making them more competitive against conventional technology [147].

5.5. Public Awareness about the Environment

Market trends and customer preferences also drive growth to a low carbon economy. As the climate movement gains momentum across the globe and in Sweden, such as Fridays for Future, a gradual shift in consumer and business sentiment towards low carbon goods has been started. The public's awareness of the environment could also incentivise industrial decarbonisation by influencing governments to enact certain policies. Generally, Swedish are environmentally conscious consumers with positive knowledge and attitude on green product and green purchase [148].

6. Opportunities and Barriers

6.1. Opportunities

Industrial decarbonisation can offer some environmental, technical, economic and political opportunities. From an environmental perspective, significant emissions reductions contribute to global climate change mitigation and local air quality improvement. On the other hand, significant decarbonisation efforts allow a country to become a frontrunner in industrial decarbonisation. For instance, it may lead to a higher probability to obtain grants for RD&D and innovation projects. Moreover, through RD&D in low carbon technologies, businesses can build up competencies and generate technical and best practice expertise that substantially contribute to a nation's competitiveness [149]. Successful technology implementation can be transferred and being adopted in other industries around the world.

International cooperation can strengthen the coordination of RD&D efforts and pool resources for developing and transferring new technologies and other solutions needed to decarbonise EIIs [150]. For instance, the Swedish refinery company intends to collaborate with the Northern Lights project, which is part of the full-CCS Norwegian project. The captured CO_2 from the Swedish refinery is planned to be stored in Norway, considering Norway is leading in this area and has better geological conditions for storage than Sweden.

Several studies have shown that a transition to a low carbon economy, though it needs large investment, will also bring welfare benefits and economic opportunities [151–153].

A low carbon transition can offer innovative companies opportunities to develop and enter new 'green' markets. It could also bring emerging employment opportunities and emerging skills requirements in a low carbon economy.

Finally, the regulatory pressure has increased due to covid-19, with the EU's 2030 Climate Target Plan requiring a green economic recovery and therefore stepping up the EU's ambitions for achieving GHG emissions reduction targets of 55% or more by 2030 and carbon neutrality by 2050 [154]. This will require industrial decarbonisation in the next couple of decades.

6.2. Barriers

The barriers to the deep decarbonisation of industries are divided into four categories, namely technical, economic, market-related and institutional.

- Technical

From a technical perspective, many barriers exist, such as the fact that many low emission technologies or even negative emission technologies are still at an early stage (e.g., R&D, pilot stage, demonstration phase). It will take many years before some technologies will be market ready and commercialised at large scales, such as for hydrogen-based steel production or BECCS. In addition, significant additional electric capacity and biofuels will be required to accommodate the increased electricity and bioenergy demand of EIIs (see Section 4.7). In the case of steel production in Sweden, the HYBRIT project alone will require an additional 15 TWh/year of electric capacity [155]. Other additional capacities will be required if other EIIs also require higher amounts of electricity, such as electrification, hydrogen production, digitalisation and automation. A higher electricity demand will create immense pressure on the already strained electricity grid. Lack of grid capacity may delay the electrification of the processes in the industries and entail risks for Sweden not reaching the climate goals. Therefore, it will require more enhanced energy planning at the local, regional and national level

The widespread adoption of hydrogen in industrial sector requires upscaling of hydrogen production, distribution, and storage infrastructure. Large scale deployment of CCS also needs supporting CO_2 transport and storage infrastructure. Thus, the co-evolution of infrastructure and new technologies are the key to overcome barriers to industrial decarbonisation.

- Economic

Another barrier is of economic nature. Decarbonising the energy-intensive industries will, in the short-term be more expensive than business as usual. Currently, the exact costs of many future technologies for decarbonisation are not entirely known, however estimates exist which vary a lot between technologies, size and industrial sector. In the long-term decarbonisation will be economically beneficial for EIIs they will save on fuel costs, which are often a considerable share of the overall costs. There will be steep technological learning curves, which will in the long-term result in economies of scale and hence reduced costs. Renewable energy is the cheapest energy source in Sweden, particularly hydropower, due to abundant hydropower resources that can be exploited at large scales, no fuel costs, electricity pricing policies that dis-incentivise fossil fuels due to carbon taxes and the EU ETS.

- Market

Market barriers are related to uncertainties around the creation of new markets, new customers, new business models, new customer behaviour and pricing strategies. For example, it is too early to say how large the demand will be for hydrogen-based steel or low carbon cement. At the same time, new value chains will be formed in future industrial transitions towards decarbonisation. This means that industrial sectors will be linked to each other that previously were not linked to each other or that were linked through different products and in different ways. One example is the refineries sector and its planned transition to biofuels which could be linked to the byproducts of the pulp and paper industries.

- Institutional

From an institutional perspective, policies are a strong driver of deep decarbonisation of EIIs. Key driving policies are the Paris Agreement and the EU Green Deal to achieve climate neutrality by 2050, Sweden's targets to have 100% of energy from renewable sources by 2040 and to have net zero emissions by 2045. At the same time, there are several institutional barriers. For example, the long planning times required for building up electric capacity, the bottleneck of environmental and other permits that can often take years to obtain before a power plant or a wind farm can be built, the lacking coordination between various governmental agencies such as the ministries for environment and the ministries for industries.

Carbon leakage and competitiveness concerns have been a crucial policy challenge and barrier for decarbonising EIIs, even they have not been proven empirically [4]. Under EU ETS, most EIIs have been protected through the free allocation of permits to avoid leakage, yet the effectiveness of the free allocation is a contested issue (see Section 5.2.2). Besides the free allocation of emissions allowances, other alternative policy options for mitigating leakage have been assessed with economic models [124,128]. For instance, carbon border adjustment (CBA), which the EU considers, can lower carbon leakage occurring through goods markets [124]. Carbon border adjustments impose tariffs on CO_2 embodied in imports of certain goods from outside the EU and rebate taxes when certain EU products are exported [128]. These approaches can compensate for differences in carbon prices between domestic and imported products, but they require reliable information on GHG emissions from production activities inside and outside the jurisdiction [5]. The main advantage of a CBA is that more efficient carbon pricing without causing carbon leakage can be introduced while putting pressure on both EU and non-EU companies to reduce their carbon emissions. However, CBA should be thoroughly analysed due to possible retaliation by other countries and burden shift to developing countries [124]. All in all, carbon pricing should be carefully designed and implemented to limit carbon leakage and create a level playing field for EU and non-EU companies.

Many of the above-discussed barriers can be overcome by technological innovation, innovation in business models, adequate policies and financial support. In the Swedish context, there is also a willingness to mitigate climate change and lead the transitions to decarbonised industries by a wide range of actors, including incumbent firms, niche players, the government, financial institutions and the public. Therefore, it is relatively likely that many of the barriers stated above will be overcome within the next couple of decades or even sooner.

7. Concluding Remarks and Recommendations

Industries account for about 30% of total final energy consumption worldwide and about 20% of global CO_2 emissions. While transitions towards renewable energy have occurred in many parts of the world in the energy sectors, the industrial sectors have been lagging behind. Decarbonising the EII sectors is however important for mitigating emissions leading to climate change. Many studies on decarbonisation pathways have focused much on the technological pathways and less on the supportive enabling reforms that would facilitate their uptake. The paper discusses the technological pathways as well as enabling reforms in the review of relevant policies and the analysis of the barriers. The study focused on Sweden as a reference case, as it is one of the most advanced countries in the decarbonisation of industries.

Sweden aims to have 100% renewable energy by 2040 and net zero emissions by 2045. These ambitious climate targets can help put the foundation for both a stable climate and a clear development path. A focus on short-term goals (e.g., 2030) without considering long-term ones would lead to emission mitigations based on the cheapest options, which may lack the potential to reach full decarbonisation. Moreover, it can lead to a carbon lock-in, making it more costly to meet the long-term target. The key to designing long term decarbonisation plan is therefore to consider cost, mitigation potential, and time needed to deployment. The HYBRIT project in Sweden is an example of how a high GHG reduction potential project is prioritised, politically and financially supported despite having a long lead time and high investment needs. Other countries can identify early action that aligns within their overall development strategy. Specifically, with decreasing technology costs, developing countries have opportunities to "leapfrog" fossil-based technologies and follow a low-carbon pathway while avoiding risks of being locked into high carbon energy for decades.

Establishing a shared vision and strategy and co-develop practical roadmaps involving all key actors is critical in achieving complete decarbonisation. Fossil Free Sweden is a unique initiative in Sweden that facilitates both the business sector and politics to find common ways to accelerate the transition needed. Several of the largest industrial firms in Sweden, cities and municipalities have aligned their targets with Swedish goals and developed their roadmaps. The other interesting insight from the Swedish case is that inter-firm collaboration within EIIs become more common and a preferred strategy. Collaboration among partners in the value chain as a need to share risks and costs, exploit complementary know-how between firms as well as co-develop innovative concepts in connection to low carbon technology development. Swedish experiences thus can be an example for other countries in enhancing collaboration across stakeholders, sectors, and borders (e.g., collaboration on international projects).

Early and substantial decarbonisation efforts offer Sweden the possibility of becoming a frontrunner in industrial decarbonisation. If the key innovative technologies to achieve deep decarbonisation (e.g., HYBRIT, CCS/BECCS, electrification etc.) developed by Sweden become successful, the technology can be transferred and adopted in many other countries. Swedish decarbonisation pathways can therefore be a source of inspiration in other countries. The lesson from Swedish experience are applicable across much of the industrialised world. There will be some contextual differences among countries, but combining technical pathways and enabling environment discussion can be more broadly applicable.

The technologies required to achieve complete decarbonisation need to be further developed and tested on a larger scale to reach commercial viability. R&D should target cost reduction, improved performance and reliability of decarbonisation technologies in order to upscale their deployment. Moreover, R&D programs should focus on promoting the electrification of heat-related industrial processes, use of biomass feedstocks, circular economy as well as developing CCUS technologies. Specific R&D programs should target the development of disruptive technologies such as hydrogen, particularly to improve green hydrogen production technologies and finding more efficient hydrogen carriers and energy storage. Lastly, a system-based approach is needed, for instance, considering the continuous nature of many energy-intensive production processes in relation to the intermittent availability of renewable energy.

Government support is essential throughout the innovation process- from basic research, pilot-scale projects to full-scale implementation, to counteract innovation-related market failures, both in the form of financial support for RD&D and market-driven controls. Here, the Industrial Leap is a good example of long-term financial support schemes to make the necessary technological advances. However, to speed up large-scale efforts and put Sweden on track to reach its climate goals, increasing direct public support throughout the coming decade is required. On the other side, the government should also adopt measures that create markets for low-carbon materials, for instance, through regulatory standards or public procurement. Demand for products with good climate performance and public procurement can be powerful incentives for transition.

It is essential to create the right enabling environment so that the needed technology, infrastructure, and financing are available. Policies and incentives that ensured low carbon technologies are developed and deployed at scale are of paramount importance. The EU

ETS is an essential instrument for industrial decarbonisation, but given the current level of ambition and future development of the EU ETS, there is a clear need to identify other mechanisms to accelerate the pace of change. One possibility is to improve integration of climate aspects into environmental assessments according to the Environmental Code for industrial sectors within EU ETS, as being investigated by Swedish Environmental Protection Agency. Moreover, carbon border adjustment may be an option that can be implemented alongside higher carbon prices to address carbon leakage risk.

Some areas of ambiguity in the regulations (e.g., emission calculation methodology, sustainability constraints etc.) should be overcome since it can create high uncertainty about investment condition. Furthermore, there is some scope for improving and streamlining the environmental permit process without eroding environmental protection. Unclear and outdated regulation can slow down industrial decarbonisation, but they are not significant hurdles in general. On the other hand, lack of policy targets, regulatory frameworks, and standardisations to guide and accommodate technology development, such as CCS and hydrogen, are key barriers to be addressed by policymakers.

Industrial decarbonisation requires biomass, electricity and other resources within a sustainable framework. Increase electrification means challenges in terms of capacity and security of supply in the electricity grid. Parallel to this, the electrical system will be converted to 100% renewable by 2040. The electrification strategy that includes an electricity grid expansion plan, and can coordinate these parallel conversion, remove of obstacles, take advantage of possible synergies and ensure transitions take place in a sustainable way is crucial. A significant part of the costs of the transition towards a carbon-neutral economy would come from investments in infrastructure, both for electricity grids and for pipelines of hydrogen and CO_2. To address the infrastructure challenge, governments could consider financing the initial infrastructure.

This paper focuses on supply-side decarbonisation options, yet demand-side measures are inextricably connected to supply-side measures and needed to limit warming to 1.5 °C. For instance, mitigating CO_2 emission using less basic materials (e.g., steel, concrete etc.), improving material efficiency, and implementing circular economy interventions to change the demands. However, demand-side measures do not only depend on innovative technologies and policies, but also on behavioral change, which makes it more challenging. Therefore, policymakers also need to adopt measures that drive behavioural changes and sustainable consumption patterns.

Changes in lifestyles, energy system, and GHG emission-intensive industries will have fundamental implications for Sweden and the EU's economic system and influence the external trade linkages with the rest of the world. The changing external trade patterns and trade flows caused by the actions to reduce the EU's internal emissions could lead to carbon leakage. This carbon leakage phenomenon is thus an important issue that needs to be addressed in formulating climate policy.

Mitigating global climate change requires energy-intensive industries to decarbonise as soon as possible. What we see today is the beginning of a wide-ranging industrial transformation that could well be completed within one generation. The paper concludes that it may be technically feasible and politically mandated to deep decarbonise energy-intensive industries by 2045 or shortly after.

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