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Green Steel Transition

A comparative analysis of Hydrogen-Direct Reduction Pathway Technological Innovation Systems in Korea and Sweden

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Abstract

The steel industry is the world's largest coal consumer and CO2 emitter in the industry sector. When indirect emissions are included, the steel industry is the largest emitter among all other sectors, mainly due to the iron reduction process. However, there are increasing efforts to decarbonize steelmaking technology, e.g., Hydrogen Direct Reduction (H-DR). For instance, Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project in Sweden, - a joint project with SSAB, LKAB, and Vattenfall - succeeded in piloting H-DR and delivered the world's first fossil-free steel. This achievement has inspired other countries to decarbonize their steel industry through a variety of sustainable approaches. The Korean steel industry, particularly POSCO, announced that the company also endeavors to achieve decarbonization through H-DR with its unique technology applied, called HYREX. The H-DR technology adopted in POSCO and in HYBRIT is slightly different, but both companies share the principle of using hydrogen produced from fossil-free energy sources, as an iron reducing agent instead of coal. Nevertheless, getting the technology up and running in Korea is another hurdle, as well as scaling up H-DR in both countries. Therefore, this research aims to examine and compare how the H-DR technology can be diffused in Korea and Sweden to meet the climate target considering the technological innovation system and how they interact to shape the technology development. By analyzing functions that influence the technology diffusion in Korea and Sweden, this research delineates insights into how each country approaches the adoption and diffusion of the technology to meet climate goals based on their different contextual factors. Some highlights from the findings show that Sweden has strong domestic (or EU) cooperation while Korea is much stronger in terms of international cooperation with regards to knowledge sharing network. Moreover, policies, such as Carbon Border Adjustment Mechanism (CBAM) brought all actors in the steel industry, strengthening particularly the public-private partnership in Korea that has been previously lacking compared to Sweden. Domestic market for green steel is stronger in Sweden. Some lessons are drawn from each country: 1) strengthen alliances; 2) enhance international cooperation; 3) revisit policy instruments to support demand-side measures for green steel; 4) maintain consistent investment in R&D; and 5) conduct transdisciplinary research.

Keywords: green steel, industry decarbonization, H-DR, POSCO, HYBRIT, Sweden, Korea, CBAM

Executive Summary

Background & Problem definitions

According to the Intergovernmental Panel on Climate Change sixth assessment report, the largest GHG emissions come from the energy sector (34%), followed by industry sector (24%)[1] in 2019 (IPCC, 2022). Yet, when indirect emissions from electricity and heat production are included, industry sector becomes the single highest GHGs emitting sector imposing energy-intensive industries more burden to decarbonization efforts (ibid). Among the heavy industry sectors, the steel industry uses the largest amount of coal as a fuel, accounting for 8% of global CO2 emissions (IEA, 2020a). Nevertheless, there is a growing effort to decarbonize the steel industry. For example, two steel producers, POSCO – a Korean steel conglomerate, and SSAB – a Swedish steel producer, co-hosted the Hydrogen Iron & Steel Making Forum (HyIS) 2022 in Stockholm, Sweden. At the forum, actors who are involved in steel industry gathered and discussed near zero emission steel transition (HYIS, 2022). The purpose of the forum is to highlight the role of steel industry in reducing GHGs to meet climate targets, focusing on hydrogen iron and steelmaking technology (ibid).

POSCO is a steel producing conglomerate in Korea and the 6th largest global steel producer in 2021 (World Steel Association, 2021). POSCO announced its long-term planning of development of hydrogen steelmaking already in 2010 as a part of its Green Growth Strategy (POSCO, 2010). Since 2016, POSCO has realized the importance of hydroge-reduced steelmaking technology and started mentioning about H-DR process in its annual report (POSCO, 2017a). Soon after, POSCO come up with its own hydrogen iron & steel making technology called HYREX (POSCO, 2022c). In 2020, POSCO made a pledge to achieve net zero by 2050, and in 2022, POSCO announced its plan to enter the demonstration stage of HYREX in 2025 (ibid). The HYREX technology is yet in a theoretical stage, with land acquisition underway for the plant construction (Kyongbuk Ilbo, 2023).

SSAB is the 50th largest global steel producer, located in Sweden (World Steel Association, 2021). The scale of steel production is smaller compared to POSCO, however, SSAB is a pioneer of hydrogen-based ironmaking technology. In 2016, SSAB together with two other companies, Vattenfall – a state-owned electricity utility, and LKAB – state-owned iron ore mining, announced their climate ambition by collaborating the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project. The project succeeded in operating the pilot plant for sponge iron production in Luleå, Sweden in 2020, delivering the world first fossil-free steel ((Swedish Energy Agency, 2021a). The project plans to enter a demonstration plant to produce fossil free sponge iron on an industrial scale to develop an entire fossil-free value chain for primary steel production (Vogl et al., 2018). Notably, HYBRIT has identified the demand side by teaming up with Volvo Cars to contribute to the creation of a green steel market.

Despite the remarkable low-emission transition technology, there is considerable uncertainty about the technology scale-up and its impact on society. The EU's recent announcement on the Carbon Border Adjustment Mechanism (CBAM) could add a layer of uncertainty for both European and Non-European steel producers and ultimately its effectiveness in achieving carbon neutrality. Given this dynamic context in which both countries are in, it is important to note that all countries are in different economic, geopolitical, social, environmental, and technical status, therefore, there is no absolute one-size fit all solution to achieve the industry's

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[1] Global GHG emissions by sector: energy system (34%), Industry (24%), AFOLU (22%), Transport (15%) and Buildings (6%) (IPCC, 2023).

climate goal. All countries have different resource availability, different backgrounds and context. Therefore, this paper aims to identify drivers and obstacles in terms of H-DR technology diffusion in Korea and Sweden.

Research aims and questions

This research paper first seeks to identify the current state of the steel industry in Korea and Sweden in terms of green H-DR and what drives and hinders the technology diffusion and delineate pathways for the further development of hydrogen based green steel to ultimately reach carbon neutrality in both countries. Therefore, the main aim of this paper is to understand and identify the factors through a comparative study between Korea and Sweden which influence the diffusion of green H-DR technology, considering the socio-economic and policy perspectives of technological innovation, and how factors interact to shape and influence the technology development in each country. To better understand the different contexts of Korea and Sweden, research questions are formulated based on the Technological Innovation System (TIS) framework as it helps to identify an internal and external source of dynamics in the structure and functions in a technological innovation system (Bergek, Jacobsson, et al., 2008). The emergence and evolution of the TIS reflects the diffusion of a particular new technology. Using the TIS approach allows to identify the means of diffusion of a technology that has been determined or influenced by entrepreneurs, policy makers and/or other relevant stakeholders (ibid). Among 7 functions, this thesis chose 3 and formulated research questions accordingly (Figure 1-2).

Research design

This research paper chose a qualitative research method to investigate the diffusion of H-DR technology in Korea and Sweden. The choice of this method is motivated by the exploratory nature of this study in order to gain a comprehensive understanding of the drivers and challenges identified by a various set of actors in the steel industry. To ensure the validity, of the findings, this research employed a data triangulation incorporating various sources of data including literature review, interviews with experts in the field, discussions held within steel-related inter/national forum. The decision to use a comparative method along the diffusion of H-DR technology stemmed from the author's motivation to understand diverse backgrounds, contexts and interests in the steel industry that cannot be captured by a technological perspective alone. By conducting a comparative analysis between different regions, Korea and Sweden, this research aims to provide context-specific insights and bring out tailored recommendations for each country which has its own unique opportunities and challenges within its own context.

Results & Implications

The results showed some pronounced differences between Korea and Sweden. With regards to knowledge development whose indicators were the number of R&D and the investment for R&D etc., Sweden is ahead in terms of both the number and the amount of total investment received from Swedish government. Moreover, the domestic collaborations with academia and research institutes have been well settled. Korea, on the other hand, according to the national project platform, there were a couple of joint projects for Green H-DR and the amount of investment from the government was smaller. However, POSCO has been actively engaged in joint international study on H-DR with Australia. Also has organized an international knowledge sharing platform.

In terms of Influence on the direction of search such as additional investment after R&D and policy, the HYBRIT project received additional investment from the EU Innovation Fund with

HYBRIT's shareholders' own cashflow. In Korea, it was not until the EU's announcement on Carbon Border Adjustment Mechanism (CBAM), the cooperation between public-private became more pronounced. However, the amount of investment that the government announced is still smaller considering that the amount of steel production is more than 10 times that of Sweden. In terms of policy, the Industrial Emission Directive, Emission Trading Scheme (ETS) and Eco Design Directive were mentioned by the Sweden/EU respondents, while the Carbon Border Adjustment (CBAM) was mentioned from Korean respondents.

Lastly, in relation to market formation, neither government significantly intervene to create a market for green steel. Instead, it is the steel producers themselves, HYBRIT (or SSAB) and POSCO who have taken the initiative with buyers to establish a value chain within the market. However, the EU acknowledges the important role of the demand side, coming up with the proposal of the revised Ecodesign Directive which tries to include steel. To further boost market formation, governments can play a crucial role as big buyers such as Green Public Procurement. Thus, further discussion and investigation are needed in this regard.

Conclusion & recommendations

Sweden identified key actors and created a strong domestic network to collaborate on R&D with universities, research institutes, etc. Sweden shows that a successful TIS needs stable institutional conditions (Swedish Energy Agency & EU Commission), where actors are supported to gain knowledge and skills from technology experimentation, strong networks (universities, research institutes, corporates, etc.), and invest consistently in learning and policy making process. POSCO, on the other hand, is very active in international collaboration. POSCO has strong international supply chain network with Australia, Southeast Asia, Oman, etc. POSCO endeavers to create a knowledge network platform with other international steel producers to facilitate H-DR whereas a domestic knowledge network was hard to identify. With regards to policies, there are already well formulated policy for the steel industry in Europe, such as Industry Emissions Directive, EU ETS, Ecodesign Directive, but need a room to improve, whereas in Korea, CBAM was the main driver as the EU (6.6%) is one of important POSCO's export market. The market for green steel is not evident, however, a lot of strong signals for green steel demand is emerging which is relatively more pronounced in Swedish domestic market than that in Korea. However, policy tools to support the green steel market formation or green steel price subsidies such as Green Public Procurement, etc., have not been actively considered by either Korea or Sweden. Some recommendations are: 1) strengthening regional alliances; 2) enhancing international collaboration; 3) revisiting policy instruments to support demand-side measures for green steel; 4) maintaining consistent investment and other forms of support in R&D; and 5) conduct cross-disciplinary research.

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Abbreviations (if required)

H-DR	Hydrogen-Direct Reduction
HYBRIT	Hydrogen Break Through Iron making Technology
HYREX	Hydrogen Reduction Ironmaking
TIS	Technological Innovation System
CBAM	Carbon Border Adjustment Mechanism

1 Introduction

Throughout history, iron and steel have had a significant impact on people's lives. Iron and steel have been indispensable, playing a crucial role in shaping human civilization, the rise and fall of global power dynamics between countries, for example through the production of weapons, agricultural tools and so on. In modern society, the role has become even more important in everyday life, including transport, construction, household appliances, and many more. Despite its importance to human society, the steel industry is the largest coal using industry as it is a reducing agent during the ironmaking process (Figure 1-1) and overall is responsible for about 7-8% of global carbon dioxide emissions (IEA, 2020a). The latest report of the Intergovernmental Panel on Climate Change (IPCC) highlights that the primary sources of GHG emissions are energy systems accounting for 34%, followed by the industry sector at 24% (IPCC, 2022).[2] Nevertheless, when considering both the direct emissions from steel industry itself and its indirect emissions such as electricity and heat production that attributed to the industry sector, the GHG emissions share of the industry sector becomes equal that of the energy supply sector (34%) making abatement efforts to decarbonize energy-intensive industries more complicated (ibid).

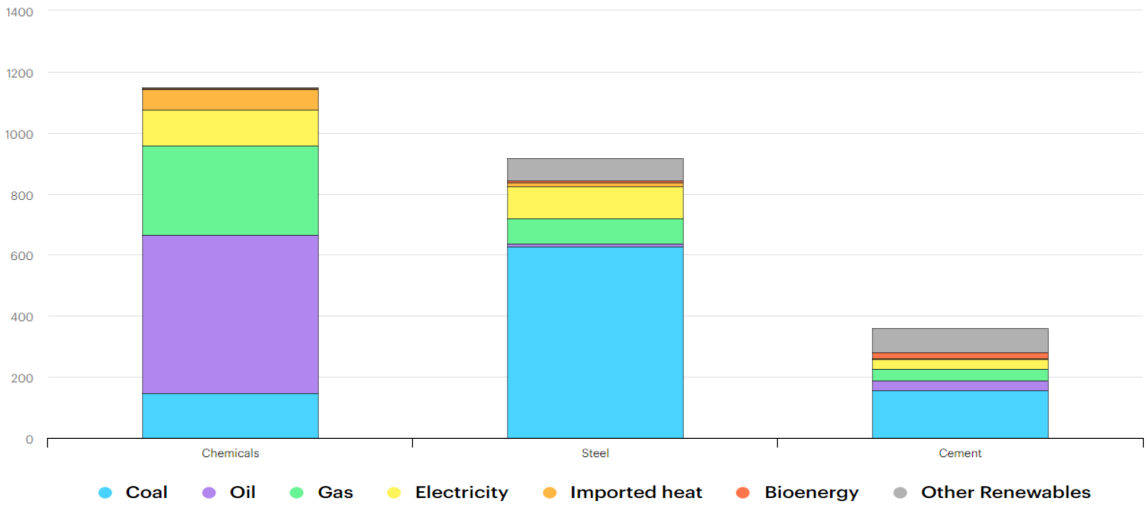

Figure 1-1 Final Energy demand of the heavy industry sector by fuel (unit: Mtoe per year)

Source: IEA, Final energy demand of selected heavy industry sectors by fuel, 2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/final-energy-demand-of-selected-heavy-industry-sectors-by-fuel-2019, IEA. Licence: CC BY 4.0

The steel industry is the backbone industry in both Korea and Sweden; however, it is one of the largest GHG emitters in both countries, being responsible for 11% of the Sweden's total emissions and 15% of the Korea's total emissions (Jernkontoret, 2018; Korea Institute for Industrial Economics & Trade, 2022). This highlights the pressing necessity to decarbonize the steel sector by identifying opportunities and challenges for green transition of the steel industry, as well as addressing gaps between theory and practice. In order to achieve decarbonization, it

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[2] Global GHG emissions by sector (IPCC, 2022): Energy system (34%), Industry (24%), AFOLU (22%), Transport (15%) and Buildings (6%).

is necessary to consider countries' own characteristics and develop context-specific plans and strategies.

There is a growing number of efforts to reach decarbonization in the steel industry both domestically and globally. For example, in 2022, two global steel producers, POSCO – a Korean steel conglomerate, and SSAB – a Swedish steel producer, co-hosted the 2nd Hydrogen Iron & Steel Making (HYIS) Forum 2022 in Stockholm, Sweden (HYIS, 2022). The forum brought together relevant actors - including steel producers, international organizations, hydrogen producers, steel consumers, engineers, academia, researchers, etc. – to discuss the transition to hydrogen-based near zero emission iron and steelmaking technology to highlight the role of the steel industry to meet the climate targets (ibid).

POSCO started as a state-owned steel producer and later privatized in 2000 (POSCO, 2015). It then expanded its business to battery materials, lithium/nickel, hydrogen, energy, construction, and agri-bio, and became POSCO Holdings in 2022 (POSCO Holdings, n.d.). The company is the 6th largest global steel producer in 2021 accounting for 42.96 Mt (World Steel Association, 2021) and announced its 2050 carbon neutrality roadmap in December, 2020 (POSCO, 2020). The roadmap sets out the medium and long-term targets: in short-, mid-term, POSCO is focusing on productivity and energy efficiency by optimizing the raw material mix and the streamlining of operations such as increase the use of scrap in the Blast Furnace - Basic Oxygen Furnace (BF-BOF) process and using H2-rich off-gas as a reducing agent in the existing blast furnace (BF) as well as scaling up Carbon Capture Utilization and Storage (CCUS) technology. The long-term plan is to develop the hydrogen-based ironmaking technology called HYREX and to commercialize the hydrogen-based steelmaking process (ibid). In 2022, POSCO announced its plan to enter the demonstration stage of HYREX from 2025 (POSCO, 2022a). POSCO's HYREX technology is still at a theoretical stage, with land acquisition for the plant construction underway (Kyongbuk Ilbo, 2023).

SSAB is the 50th largest global steel producer, located in Sweden ((World Steel Association, 2021). The annual crude steel production is 8.18 Mt in 2021 (ibid), but SSAB, together with its partner companies, is a pioneer in the hydrogen-direct reduction ironmaking technology. In 2016, after the Paris Agreement, SSAB together with two other Swedish companies, Vattenfall - a state-owned electricity utility, and LKAB – state-owned iron ore mining, announced their climate ambition by collaborating the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project (Pei et al., 2020). In 2018, the project constructed a pilot plant at the SSAB site in Luleå, Sweden and it succeeded in operating the pilot plant for sponge iron production in 2020, becoming the world's first fossil-free steel producer (ibid). The project aims to enter the demonstration stage by 2025 to produce fossil free sponge iron on an industrial scale to develop an entire fossil-free value chain for primary steel production (Åhman et al., 2018). Moreover, Volvo Cars joined the project and collaborated with the HYBRIT consortium, becoming the first customer of fossil free steel (SSAB, 2021).

Although Sweden's success in piloting the H-DR process has clearly shown the world that the steel industry is not a "hard-to-abate", but can be a "fast-to-abate" sector (Agora Industry & Wuppertal Institute, 2023), the actual application and diffusion of the technology may be a different story for other steel producers with different contexts and environment. Therefore, it is necessary to understand the unique characteristics of each country, to examine the factors that lead some countries to successful technology development while understanding the disparities in other countries, to learn lessons from each other, and ultimately to develop context-specific decarbonization plans and strategies.

1.1 Problem Definition

Despite the ambitious plan and collaborative efforts of the steel producers to decarbonize their steel making process, there is a considerable uncertainty about how the H-DR technology can be scaled up and contribute to carbon neutrality while maintaining competitiveness in the market (Vogl et al., 2021). For example, uncertainties remain in areas such as securing renewable electricity supply, grid connectivity, the electricity cost associated with electrolysis to produce green hydrogen for H-DR process, storage of hydrogen, hydrogen cost, investment, trade conflicts and more (Åhman et al., 2018; Kang, 2022; Korea Institute for Industrial Economics & Trade, 2022; Kushnir et al., 2019). In the broader global landscape, the potential impact on climate and international trade of the EU's introduction of the Carbon Border Adjustment Mechanism (CBAM) and the US Inflation Reduction Act (IRA) is yet to be fully anticipated, making it difficult for the steel industry to navigate and adopt adaptive strategies (KEEI, 2022; Project Syndicate, 2022). Given this dynamic context, it is important to acknowledge that each country possesses its own unique economic, geopolitical, social, environmental, and technical conditions. This demonstrates that technology diffusion is shaped by the dynamic influences of various factors, highlighting the importance of considering different dimensions of the socio-technical landscape, encompassing social, economic, and political views.

To be more country- and company-specific, POSCO has published a sustainability report since 1994, with the topic of the hydrogen steelmaking first mentioned in the 2008 report (POSCO, 2008). It was not until 2016 that the company began to address this matter with greater emphasis (POSCO, 2008, 2021a). Despite its early interest in hydrogen-based steelmaking, its HYREX concept was not pronounced publicly until CBAM announcement around 2021. Instead, POSCO was known for being the largest GHG emitter among Korean corporates for the past 10 years, with POSCO alone accounting for 11.5% of total national GHG emissions in 2021 and is still expected to receive the free allowances until 2025 (GIR, 2022; Greenpost Korea, 2022). Although POSCO announced its plan to achieve carbon neutrality by 2050 and its plan for HYREX, details need further clarification, and progress has been relatively slow.

For the HYBRIT initiative, despite Sweden's relative abundance and access to renewable electricity, some concerns are mentioned, such as securing a large amount of renewable electricity for electrolysis for the H-DR process, fluctuating electricity prices, ensuring sufficient transmission capacity of renewable electricity demanded by the H-DR and by other green industrialization initiatives, and grid connection as the technologies scale up (Åhman et al., 2018; Kushnir et al., 2019; Swedish Energy Agency, 2021a). In addition, there have been some worrying voices about excessive public investment in green steel as well as about the potential neglect of the rights of the indigenous Sami people (Henrekson et al., 2021; McVeigh, 2022).

Considering the different pace of H-DR technology diffusion as well as the distinct challenges faced in Korea and Sweden, a comprehensive understanding of each country's own features is prerequisite to formulate plans and strategies that harmonize with their distinct contexts. Therefore, given this significant influence of the steel industry in both countries and their efforts to develop the H-DR technology to meet the climate target, this research focuses on comparing the H-DR development in the Korean and Swedish steel industry, more specifically HYBRIT and POSCO, with an innovation system approach.

1.2 Aim and research questions

The aim of this research is to complement the growing body of knowledge on the H-DR development by applying an innovation systems approach in Korea and Sweden and to contribute to the existing literature on the steel industry decarbonization. By examining the dynamics of technology development and diffusion in these two different geographical locations, this study seeks to understand their different contexts and different approaches to the technology development and diffusion. This research aims to identify the internal and external environments of Korea and Sweden that contribute to accelerating and hindering the diffusion of H-DR as well as the opportunities and challenges that Korea and Sweden face in their green steel transition.

To better understand the different contexts of Korea and Sweden, research questions are formulated based on the Technological Innovation System (TIS) framework as it helps to identify internal and external sources of dynamics in the structure and functions of a technological innovation system (Bergek, Hekkert, et al., 2008). The emergence and evolution of the TIS reflect the diffusion of a particular new technology (ibid). Using the TIS approach, it is possible to identify means of accelerating the diffusion of a technology that have been determined or influenced by entrepreneurs, policymakers and/or other relevant stakeholders (ibid). Bergek, Hekkert et al. (2008) have outlined seven functions and indicators as Table 1-1:

Table 1-1 TIS functions and indicators

System function	Examples of indicators / Data types
1. Knowledge development and diffusion	R&D projects, Patents, Investments in R&D, Workshops and conferences, Size, and intensity of learning networks
2. Influence on the direction of search	Factor / product prices (e.g., taxes and prices in the energy) Regulatory pressures (e.g., quota systems for renewable electricity) Government / industry targets regarding the use of a specific technology Estimates of future growth potential Articulation of interest by leading customers
3. Entrepreneurial experimentation	Number of new entrants. Number of experiments with the new technology. Degree of variety in experiments (e.g., number of different applications)
4. Market formation	Number, size, and type of markets formed. Timing of market formation Drivers of market formation (e.g., support scheme)
5. Resource mobilization	Volume of capital and venture capital Volume and quality of human resources (educational data) Volume and quality of complementary assets
6. Legitimation	Attitudes towards the technology among different stakeholders Growth of interest groups Lobbying activities Political debate
7. Development of positive externalities or “free utilities”	Strength of political power of TIS actors. Activities aiming at uncertainty resolution. Existence / development Pooled labor market

	Information and Knowledge flows

Source: Bergek et al., 2008

All indicators and their functionalities can be crucial to examine, however, this study accentuates more on “knowledge development”, “influence on direction of search,” and “market formation” than the other functions; consequently, research questions derived directly from these functions were formulated. The research questions are as follow:

RQ 1.1 How has knowledge development and diffusion been supported in Korea VS Sweden?;
RQ 1.2 How has the influence on the direction of search been supported in Korea VS Sweden?;
RQ 1.3 How has the market formed for the green steel in Korea VS Sweden?

1.3 Scope and Delimitations

The research focuses on the decarbonization of the steel industry in Korea and Sweden, where the steel industry plays a central role in economies of both countries. There are several different pathways to decarbonized steel production, including hydrogen-based steelmaking, Carbon Capture Usage and Storage (CCUS), scrap, steel substitution, etc. (Bulkeley et al., 2022). This paper concentrates on the hydrogen-based iron and steel making, also known as Hydrogen Direct Reduction (H-DR), as the technology is seen as a promising enabler to realize the respective countries’ fossil-free plans by 2030 in Sweden and by 2050 in Korea (POSCO, 2021a; SSAB, n.d.). The focus on Korea and Sweden was chosen for several reasons: 1) the steel industry is an important backbone industry contributing to the economies of both countries; 2) the steel industry is the largest GHG emitter in both countries, hence the urgency of decarbonization; 3) both Korea and Sweden are committed to developing H-DR; and 4) Sweden, specifically the HYBRIT initiative, is a pioneer in H-DR. This paper examines the decarbonization plans of the steel industry in Korea and Sweden, respectively, with a focus on their individual approaches rather than their interrelationships. Although there are various issues from the global landscape, i.e., overcapacity, scrap availability, grid connectivity, etc., the study remains dedicated to an assessment of the H-DR innovation system as a first step in my research on the decarbonization of the steel industry.

The theoretical and analytical approach of the thesis uses is based on the Technological Innovation System (TIS) framework, which was devised by Hekkert et al. (2007) and soon updated by Hekkert & Bergek & Jacobsson (2008). When it comes to investigating innovation systems, it often uses statistical approaches and overlooks the qualitative aspects of process and information (Hekkert et al., 2007). To solve this, Hekkert et al. proposed the TIS framework that highlights the most important processes that need to take place in innovation systems to succeed in technology development and diffusion. The purpose of using functions of the TIS concept is to understand processes of technological change and innovation (Hekkert et al., 2007; Bergek, Hekkert, et al., 2008; Bergek, Jacobsson, et al., 2008). The choice of applying the TIS framework in this research was motivated by the need to analyze technological change and innovation comprehensively, taking qualitative factors that are often neglected, into account to provide holistic picture of the hydrogen-based steelmaking technology and its surrounding environment (Hekkert et al., 2007). Though the TIS framework is a complete package with seven functions and their indicators, due to the time constraints and some confidentiality that surrounds the technology, not all seven functions could be answered. Instead, the author had to select and tailor some of the functions to focus more on understanding the internal and external environment and its influence on technology development as Korea and Sweden have different socio-economic context and climate strategy around the steel industry and its H-DR technology. Thus, as a first step in analyzing the steel industry decarbonization, the author needed to thoroughly understand the external surroundings of the H-DR holds in two countries. I focused on the "direction of search" (in particular, policy) and "market formation" functions to gain insights into how the external factors have shaped the technology diffusion initiative and the process. Secondly, the "knowledge development" function was chosen to understand the internal factors of two countries. R&Ds in knowledge development is essential in technological innovation as it is the foundation of technological innovation and then used in the production of final goods and leads to increases in growth and enabler of sustainable economic growth (Ulku, 2004). Therefore, due to the aforementioned reasons, functions that are closely related to Function 1. knowledge diffusion, Function 2. guidance on research and Function 4. market formations were prioritized to examine in this paper.

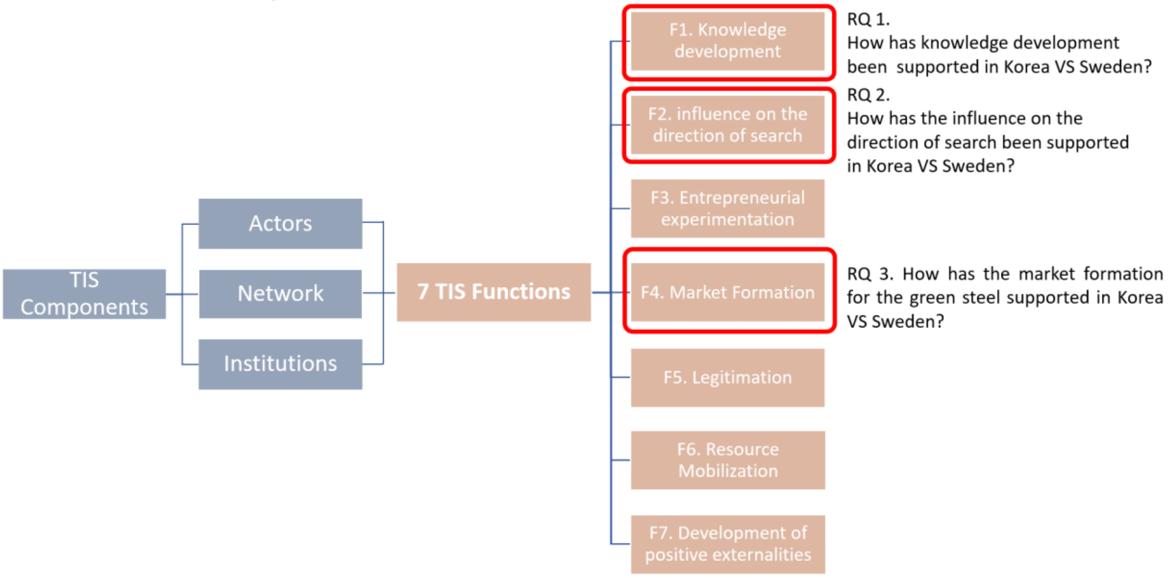

Figure 1-2 Selected TIS for the study

Source: Author's own based on Bergek et al. (2008)

To enhance the reliability as well as validity of the thesis, triangulation of data collection was used i.e., data from grey and white documents, interview, and observation. One of important thesis aims was to capture various stakeholder perspectives who are either indirectly or directly involved in steel space to understand the overall steel industry decarbonization process. Eight interviews were conducted, four from Korean side and four from Swedish side. This process approach conceptualizes development and change processes as sequences of events that occur within the technology specific innovation system under investigation. These events may include seminars on technology, the startup of R&D projects, announcements of the availability of resources and so forth.

1.4 Ethical Consideration

There were no conflicts of interest, and this research was conducted independently by the author on the topic of H-DR technology innovation systems in Korea and Sweden. No one was in the position to influence my analysis and conclusions other than my supervisors. Contributions towards field work expenses in Luleå, Gällivare, and Boden in Sweden were provided by the Central European University in Vienna, Austria, and Lund University. There was no outside organization or third party funding this research.

Participation in the interviews was voluntary, and the participants were offered the choice of anonymity before the interview began and were given sufficient time to consider their participation. Participants were kept anonymous upon request. Data will be carefully stored under the Lund University system. As a researcher, I will ensure non-disclosure, and no harm and comply with all necessary regulations, such as the General Data Protection Regulation (GDPR). Interviewees had the opportunity to screen their responses on the paper prior to the publication upon request. This will include an explanation of the research project, its aim and assurance of confidentiality, and the right to withdraw from the interview. If there is any confidential or sensitive data shared, it will be kept completely undamaged and stored either on the hard drive of a password-protected or in the LU Box.

1.5 Audience

This thesis is intended for a wide audience, including experts, academics, and policymakers interested in industrial decarbonization, especially the steel industry. Given the context-specific character of this comparative study, the actors who are likely to find this thesis useful include stakeholders in Korea and Sweden who are working in the steel industry as well as members of civil society and non-governmental organizations who are working on steel industry decarbonization. It is hoped that this research would offer specialists in the fields of energy and industry, as well as policymakers, with insight that will help achieve carbon neutrality by 2050.

1.6 Disposition

Chapter 1 illustrates the topic of H-DR and the general background of H-DR technology adopted by Korea and Sweden and its importance for the decarbonization of the steel industry in both countries. It then presents the current status and the distinct challenges in H-DR transition in both countries. It further introduces the general characteristics of this research including the research aim, research questions, delimitations and ethical considerations and audience, etc.

Subsequently, Chapter 2 provides a more in-depth analysis of the literature on the green steel transition focusing on the H-DR process as well as conventional steelmaking, i.e. the blast furnace route. It also explains the theoretical and analytical framework that this uses for its analysis and its justification.

Chapter 3 describes a detailed description of the research design, introducing the advantages of using qualitative research method and justification of its use for this study. The methods for data and material collection are introduced, followed by a detailed description of the interview respondents.

In addition to the literature review on existing literature, Chapter 4 further esplains a comprehensive context of each country in terms of its electricity system and its steel industry as a groundwork to better understand aspects that influenced their respective initiatives, positions, etc.

Chapter 5 of this study presents the findings of the interviews, search and observation, providing insight into different perspectives and elements of the H-DR process in each country. The findings are examined in accordance with the tailored TIS framework.

Chapter 6 presents the discussion in which the findings from the interview, search and observation are further discussed and interpreted and placed in the context of existing literature and research. After, the author articulates reflections of this research.

Finally, in the last chapter, conclusions and recommendations are proposed summarizing the overall research, highlighting the importance of the research, and also suggesting further research in this area.

2 Literature Review

This chapter illustrates the literature review, followed by the theoretical & analytical frameworks that the research is based on.

2.1 Current knowledge related to H-DR

2.1.1 Iron and steel production

Simply put, steel is an alloy of iron and carbon that is the most widely used material in the world (Bulkeley et al., 2022; Vogl, 2023). Steel can be produced from two different raw materials: iron ore and steel scrap. Primary production is the process of manufacturing steel from iron ore, while secondary steel production is the recycling of scrap (Vogl, 2023). The distinction between primary and secondary production, however, can become less definitive, since scrap is also used as a feedstock in primary production and virgin iron can be used in secondary production (IEA, 2020; Vogl, 2023). Primary steel production is more complex than secondary production, with the blast-furnace - basic oxygen furnace (BF-BOF) route being the most common method, accounting for around 70% of global steel production and 90% of primary production (IEA, 2020a). Figure 1-3 shows the three main stages of steel production: raw material preparation, ironmaking, and steelmaking (ibid). Following mining and beneficiation, iron ore requires further processing prior to the ironmaking stage. Iron ore fines need to be agglomerated through sinter or pellets (ibid). The ironmaking stage involves two chemical reactions: the reduction reaction and the melting reaction.

Coal serves as the main energy source for the steel industry, accounting for around 75% of its energy demand (IEA, 2020) and is referred to as metallurgical coal (Vogl, 2023). Some of its main roles are as: a fuel to supply heat to the plant, and a chemical reducing agent to convert iron ore (iron oxide) into iron, etc. (Díez et al., 2002; Vogl, 2023). The steel industry is currently the biggest industrial consumer of coal followed by the power sector (Vogl, 2023).

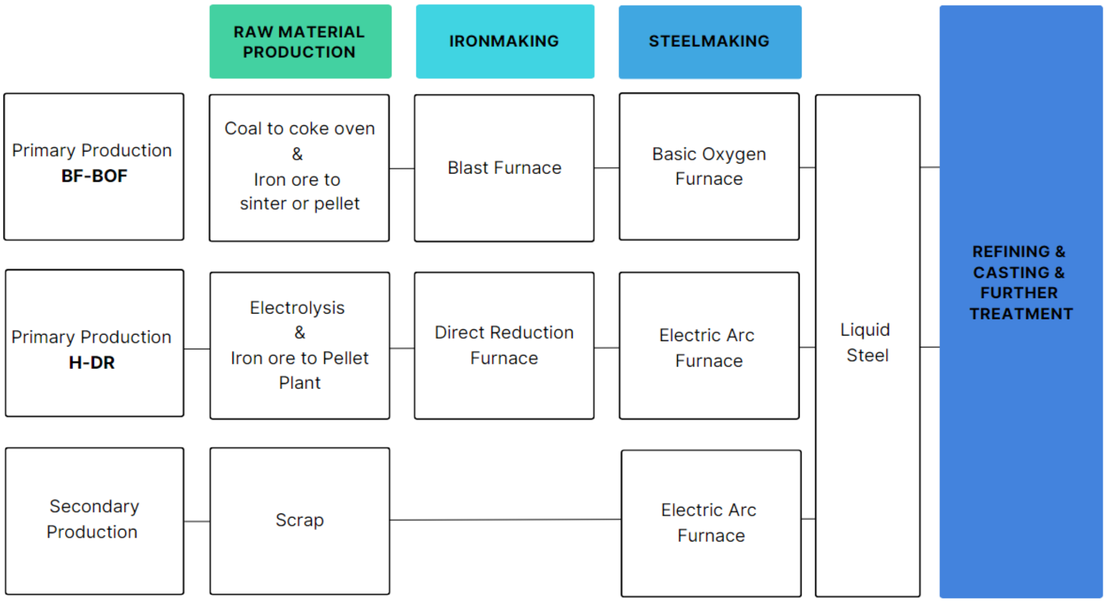

Figure 2-1 Primary production (BF-BOF) & H-DR, and secondary production pathways

Source: Author's own based on IEA (2020) and Vogl et al. (2021)

Blast Furnace - Basic Oxygen Furnace (BF-BOF) Route

The blast furnace is the most dominant plant used in ironmaking stage for the primary production (IEA, 2020). The blast furnace is a mature production system that has been used for the last thousand years, and fossil coke has unique desirable mechanical properties making it hard to replace with less emitting alternatives (Vogl et al., 2021). One reason why the steel industry is often labeled as 'hard-to-abate' sector is that the majority of steel industry emissions come from the ironmaking stage, where fossil coke is used to reduce iron in the blast furnace (Vogl et al., 2021). During the reduction reaction, when iron ore (Fe2O3) meets coke (CO), liquid iron (Fe), known as hot metal or pig iron, and carbon dioxide (Co2) are produced, and this is where the highest direct CO2 emissions are generated in the steel industry (Korea Institute for Industrial Economics & Trade, 2022; V. L. Vogl, 2023). The hot metal produced is put into the basic oxygen furnace (BOF), where oxygen is injected to decrease the carbon content of the steel produced. Following that, the liquid steel produced in the BOF is subsequently casted, rolled and processed into steel products (Suopajärvi et al., 2017; IEA, 2020).

Due to the steel industry's dependence on metallurgical coal, primary steel production, especially the BF-BOF route, is by far the largest source of GHG emissions from the steel industry. Blast furnaces have relatively long lifetimes, about 17 years, thus, investment decisions to construct new or refurbish existing plants can lock-in significant emissions and future climate change (Vogl et al., 2021). Vogl, Olsson, and Nykvist emphasized that substantial changes must be made to the primary production process in order to decarbonize the steel sector. These changes can be made either by redesigning the blast furnace with a lower-emission application or by replacing the blast furnace with another technology, such as the H-DR process, which has recently gained significant attention in the steel industry (Vogl et al., 2021). Subsequent to the Paris Agreement, several steel producers have announced their plans for green steel (ibid). However, due to the geographical variations, predominantly in Asian countries with relatively young and large-scale BF-BOF route makes it difficult to rapid transition and maintain industrial competitiveness (Kim & Sohn, 2022).

2.1.2 Green steel transition and H-DR

Until 2010, EU climate policy for energy-intensive industries was mostly focused on efficiency improvements and marginal emission reductions (Åhman & Nilsson, 2015; Vogl et al., 2021). This was done by conserving industrial structure rather than encouraging the systemic change that is necessary to achieve zero emission (ibid). Following 2010, the emphasis shifted to developing technology and innovation to enable deep decarbonization. Innovation funding programs such as Horizon 2020, EU Innovation fund, etc., have fostered technical innovation and the scale-up of novel technologies (Vogl et al., 2021).

As new regulations imposed on emission-intensive industries as well as increasing sustainable investment have contributed to a growing interest in 'green steel', there is a growing body of existing literature on low and zero emission steel production. Green steel is commonly referred to as a strategic approach aimed at making the steelmaking process greener and more sustainable (SSAB, n.d.). According to Griffin & Hammond (2021), green steel refers to a steelmaking process designed to reduce GHG emissions, potentially cut costs, and improve the quality of steel in contrast to conventional processes (Griffin & Hammond, 2021). However, there is no precise definition of green steel yet, rather, it encompasses many different low and zero emission pathways. As the processes of procurement and manufacturing include a wide variety of stakeholders across the globe, there is a different understanding of what 'green steel' really is (Anderson, 2022). Therefore, to understand whether the final steel product falls into the 'green' category, steelmaking technologies, R&Ds, emissions reduction initiatives, and each step of the production process need to be thoroughly investigated (ibid).

The European Steel Association, EUROFER, has defined two pathways for low CO2 steel production: Smart Carbon Use (SCU) and Carbon Direct Avoidance (CDA) (European Steel Association, 2019; Anderson, 2022). SCU involves modifications to existing iron and steelmaking plants that still rely on fossil fuels that help reduce the use of CO2, such as Carbon Capture and Usage (CCU) and Carbon Capture and Storage (CCS), while CDA includes hydrogen-based metallurgy, generated from renewables, to replace coal as the main reduction agent for ironmaking stage (ibid). However, the EUROFER roadmap did not define what green steel is, nor did it explicitly categorize the extent to which low or zero CO2 pathways, based on different technologies, qualify as green steel. Muslemani et al. (2021) pointed out that the research or consensus on concept of green steel remain lacking. The definition of green steel has been seldom used in the academic literature and when its used, its meaning is broad (Muslemani et al., 2021). The existing literature on green steel indicates a gap in the definition of what green steel is, therefore, it shows the need for further clarity in categorizing pathways that qualify as low or zero emission pathways in primary or secondary production.

In addition to the issue of varying interpretations of green steel, the steel industry encounters the problem of cost competitiveness of lower emissions steel. In spite of the substantial investment allocated to R&Ds on technical innovation, there are uncertainties around the business case for green steel production (Kushnir et al., 2019; Vogl et al., 2021). The reason for the lack of widespread adoption of low-emission steel production is that the lack of certainty on cost competitiveness both in Europe and non-Europe, requiring the provision of public support for its implementation (ibid). This is where active policy can come and play a significant role in providing support to the green steel (Vogl et al., 2021). Vogl et al. (2021) conducted an extensive analysis to identify the policy instruments available for the early commercialization phase of green steel including both the supply and demand sides.

Hydrogen-Direct Reduction (H-DR)

To completely decarbonize primary production, GHG emissions must be entirely avoided or must be captured and stored (Vogl et al., 2021). One of GHG-avoided pathways for primary production that can replace blast furnace is hydrogen direct reduction (H-DR). In this pathway, hydrogen, that is produced through electrolysis from renewable electricity, replaces the use of coke as a reduction agent. Consequently, when iron ore (Fe2O3) meets hydrogen (H), water (H2O) is generated as a by-product and no carbon dioxide is produced (Åhman et al., 2018). The H-DR process typically involves the feeding of pre-heated iron ore into a reduction shaft, where it is converted to direct reduction iron (DRI) and then further compacted to produce hot briquetted iron (HBI). HBI is then fed into an electric arc furnace (EAF) and melted and transformed to liquid steel (Vogl et al., 2018). As the H-DR process is expected to be entirely electrified, the emissions are largely determined by the power grid emission intensity (GEI) (ibid). The decarbonized electricity required for hydrogen production and EAF operation therefore, needs to be ensured (Kim & Sohn, 2022). Although decisions for green steel is pivotal and inevitable, many challenges arise as achieving deep decarbonization requires not only technology innovation but also a systemic change of the steel production process (Vogl et al., 2021). This underscores the industry's commitment to advancing lower-emission technologies, addressing environmental concerns while navigating complex global dynamics. Additionally, although the H-DR process is considered as a fossil-free alternative, and CO2 emissions from the BF-BOF route can be avoided in the H-DR route if renewable electricity is available, it is not completely CO2-free. CO2 emissions are nevertheless still occur in processes such as the mining and manufacturing of iron ore and limestone, lime calcination and the addition of carbon as an essential component of steel (ibid).

At present, H-DR is still under development, and the H-DR process can vary from company to company. Broadly speaking, it can be divided into two main process methods: the shaft furnace method used by HYBRIT and the fluidized-bed reactor adopted by POSCO (Kang, 2022). There are three main differences: difference in materials, in methods, and in carbon emissions (POSCO, 2022a). A shaft furnace uses pellets, iron ore that has been processed into a round shape of a certain size, while a fluidized bed reduction reactor uses iron ore fines directly, which do not require processing (ibid). In terms of method, shaft furnace use hydrogen which is a high-temperature reduction gas, moves from the bottom to the top through the empty spaces between pellets (ibid). These pellets then become DRI by going into the reduction furnace. In a fluidized bed reactor, high-temperature reduction gas is evenly spread through a perforated grid at the bottom of the reactor to mix iron ore fines and start a reduction process (ibid). After going through several steps of reactors, the reduced iron ore fines become DRI. According to the POSCO article (2022), the production of 1 ton of pellets in the absence of renewable energy source can result in 50-150kg of CO2 emission (POSCO, 2022a). However, fluidized bed reactors are not required to produce pellets, as iron ore is used directly without any processing (ibid). The HYBRIT project has set a good example by successfully piloting H-DR and demonstrating the feasibility of fossil-free production to a global audience. The fluidized bed reactors method that POSCO adopted has the potential to exhibit energy and material efficiency, nonetheless its implementation and operation have not yet been realized. Regardless of where the H-DR process stands today, there are several uncertainties surrounding the actual scale-up of the H-DR process.

Figure 2-2 DRI and some stacks of experimental HBI behind

Source: Author's own, photographed at HYBRIT in May 2023

The HYBRIT project has set a good example in terms of H-DR technology and showed the world that steel industry can go fossil-free. SSAB, LKAB and Vattenfall have collaborated HYBRIT project with funding from the Swedish Energy Agency and EU's Innovative Fund. In early 2016, these three companies announced to implement a fossil-free steel production process in Sweden and a pre-feasibility study was initiated (Åhman et al., 2018). In 2017, a research program was set up with the help of the Swedish Energy Agency. Many different partners such as universities and research institutes have been able to engage in this process, such as Luleå University of Technology, Lund University, KTH, Stockholm Environment Institute (SEI), etc. Therefore, knowledge development for H-DR in Sweden has been supported by many different actors (HYBRIT, n.d.).

For Korea, on the other hand, it was hard to find literature, reports or articles that address funding sources for technology development and its associated research or knowledge sharing in Korea. Only a few domestic cooperations with different actors, networks or institutions inside Korea for H-DR development were identified to a limited extent until 2023, the year when reporting under the Carbon Border Adjustment Mechanism (CBAM) comes into effect. It was only some articles published by POSCO described that POSCO will work with the government and Korean steel companies to promote hydrogen-based steelmaking but did not specify. Overall, it gives a strong impression that POSCO is a lonely wolf that needs to pave its way on its own. However, POSCO has been actively seeking cooperation with international actors outside Korea, particularly Australia. For instance, POSCO Group plans to invest in Australia in renewable energy and water electrolysis for hydrogen manufacturing and to manufacture hot briquetted iron (HBI) (POSCO, 2022b). Moreover, POSCO has initiated the first international Hydrogen Iron & Steel Making Forum (HyIS) and it provided a platform for international steelmakers and stakeholders to gather and share knowledge on decarbonized hydrogen steelmaking technology (HYIS, 2022). Such an initiative has fostered knowledge development on a global scale, although knowledge development among academia, firm and government appears to be lacking inside Korea. Recently, the Korean Ministry of Trade, Industry and Energy (MOTIE) announced the Korean steel industry development strategy for the transition to low-carbon steelmaking to respond to the urgency of addressing CBAM (MOTIE, 2023b). It involves R&D investment, publishing steel industry roadmap for the carbon neutrality establishing scrap industrial ecosystem (ibid).

2.1.3 Policy instruments surrounding green steel: Carbon Contract for Difference, Emissions Trading System, and other demand-side policies

Carbon Contract for Difference (CCfD)

Vogl et al. (2021) conducted a comprehensive policy evaluation of supply-side production subsidies and of demand-side market creation policies for the early-commercialization phase of the green steel technology (Vogl et al., 2021). They introduced several policies, including CCfD as a part of a supply-side policy. A CCfD is an EU subsidy agreement that compensates for the difference between the strike price, i.e. the agreed price in the contract between the regulator and a steel producer, and the yearly average price of emissions allowances, i.e. EUAs for a decarbonization project (EUROFER, 2021). It is a project-based financial instrument that provides a fixed carbon price usually over a long-term period around 20-30 years for decarbonization projects (ENGIE, n.d.; Vogl et al., 2021). When carbon prices in markets are lower than the strike price, the government compensates for the difference for each ton of reduced emissions realized by the project in comparison to the conventional technology. When the carbon price is higher than the strike price, the project pays back to the government for the disparity (Figure 2-2) (Richstein & Neuhoff, 2022). This policy applies to the steel industry that allows the steel industry receive the difference between the strike price and the average annual carbon price in the ETS for each ton of CO2 that remained unemitted as a result of opting for a lower-carbon investment option (Vogl et al., 2021). CCfD can be an effective tool by enabling the provision of carbon prices above the level of market prices. Additionally, it can mitigate carbon price risks, hence reducing financing costs. Thus, CCfD can facilitate the realization of the first industrial-scale production of low-emission steel (Richstein & Neuhoff, 2022; Vogl et al., 2021). Nevertheless, there are several concerns that CCfDs alone may not be enough in mitigating the investment risks associated with low-emission primary steel production, particularly for producers moving towards electrification, where electricity prices drive production costs (ibid). A stable carbon price from a CCfD may not always guarantee a business case for green steel, therefore, government support for long-term electricity price arrangement is needed to supplement CCfD (ibid). Most EU energy-intensive industries already get tax and renewable levy exemptions for electricity production (Åhman & Nilsson, 2015; Vogl et al., 2021). In the context of Korea, it has been observed that Korean industries also benefit from low industrial electricity prices (IEA & KEEI, 2022). The industrial electricity price in Korea is among the lowest in OECD countries, with USD 95/MWh in 2019 (ibid). Moreover, additional policies may be required to effectively reduce emissions from energy-intensive materials production, such as more rigorous carbon pricing, including carbon leakage protection is required to ensure a stable investment framework and to incentivize the efficient use of materials (Richstein & Neuhoff, 2022). Although CCfDs have a great potential to support clean technology innovation in energy-intensive industries such as steel industry, thereby reducing CO2, this policy only pertains to the EU member states, and not yet to Korea.

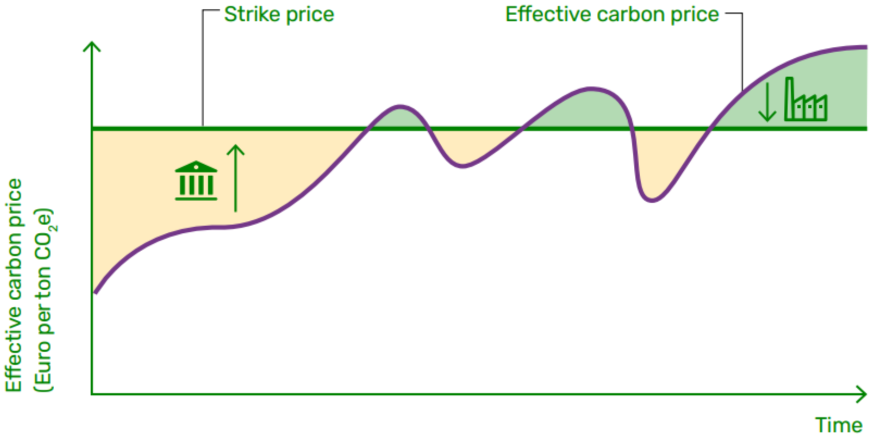

Figure 2-3 Basic functioning of CCfD

Source: Gerres & Linares, 2022

Emissions Trading Scheme (ETS)

Many studies have highlighted the importance of policies for the steel industry decarbonization, such as the Emissions Trading Scheme (ETS), as well as its link to other policies, such as CCfDs (Muslemani et al., 2021; Richstein, 2017; Richstein & Neuhoff, 2022; Vogl et al., 2021). The ETS is a market mechanism that allows countries, companies or industrial facilities that release GHGs to buy and sell their emissions as permits or allowances (Eurostat, 2023). The need for legally-binding GHG reductions was acknowledged and agreed among participating countries in the Kyoto Protocol in 1997 (European Commission, 2015). The EU was the first in the world to present initial concepts for the ETS in 2000, then the EU ETS Directive was adopted in 2003, and the EU ETS was launched in 2005 (ibid). Korea became the first country in East Asia to launch the Korean ETS (K-ETS) in 2015, based on the Green Growth Act and the Act on Allocation and Trading of GHG Emission in Korea (GIR, 2022), and is in the third phase of the K-ETS (2021-2025) (Table 2-1). Both EU ETS and K-ETS work based on the same 'cap an trade' principle where GHG allowances are treated as a product that can be traded on the carbon market (European Commission, 2015). A cap determines the amount of GHG that can be emitted into the air by industries covered by the ETS. (ibid).

Table 2-1 EU-ETS & K-ETS

	EU ETS	**K-ETS**
Phase I	2005 – 2007 (3 years)	2015 – 2017 (3 years)
Phase II	2008 – 2012 (6 years)	2018 – 2020 (3 years)
Phase III	2013 – 2020 (8 years)	2021 – 2025 (5 years)
Phase IV	2021 – 2030 (10 years)	

Source: Korea Exchange, 2018

According to Vogl, Åhman and Nilsson (2021), CCfDs are co-dependent with ETS development (Vogl et al., 2021). This interdependence is particularly linked to the fate of free allocation and the respective benchmark levels that reflect the most emission-efficient installations (ibid). Allowances are allocated either by free allocation or by auctioning allowances (European Commission, 2015). The benchmark is one of the free allowance allocation measures in the ETS which determines how many free allowances an installation will receive based on its performance below a certain threshold of emissions (IEA, 2020b). To be more specific, the European Commission explains, "a benchmark is a reference value for the greenhouse gas emissions, in tCO2, relative to a production activity," (European Commission, 2015). Especially in the EU ETS, product benchmarks are determined by using "the average GHG performance of the 10% best performing installations in the EU" that produce the product (ibid). When benchmarks are used, all installations within a sector are allocated the same amount of allowances per unit activity, and the best performing installation, whose GHG emissions are lower than the benchmark, will receive more free allowances than they need (ibid). In principle, efficient facilities do not need to buy allowances, but installations that emit more than benchmark level need to buy more allowances to cover their emissions (ibid). In the case of the EU ETS, since 2013 (EU ETS phase 3), the industrial sector has received free allowances using a benchmark approach, with the benchmark level set at the average emissions of each sub-sector's 10% best-performing facilities (IEA, 2020b). According to the EU Commission, during phase 3, European industry associations voluntarily collected benchmark data in order to determine benchmark curves. These curves provide data points that indicate the greenhouse gas intensity per installation. The methodology used for this purpose was established by the EU commission. Based on this, the Commission selects the benchmark value by determining the average GHG emissions intensity of the 10% most efficient installations (European Commission, 2021). Benchmark values for sintered ore and hot metal are given as examples in the appendix of this paper.

If benchmarks are lowered and the number of free allocations in the sector is reduced, the recipients might get less support than anticipated (Vogl et al., 2021). The paper points out that one of the main problems is the uncertainty about the amount of free allocation if companies shift from the blast furnace to cleaner technology and might be held to another benchmark. If a company worries that it will lose its free allocation upon switching to a low-emission production process, it will lose the incentive that carbon pricing is supposed to provide, as well as create perverse incentive that prevents companies from investing in technical innovations (ibid). Therefore, it is essential to clarify and commit to the allocation levels for development of low and zero emissions technical innovation (ibid).

Carbon Border Adjustment Mechanism (CBAM)

The CBAM is a climate measure that aims to contribute to the achievement of the EU 2050 climate target in accordance with the Paris Agreement by addressing the risk of carbon leakage[3] by, for example, ensuring equivalent carbon pricing for imports and domestic products, including iron and steel (Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control) (Recast) (Text with EEA Relevance), 2011). CBAM is a levy on imported goods, such as steel, based on their carbon content, with the goal of balancing the costs that the EU ETS charges on European manufacturers (Vogl et al., 2021). The rationale behind the CBAM stems from the European Green Deal which outlined a path to realize the EU ambitious target of 55% reducing carbon emissions in comparison to 1990 levels by 2030 to ultimately become a climate neutral by 2050 (European Commission, n.d.-a). In line with this target, in 2021 the Commission formulated the Fit for 55[4] policy proposals to realize this ambition (ibid), and as a part of the 'Fit for 55', the CBAM was proposed (European Union, 2023). The purpose of the CBAM is to make sure that the emissions reduction efforts of the EU are not offset by increasing emissions outside its EU borders through the relocation of production to non-EU countries especially where climate policies are less stringent and ambitious, or through increased imports of carbon-intensive products, which can undermine not only EU but global climate efforts (European Commission, 2023).

According to Vogl et al. (2021), CBAM can theoretically serve as an alternative to free allocation of emission allowances, but both schemes can be simultaneously used, which could overcompensate European manufacturers (Vogl et al., 2021). However, the paper points out that if the CBAM does not include a reverse adjustment in the return, i.e., to compensate or equalize the situation for steel that is exported from the EU to other countries, then these European steel exports would be disadvantaged. This is because it could lead to additional costs when entering non-EU markets that have their own carbon pricing mechanisms or do not have the same support system as European producers, such as CCfD (ibid).

Other demand-side market creation policies

Vogl et al. (2021) also outlined other demand-side market creation measures, including issuance of green steel certificates, labels, Green Public Procurement (GPP), quotas, etc. (Vogl et al., 2021). The paper divided market creation measures into two types: i) tradable certificates where green steel producers issue certificates that can be purchased by users in a certificate market;

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[3] Carbon Leakage refers to companies based in the EU moving their carbon-intensive production abroad to avoid EU regulations and to take advantage of less stringent standards, or EU products being replaced by more carbon-intensive imports (EU Commission, 2023).

[4] The Fit for 55 package comprises a series of proposals to revise and update EU legislation and to put in place new initatives in order to align EU policies with its climate goals agreed by the Council and the EU Parliament (EU Commission, 2023). The package also aims to reform the EU ETS by increasing its level of ambition, e.g. phasing out of free aloownaces for some sectors, increasing funding for the modernisation fund and the innovation fund, etc. (ibid).

and ii) carbon footprint trancing which necessitates the collection of data at every stage of the value chain (Vogl et al., 2021). They raise concerns about the effectiveness of these measures in achieving the policy goal of supporting low-emission primary steel production. This may be attributed to an additional certificate price risk for investors, the fluctuation in the carbon price, etc (ibid). Additionally, their analysis indicates that while the implementation of these certificate schemes is viable within EU policy frameworks, such as the Ecodesign Directive, it is necessary to be extended to non-EU countries in order to adhere to World Trade Organization regulations and be applicable globally (ibid).

Green Public Procurement (GPP), for example, Vogl et al. (2021) suggests that reliable information about the embedded emissions is required to procure lower-emissions materials. GPP can be undertaken voluntarily or in conjunction with quotas or restrictions (Vogl et al., 2021). However, steel-using sectors that rely heavily on public procurement, such as construction, defense, etc., use certain steel products, e.g. rebar[5], which are usually produced through the secondary production (Sekiguchi, 2017; Vogl et al., 2021). Therefore, GPP of green steel is not expected to significantly contribute to fostering low-emission primary production (ibid). Another study conducted by Muslemani et al. (2021), mentions GPP, as a demand-side policy, can be used as a tool by governments to set minimum green steel requirements for green steel in public procurement, or to mandate the use of a certain amount of green steel within industries (Muslemani et al., 2021). This can be implemented at industry level or applied to individual private companies operating within these industries, such as construction companies or car makers (ibid). Despite the existence of various approaches for implementing GPP, their analysis raises concerns. These include the insufficient emphasis on prioritizing economically advantageous bids that offer better life cycle performance with low GHG emissions in public tenders, and a lack of expertise within procuring authorities to develop tenders that prioritize low-carbon objectives (ibid). Moreover, in the short term, only a few green suppliers and projects that receive government support are likely to gain benefit of GPP (ibid).

Labels, for another example, which are to make externalities visible to the consumers, can support the market formation, and there are several industry labels exist nowadays such as Responsible Steel (Vogl et al., 2021). Nevertheless, due to the complexity of the steel market, market formation policy instruments could either bring new risks to deliver the full intended benefits to the producers (ibid). However, market formation policies can be supported by other policy goals, such as creating international demand for green basic materials and thereby incentivizing decarbonization efforts in other countries. The global spillovers that are created by the required effects that market formation has on the world can stimulate investment in low-emission steel production around the world (ibid). The early creation of premium markets and making information accessible could lead to an increase in the willingness to pay more for green steel (ibid).

2.2 Theoretical & analytical framework

This chapter presents the theoretical and analytical framework and ideas that underpin the study.

2.2.1 Technological Innovation Systems (TIS) framework

This study uses a theoretical and analytical framework called the Technological Innovation Systems (TIS) to examine the overall conditions for the implementation and/or

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[5] Reinforcing bar (also known as rebar) is a high-tensile steel bar, usually made from recycled steel, used in construction to increase the strength of concrete (Wood, 2023)

commercialization of the hydrogen-based steelmaking technology. The term "(national) system of innovation" was first used by Freeman (1987) and was defined as "the network of institutions in the public and private sectors whose activities and interactions initiate, import and diffuse new technologies" (Edquist, 2006; Freeman, 1987). Later, innovation systems were defined more broadly as "all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion and use of innovation" (Edquist, 2006). Various researchers and policy analysts have attempted empirical studies of innovation systems to describe and understand their structure, dynamics and performance (Bergek, Jacobsson, et al., 2008). However, concerns were raised regarding the absence of comparability among these studies and the conceptual heterogeneity presenting in the literature on the innovation system. Consequently, there was a need for a practically applicable analytic framework that allows the evaluation of system performance and the identification of factors influencing performance (ibid).

The TIS framework helps to identify internal and external source of dynamics in structure and functions in a technological innovation system (Bergek, Hekkert, et al., 2008). The emergence and evolution of technological Innovation Systems (TIS) reflects the diffusion of a particular new technology. Using the TIS approach, therefore, allows to identify means of accelerating the diffusion of a technology that has been determined or influenced by entrepreneurs, policy makers and other relevant stakeholders (ibid). The framework captures the structural characteristics and dynamics of an innovation system, and the dynamics of a number of key processes - Bergek et al. referred to here as 'functions' that directly impact the development, diffusion and use of new technology, hence, the performance of the innovation system (Bergek, Jacobsson, et al., 2008). As Bergek et al. suggested, a system, in general, is defined as a group of components serving a common purpose, in other words, working towards a common objective or overall function. These components of an innovation system are the actors, networks and institutions (Carlsson & Stankiewicz, 1991) relevant to the overall function of developing, diffusing and utilizing new technology (Bergek, Jacobsson, et al., 2008). An innovation system can be primarily an analytical construct that is a tool we use to better describe and comprehend system dynamics and performance, despite the fact that the concept of a system may imply collective and coordinated action (ibid). This indicates that the system in focus may not exist as a fully-fledged entity in reality (ibid). Alternatively, it could be in the process of emergence with minimal interaction between its components, and it is also possible that the interaction among components is unplanned and unintentional, rather than deliberate even within a more advanced innovation system (ibid). These components are further explained in Chapter 4., to illustrate the context of Korea and Sweden. This research applies the framework in two ways: first, the framework helps to formulate research questions; secondly, to understand country's overall context. Berget et al. (2008) outlined seven functions and indicators in Table 1-1.

3 Research design, materials and methods

This chapter provides the research design and methodology that was used for this research as well as the processes that were carried out to construct the framework and conduct the analysis for this research to respond to research questions.

3.1 Research design

To gain a complete understanding of the challenges and opportunities associated with the adoption and scaling-up of the H-DR process in Korea and Sweden, the research design uses a qualitative, descriptive and comparative approach combined with the use of quantitative data. The research method employed in this paper is a mixed method approach, mainly qualitative research method driven with sub-quantitative analysis and data to supplement research questions and data found in the qualitative research. This approach was chosen to conduct comparative research in order to assess the strengths and weaknesses of both countries to draw lessons from each country. There have already been a several literature conducted comparative analysis using TIS framework (Bergek & Jacobsson, 2003; Vasseur et al., 2013). This literature mostly tends to focus on making comparisons across different countries to derive insights from the country that is relatively more successful in certain technologies. Inspired by the existing literature and motivated by the Swedish HYBRIT success in piloting H-DR, although the H-DR development in Sweden is more advanced than Korean, this study attempts to compare two countries on an equal footing by taking into account different contextual factors, such as differences in geography, politics, and so on to draw lessons from each country.

In order to address the first research question, i.e. "*How has knowledge development and diffusion been supported in Korea VS Sweden?",* this research screened through search engines such as steel producers' websites, national project search engine, the google scholar as well as reference tracing to identify the number of R&Ds on H-DR. The second and the third research questions, i.e. "*How has the influence on the direction of search been supported in Korea VS Sweden?"* and *"How has the market formed for the green steel in Korea VS Sweden*?" were mainly answered through eight semi-structured interviews and searches. These interviews used an open-ended, semi-structured approach, allowing researchers to engage with participants and elicit their perspectives freely (Creswell, 2018). To be specific, interviews with practitioners and relevant actors, such as policymakers, steel producers, etc., were necessary to capture the practitioners' perspective on the green steel transition and their opinions on the strengths and challenges of the green steel transition.

3.2 Data collection methods and materials collected

To ensure data triangulation, data for this thesis was collected by first conducting eight semi-structured interviews as primary data while secondary data was gathered by examining academic and grey literature, reports, and pertinent documents using the google scholar, Korean national project search engine, etc. The collection of tertiary data included the observation of regional (the EU) and international conferences, and seminars in addition to a field visit in Luleå, Boden and Gällivare in Sweden. The observation of regional and international conferences and seminar was through HYIS forum co-hosted by POSCO and SSAB, as well as seminar was "*Decarbonization standards in the steel sector -why, what and who?"* hosted by the Jernkontoret and the Sweden Institute for Standard (SIS) (Jernkontoret & Sweden Institute for Standard, 2023). The use of data triangulation or multiple methods of data collections enhances reliability as well as internal validity of research (Merriam, 1998; Creswell, 2018).

The first stage of data and material collection involved scoping this research to focus on the development of technology, H-DR, and the key actors responsible for the H-DR technical development, namely, steel producers - POSCO and HYBRIT - along with some consideration of the national dimension. In the second stage, the identification of interviewees was carried out through the network of the author's supervisor and through personally reaching out to authors of relevant literature. As illustrated in the Table 3-1, a total of ten interviews were conducted, involving five different types of institution, i.e. steel producers, NGOs, academia, Swedish steel association (known as Jernkontoret) and the Korean national think tank. Specifically, seven interviews were conducted with stakeholders from Sweden side, while the remaining four interviews from Korean side. This paper conducted four interviews from the same institution - Lund university, which is a part of the HYBRIT project, thus considered as one institution and one respondent (Respondent #8) in this research. Firstly, an email was sent to interviewees outlining the study objectives, and interview questions were sent to those who requested. Most of the interviews were conducted through the Zoom video call, and a few were conducted in person.

Table 3-1 Interviewees for this research

Country	Respondent	Organization	Department	Type of Organization
Korea	Respondent #1	POSCO	Low-carbon iron making / HYREX	Corporate
	Respondent #2	Korea Institute for Industrial Economics & Trade (KIET)	Material & Industrial Environment	Government Think tank
	Respondent #3	Korean NGO (anonymous)	Steel industry	NGO
	Respondent #4	Korea University	Energy & Environment Professsor	Academia
Sweden	Respondent #5	HYBRIT AB	HYBRIT project management	Corporate
	Respondent #6	Jernkontoret	Energy, Environment and Sustainability	Iron & Steel industry's trade association
	Respondent #7	Climate Action Network (CAN) Europe	Industry policy	NGO
	Respondent #8	Lund university	Energy & Environmental system	Academia

Source: Author's own

3.3 Methods used to process data

The preparation of the analysis involved all the information that was obtained for this research. In terms of data collected from the interview, because of the number and the duration of interviews as well as the time constraints of this research, the transcriptions of the interviews were either fully or partially transcribed and important key notes were all included. Following this step, the data was digitized using a program called NVIVO, which is a software application for qualitative research.

4 Introducing country context

In this chapter, the overall electricity system and the background of the steel industry in each country are presented. This study does not delve further into investigating the correlation between the market system and H-DR. However, in order to provide a comprehensive understanding of the advantages and disadvantages associated with electrification for EAFs and hydrogen production in both countries, brief introduction of electricity supply and its market structure is introduced in this chapter with more focus on Korea. This chapter also provides components of the H-DR innovation system – actors, networks and institutions (Carlsson & Stankiewicz, 1991) – to see how these components contribute to the overall functions of development, diffusion and exploitation (Bergek, Jacobsson, et al., 2008) of the hydrogen-based steelmaking in each country. The scope for identifying the components is primarily national and regional context. This chapter does not consider aspects beyond the national level but mentions some relevant aspects where appropriate. The use of the concept of an "overall function" does not necessarily suggest that all actors in a particular system are present to serve that function or are directed by that function (ibid).

4.1 Electricity supply

Korea is a country with resource scarcity, but it is the world's 8th largest energy consumer, which means that it is around 94.8% dependent on imported energy (Ministry of Foreign Affairs, n.d.). Unlike European countries, Korea is geopolitically isolated, making it is difficult to export and import electricity from neighboring countries (IEA, 2021). Given this unfavorable circumstance, the electricity security has been the country's major concern (IEA, 2021).

The Korean Ministry of Trade, Industry and Energy (hereinafter, MOTIE) is required by Article 25 of the Electric Utility Act to submit a master plan to stabilize electricity supply and demand (Ministry of Government Legislation, 2021). The master plan lays out matters related to the basic direction and the long-term outlook of electricity supply and demand, plans for generation installations, major transmission and substation facilities, managing electricity demand, the expansion of distribution sources and so on. MOTIE has recently published the 10th Basic Plan for Long-term Electricity Supply and Demand 2022 – 2036 (hereinafter, the 10th BPLE), which is a mid-to long-term plan that forecasts electricity demand and designs electricity facilities and power supply configuration (ibid). According to the 10th BPLE (2023), the total installed capacity at the end of 2021 was 134 GW, LNG being the largest (31%), followed by coal (28%), renewables (19%) and nuclear (17%). And electricity generation in 2021 was around 577 TWh, while the consumption was 553.4 TWh, with industrial consumers accounting for more than 50% (MOTIE, 2023a). The electricity generation by source consists of coal (34%), LNG (29%), nuclear (27%) and renewables (7%) (ibid).

Sweden, on the other hand, the generated electricity in 2021 was around 170 TWh, consisting of hydropower (42%), nuclear (31.3%), wind (16.1%), biofuel (5.7%), waste (3%) (IEA, 2022b). Electricity generation in Sweden mainly comes from hydropower and nuclear power, however, wind power has increased significantly over the last ten years (Swedish Energy Agency, 2022). The industry sector accounts for the highest electricity consumer at 39% (47 TWh) of the total, followed by households at 35% and the commercial sector at 22% (IEA, 2019). In terms of total installed generating capacity in 2017 was 39 GW, with hydropower being the largest (41%), followed by nuclear (23%), combustible fuels (19%), wind (17%) and solar (1%) (ibid).

4.1.1 Electricity market structure

According to the many studies, a key determinant for the future competitiveness of fossil-free hydrogen steel is the cost of electricity (Åhman et al., 2018; Vogl et al., 2021; Kim & Sohn, 2022). Electricity prices can be shaped by many aspects such as electricity market structure (EDF, 2016; Strbac & Wolak, 2017). Therefore, understanding the complex relationship between the electricity market structure and electricity price is an important factor for hydrogen production and H-DR scale-up, and requires in-depth studies. In order to provide the groundwork for future research, this chapter presents a brief overview of the electricity market system in Korea and Sweden and does not discuss the relationship between the market and the H-DR development.

The Korean electricity market exhibits a day-ahead wholesale market operated by Korea Power Exchange (KPX), and by a regulated monopoly - Korea Electric Power Corporation (KEPCO) - that manages the transmission, distribution and retail of electricity to the end users (IEA, 2021). The power generation unit was liberalized in 2001 and KPX was established to install and operate the electric power market as well as the Electricity commission regulating body (Korea Energy Economics Institute, n.d.). The power generation unit comprises of six subsidiaries of KEPCO and numerous Independent Power Producers (IPPs) (IEA, 2021). Among IPPs, twenty companies operate 21 GW of installed capacity including POSCO, the first and the largest IPP in Korea (POSCO International, n.d.), and 3442 renewable energy producers registered 5 GW (KPX, 2020; IEA & KEEI, 2022). It is true that a regulated market system can help stabilize electricity supply, however, in the long-term, a liberalized market allows the risk to be shifted from end users to investors and creates incentives to operate the grid more efficiently, creating a constant pressure to drive down costs and encouraging innovation in low-carbon technologies to enter the market (IEA, 2021). In Korea, the carbon price is not integrated into the wholesale market price and the electricity market is not conducive to low-emission technologies (IEA & KEEI, 2022).

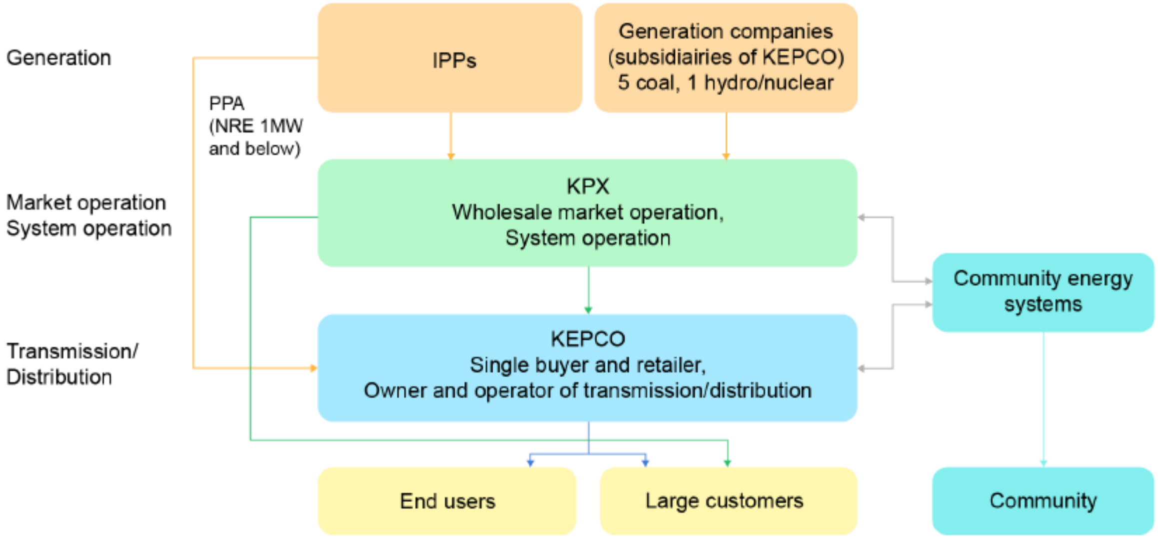

Figure 4-1 Korea's electricity market structure

Source: KEPCO (n.d.) and IEA (2021)

On the other hand, according to the IEA (2019), the Swedish electricity market, was deregulated in 1996 and is seen as a role model for the market liberalization and regional integration (IEA, 2019). The Swedish electricity market has undergone complete liberalization, allowing customers to choose their own supplier (ibid). The separation of electricity transmission and supply activities is through unbundling and distribution network operators are functionally unbundled (ibid). The Swedish wholesale power market is part of the integrated Nordic power market with around 170 distribution network companies (European Commission, 2014). It is common for production, distribution and trading to be carried out by the same group of companies but unbundled in different legal entities (ibid). A few large generators in Sweden dominantly produce electricity including Vattenfall, a state-owned being the largest, which generates around 40% of the total. Despite a small number of generators, the Swedish Energy Markets Inspectorate (SEMI) considers the competition in the generation as competitive as of the well-interconnected Nordic market (ibid). Around 95% of the physical power trade in Sweden takes place at the Nord Pool, a regional power exchange that includes Sweden with its neighboring countries: Norway, Finland, Denmark, Estonia Latvia and Lithuania. The Nord Pool has two power markets: a day-ahead market (Elspot) and a intraday market (Elbas) (ibid). Though the intraday market is growing, the trading predominantly takes place in the day-ahead market. Currently, the Nord Pool is the only power exchange operating within the Nordic region. According to the European Union's network codes, additional power exchanges are allowed, therefore, the power exchange operation may be developed within the Nordic area (ibid). The Nord Pool day-ahead price has varied between 20 and 40 EUR/MWh, and price changes are usually caused by the availability of hydropower which is the most abundant source for large-scale generation in the Nord Pool (ibid). In terms of retail market, there are more than 120 suppliers that serve around 5.4 million Swedish end-user customers. At the end of 2017, the largest suppliers were Vattenfall, E.ON and Fortum.

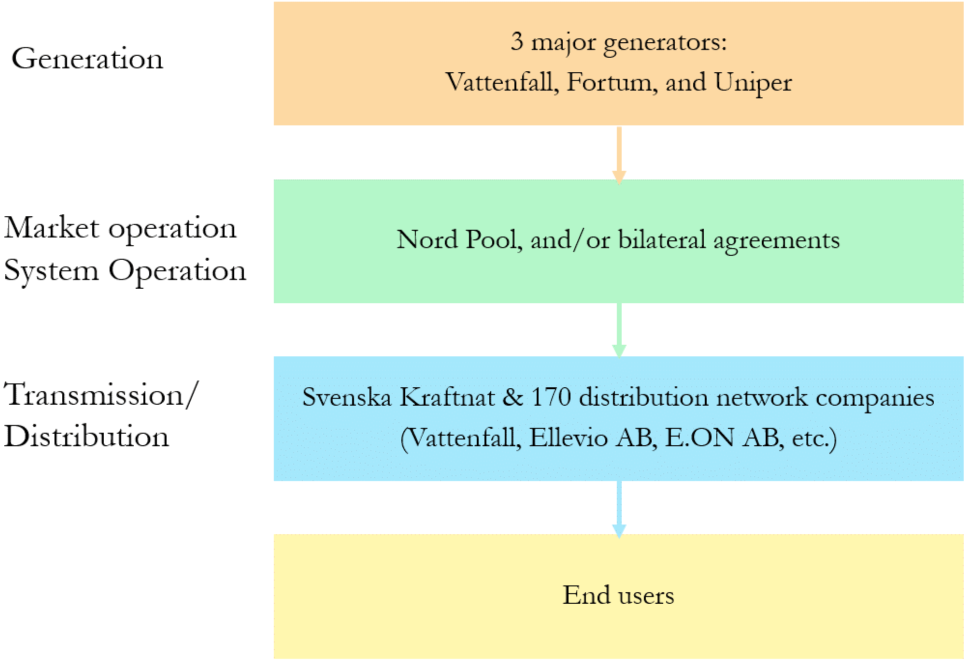

Figure 4-2 Sweden electricity market structure

Source: Author's own based on IEA (2019)

4.1.2 Hydrogen

The H-DR process is based on direct reduction of iron ore using fossil free energy and hydrogen gas (Vattenfall, 2019). To give a concise understanding of hydrogen production methods, hydrogen can be produced from several sources including: reforming fossil fuels - e.g. natural gas, coal; biomass; and electrolysis from electricity that splits water (Fossil Free Sweden, 2021). Given that the H-DR method employs electrolysis, there are three main different electrolysis technologies for the production of hydrogen from water: alkaline electrolysis (ALK); electrolysis with proton exchange membranes (PEM); and high temperature electrolysis (SOEC). The first two are currently available on an industrial scale in the commercial market (ibid).

Korea

The Korean government announced its first hydrogen economy roadmap in 2019 in parallel to its national net zero target by 2050 to accelerate the decarbonization of the energy system and encourage the hydrogen economy (Korean Government, 2019). The 1st basic plan for hydrogen economy was announced in accordance with Article 5 on the Promotion of Hydrogen Economy and Hydrogen Safety Management Act that was enacted in 2020 (ibid). However, its plan was mainly focused on developing hydrogen fuel cells and transport. The roadmap outlined its plan to establish a large-scale green hydrogen production of 250,000 tons by 2030 at a unit production cost of KRW 3500/kg (equivalent to USD $2.25/kg) and 300,000 tons by 2050 at KRW 2500/kg (equivalent to USD 1.87/kg) (See Table 4-2.) (Kang, 2022). Additionally, in the latest 10th BPLE, the Korean government plans to generate 13.0 TWh of hydrogen ammonia which accounts for 2.1% of the total energy mix by 2030 and increased to 47.4 TWh (7.1%) by 2036 (MOTIE, 2023a). Both national plans – the Hydrogen Roadmap and the 10th BPLE - outline various hydrogen technologies including ammonia co-firing, blue hydrogen and green hydrogen. In terms of hydrogen-ammonia co-firing, LNG and coal will be co-fired with hydrogen and ammonia to produce 6.1 TWh by 2030 and 6.9 TWh by 2036 respectively (ibid). Korea is considered as a fast mover in terms of officially developing the national hydrogen strategy (Hong & Kim, 2022), however, there are some shortcomings. One of main challenges is the technology gap. The average electrolysis efficiency of overseas companies is around 60% and is at the demonstration stage at the MW level while that of Korea is at 55% at the KW level (See Table 4-1) (MOTIE, 2021).

Part of POSCO's business strategy is to produce a massive amount of green hydrogen with the aim of 5 million ton of hydrogen production system by 2050 (Newsway, 2020; POSCO, 2021b). POSCO has started cooperating with many international companies, such as FMG – an Australian iron ore company – for green hydrogen business, and Orsted – a Danish offshore wind power company – to supply steel materials for the construction of an offshore wind farm as well as green hydrogen production. Furthermore, it is noteworthy that POSCO announced its business agreement with the Korean Research Institute of Industrial Science & Technology (RIST[6]) for hydrogen in 2021 (ibid). In January 2023 the Korean government has set a target of KRW 20 trillion in green industry export orders, and has formed a public-private partnership including POSCO, two subsidiaries of KEPCO[7], Samsung and etc. (Ministry of Environment, 2023). One of plans in this target includes green hydrogen production and seawater desalination with the aim of exporting a total value of KRW 17.5 trillion (equivalent to EUR 12.3 billion and USD 13.2 billion) to the Middle East including Oman, Saudi Arabia, and the United Arab Emirates (ibid). And in June 2023, this partnership for green hydrogen export plan successfully

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[6] A private research institute specialized in technology and commercialization that was founded by POSCO (RIST, n.d.)

[7] Korea Electric Power Corporation (KEPCO) is the largest state-owned electric utility in Korea and responsible for the generation, transmission and distribution of electricity (KEPCO, n.d.)

led MOU contract between the Korean ministry of Environment and the Omani ministry of energy and minerals (Chosun, 2023). It is believed that the Omani government's interest in green hydrogen stemmed from its recognition of the importance of realizing its phase-out of fossil fuels (ibid). It was important for the Omani government to secure demand for its green hydrogen production, while the Korean government also needed to establish the green hydrogen supply chain, thus their interests were converged (ibid). The project entails the production of green hydrogen from wind and solar energy with an annual production capacity of 1.2 million tons of the form of green ammonia on a 320km2 site in Duqm, Oman which is the largest scale in the world (Ministry of Environment, 2023a). According to IEA, Oman has a potential to produce green hydrogen at the lowest cost of USD 1.6/kg by 2030 (IEA, 2023). POSCO Holdings is the main shareholder with a 28% ownership followed by the ENGIE - a French energy corporate (25%), and Samsung Engineering (12%), etc. (Hankyung, 2023).

Table 4-1 Green hydrogen production target comparison

	Korea (2028)	**Sweden (2030)**	**Germany (2030)**
Green hydrogen production target	10 MW	3 GW	5GW

Source: MOTIE (2021) & Fossil Free Sweden (2021)

Table 4-2 Hydrogen price target in Korea and Sweden

Country	**2030**	**2050**
Korea (unit: KRW)	3500/kg (eq. EUR 2.12 or USD 2.25)	2500/kg (eq. EUR 1.77 or USD 1.87)
Sweden (unit: SEK)	10 –11.5/kg (eq. EUR 0.9 or USD 1)	5.5 – 6/kg (eq. EUR 0.5 or USD 0.52)

Source: KEEI (2022) & Fossil Free Sweden (2021)

Sweden

Sweden put in place the government initiative, "Fossil Free Sweden", a platform for government and industry collaboration, and published its hydrogen strategy in January 2021 (Green Hydrogen Organization, n.d.). The main focus of the strategy is to decarbonize the country's energy-intensive industries including steel production with a target of 3 GW by 2030 (Table 4-1) (Fossil Free Sweden, 2021). Later, the Swedish Energy Agency suggested a proposal for a national fossil-free hydrogen strategy to stop climate change and reduce the country's reliance on fossil fuels (Green Hydrogen Organisation, n.d.). This proposal has a more ambitious target for hydrogen production: 22-42 TWh of green hydrogen by 2030 and 44-84 TWh by 2045 as well as a total electrolyser capacity of 5GW by 2030 and 15 GW by 2045 (Swedish Energy Agency, 2021b). It is important to note that the growing interest in fossil-free hydrogen in Sweden is largely motivated by the government's goals of achieving climate neutrality by 2045 with industry's collaborative efforts towards the same objective (Ćetković & Stockburger, 2023). This goals are articulated within the Climate Policy Framework, which received substantial support in the Swedish parliament in 2017 (Ministry of Climate and Enterprise, 2021; Ćetković & Stockburger, 2023). Fossil-free hydrogen is considered as crucial to the decarbonization of the Swedish energy-intensive industries and in securing Swedish competitiveness in the future global low-carbon economy. Hydrogen is also viewed as a viable tool to help balance the electricity grid in light of the increasing share of wind power (Ćetković & Stockburger, 2023). Overall, this highlights a unique feature of Sweden that the internal partnership between the Swedish government and corporates is robust.

4.2 Korean & Swedish Steel Industry

This section illustrates the overall Korean & Swedish steel industry shedding light on POSCO and HYBRIT with emphasis on unique features in addition to blast furnaces and the H-DR process.

Steel industry in Korea

The steel industry in Korea began in the mid-1960s. The Korean government selected Pohang as the location for the integrated steel mill in 1967 and in the following year, Pohang Iron and Steel Company was founded (POSCO, 2018). POSCO operates two integrated steel mills in Korea with a total of 8 blast furnaces that are currently operating – 3 in Pohang, 5 in Gwangyang - and 2 FINEX (Figure 4-3) (Global Energy Monitor, 2022a, 2022b). The blast furnace in Gwangyang has the biggest production capacity in the world with its internal capacity of 6000m3 as the Table 4-3 shows (POSCO, 2019). The crude steel production in 2021 was 42.96 million tons (World Steel Association, 2022). The by-product gases, typically carbon monoxide, CO2 and nitrogen, that produced inside the blast furnace are emitted about 1600 m3 of gas, and POSCO recycles this by-product gas and self-produces 74% of the electricity for its own steelmaking operation (POSCO, 2019).

Figure 4-3 POSCO integrated steel mills locations

Source: Author's own created in qGIS

POSCO has a unique steelmaking technology called FINEX that has been brought online since 2007 (Yi et al., 2019). The FINEX process was initiated by POSCO and Primetals in 1992 to create an alternative process to the blast furnace by eliminating the coking and sintering processes and using lower grade, lower cost raw materials (ibid). POSCO went through a series of scale-up development from a 15 ton/day model plant started in 1996 to a 150 ton/day pilot plant in 1999 followed by a 0.6 MTPA[8] FINEX demonstration plant in 2003 (ibid). The first commercial FINEX plant with a capacity of 1.5 MTPA and the second commercial plant with a capacity of 2 MTPA were implemented in Pohang. FINEX consists of four-unit processes: a multi-stage fluidized-bed reactor, hot-compacters, coal-briquettes and a melter-gasifier (ibid).

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[8] Million Ton per Annum

Simply put, the biggest strength of the FINEX is the direct use of iron ore fines and non-coking coal while eliminating the coke-making and sintering processes that are the precursor to the blast furnace (POSCO, 2017b). With this experience of developing the FINEX process, POSCO and Primetals are again collaborating to build HYREX, which share same process method but replacing non-coking coal to hydrogen (POSCO, 2022d).

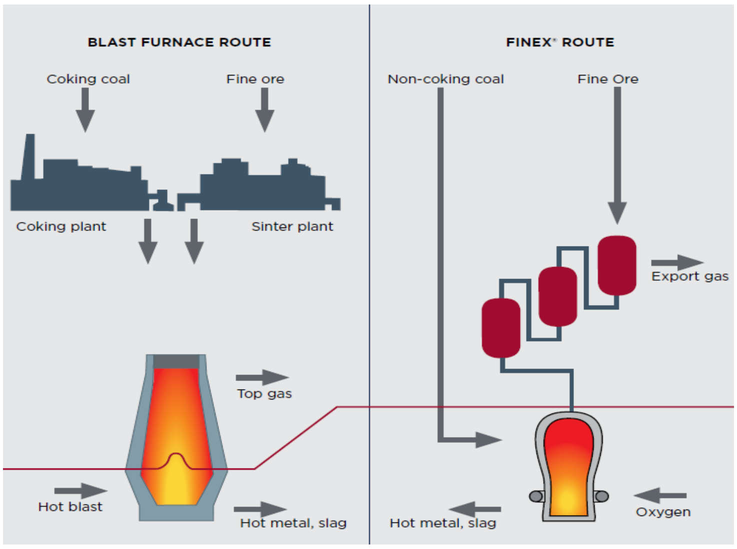

Figure 4-4 BF and FINEX process comparison

Source: POSCO & Primetals, (n.d.)

Table 4-3 POSCO plants in Pohang and Gwangyang

Location	Type	Start (Closing year)	Capacity	Size (m^3)	Crude Steel Production (2021)
Pohang	BF 2 (BOF)	1987 - 2025	5 MTPA	5600	16.9 MTPA
	BF 3 (BOF)	1978 – 2025	5 MTPA	5600	
	BF 4 (BOF)	2010 – 2025	5 MTPA	5600	
	BF-DRI	1995 -	0.8 MTPA	No information	
	FINEX No. 2	2007 -	1.5 MTPA	No information	No information
	FINEX No. 3	2014 -	2.0 MTPA	No information	No information

Gwangyang	BF 1	1987 -	5.65 MTPA	6000	23 MTPA
	BF 4	1992 -	5 MTPA	5500	
	BF 5	2000 -	5 MTPA	5500	
	BF 3	1990 -	4 MTPA	5500	
	BF 2	1988 -	4.5 MTPA	3685	

Source: Global Energy Monitor Wiki (2022)

Steel industry in Sweden

Swedish iron and steel production has a long history. Since industrialization, the Swedish steel industry has grown significantly throughout the 19th century having over 200 blast furnaces (Jernkontoret, 2018). Swedish steel products are small in volume but known for their niche steel. The history of SSAB goes back to the 1970s and 1980s, when the Swedish steel industry worked to improve its efficiency, partly driven by the state. And these activities led to the naissance of SSAB, where the production of commercial steel was concentrated in one company, initially with the Swedish state as half owner. In the 1970s, the export share was 40-50%, but in 2019 it stands around 85% (ibid). Some of Sweden's comparative advantages are: good availability of raw materials such as iron ore; cheap and stable electricity supply; abundant water; and highly educated population in metallurgical research (ibid). Crude steel production in Sweden amounted to 8.8 million tons in 2021 (World Steel Association, 2022). Sweden has two active blast furnaces in Luleå and Oxelösund, both owned by SSAB, while HYBRIT's H-DR pilot plant is located in Luleå, close to SSAB's blast furnace, and its demonstration plant is planned to be located in LKAB's industrial area in Gällivare (Figure 4-5) (HYBRIT, 2022a).

Figure 4-5 HYBRIT's H-DR facilities locations

Source: Author's own created in qGIS

Table 4-4 SSAB's BF plants

Location	Type & Unit name	Start (Closing year)	Capacity	Size (㎥)	Crude Steel Production
Luleå	BF 3	2000	2.5 MTPA	2540㎥	2.3 MTPA (
Oxelösund	BF 2	1952 – 2025	0.5 MTPA	760㎥	1.5 MTPA

Source: Global Energy Monitor Wiki (2022)

It is unclear how the three companies found each other and initiated the HYBRIT project. None of the identified literature clearly stated what motivated them to collaborate. However, what was clear is that this project started in 2016, after the Paris Agreement. Sweden's environmental leadership was already well-known even before the Paris Accord. Before the Paris Accord, the Swedish government committed to take action and to make Sweden the first fossil-free welfare state in the world moving even faster than the EU regulations (MacDonald, 2015). The Paris Agreement, where countries agreed on a new global climate strategy that lays out the basis for future long-term climate efforts, was the frosting on the cake for Sweden's environmentally conscious leadership. According to Martin Pei - the Executive Vice President at SSAB, et al., to make the steel industry the Paris Agreement compatible, 400-600 million tons of CO2 per year needs to be decreased compared to that of 2015 which is 2800 million tons CO2 (Pei et al., 2020). In response, the Swedish parliament passed a climate law with net zero target by 2045. Soon after April 2016, SSAB, LKAB and Vattenfall AB initiated the HYBRIT project conducting a pre-feasibility study with support from the SEA (ibid). Therefore, the Paris Agreement has prompted environmentally conscious leadership in three companies (or one of three companies) to initiate the project.

4.3 TIS Components

According to Bergek et al. (2008), "the components of an innovation system are the actors, networks and institutions contributing to the whole function of developing, diffusing and utilizing new products (goods and services) and processes" (Bergek, Jacobsson, et al., 2008). Therefore, this chapter presents TIS components of the H-DR technology in each country.

4.3.1 Actors

In order to identify and analyze the structural components of the system in Korea and Sweden, it is first necessary to identify the actors of the TIS. This encompasses the entire value chain, including universities, research institutes, public bodies, direct and indirect interest groups and so forth.

Numerous actors are engaged in hydrogen-based steelmaking in Korea. The major steelmakers setting the carbon neutral strategy involving hydrogen-based iron/steelmaking are POSCO and Hyundai Steel. Several Korean government bodies that are in charge of technology development are involved in the steel industry decarbonization (Respondent #1). There are some public research institutes such as the Korea Energy Economics Institute (KEEI) and Korean institute for Industrial Economics & Trade (KIET) that are actively engaged in releasing policy briefings, reports, etc. H-DR iron and steelmaking technology development has become a national project, thus, many universities have joined and become part of the project, such as Seoul National University, Korea university, Yeonsei university, Pohang University of Science and Technology, POSCO Engineering & Construction (E&C), Chosun Refractories Co., Ltd., etc. (Respondent #1 & #3).

Sweden has a large number of actors that are active in the hydrogen-based steelmaking. The main companies involved in the hydrogen-based steelmaking technology are Hydrogen Breakthrough Iron making Technology (HYBRIT) - a joint project together with SSAB, LKAB and Vattenfall - and H2 Green Steel (H2GS). The demand side is comprised of mostly automobile companies such as Volvo AB, BMW, etc. (H2GS, 2022; HYBRIT, 2021a). The public body that are engaged in steel space is Swedish Energy Agency (SEA) and the Ministry of Climate and Enterprise. The SEA is engaged in facilitating of energy efficiency measures and investments in renewable energy technologies (SEA, n.d.). The ministry is responsible for the climate, environment, energy, enterprise, innovation, and transition to a circular economy (Regeringskansliet, 2014). The Swedish parliament also an active actor in steel space setting up a committee of how to reach a climate target and the committee organized a series of roundtable discussion in terms of heavy industry, including steel, where industry and researchers discuss. The HYBRIT actively collaborates with academia and their names such as Lund university, and field of responsibility in the HYBRIT project was clearly stated. Jernkontoret, an industry institute organization, a.k.a. iron office, organizes the Sweden steel industry, plays a role as a bridge organization that links politics and industry (Respondent #8).

4.3.2 Network

The second structural component of interest is that of networks. Both formal and informal (Bergek et al., 2008). Steel is a commodity that depends heavily on global trading, therefore, the network within the steel industry is strong. Moreover, Sweden and Korea, where there was no strong interface that draws these countries together in terms of trading, nonetheless, because of the common decarbonization aim transitioning to the hydrogen-based steelmaking, organized a global annual forum that brings all relevant actors including academia, hydrogen producers, energy producers, international organization, etc. in the steel space.

In the case of Sweden, knowledge networks between the three shareholders of the HYBRIT (SSAB, LKAB and Vattenfall), public bodies (Swedish Energy Agency and RISE Research Institute of Sweden), and academic research groups (Lund university, KTH, Lulea university of Technology, Sandvik[9], have been actively engaged in the research project carried out by HYBRIT and contributed to knowledge formation and diffusion (HYBRIT, n.d.). Not many actors from non-governmental organizations (NGOs), nor networks between NGOs and Swedish steel producers were spotted, however Climate Action Network Europe (CAN Europe) said they continue dialogue with H2GS in terms of the EU Emissions Trading Scheme (Respondent #7).

In Korea, networks happen between steel producers, e.g., POSCO, Hyundai Steel, etc., public bodies, academia, NGOs and civil society. Learning networks are considerably more prominent than other networks such as political networks. Steel producers and universities often interact in national projects. Examples of current learning networks are the national project on the hydrogen-reduction steel and the international forum, HyIS, allowing more international

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[9] Sandvik is a global tech engineering group providing solutions for the manufacturing, mining and infrastructure industries to enhance productivity, profitability and sustainability.

exchange of knowledge and experience. On the other hand, networks with the government were hard to identify.

4.3.3 Institutions

The third element that needs to be identified is institutions, which include culture, norms, regulatory aspects, cognitive rules that regulate interactions between actors, define the value base of different segments of society, influence the decision of businesses, and structure learning processes and routines (North, 1994; Bergek et al., 2008; Bergek et al., 2008a). Institutional change and its associated politics are crucial in the process of new technology becoming effective (Bergek et al., 2008). In order to accommodate and promote the adoption of technologies, the rules and systems that regulate how things work need to be adjusted (ibid). This shows that firms that compete TIS, compete market for products and services, and institutional influence (ibid). Thus, rival enterprises frequently cooperate to manipulate the institutional environment to acquire access to resources for their collective survival (Van de Ven & Garud, 1987).

The institutions have played an important role in Sweden in terms of accelerating climate action in the steel industry. On behalf of the Swedish steel companies, Jernkontoret, the Swedish Iron & steel Association (translated by the author), has released the Climate Roadmap for the steel industry in Sweden that laid out possible measures for emission reductions, policy for a competitive decarbonized steel industry, demonstrating their shared commitment (Jernkontoret, 2018). SSAB, LKAB and Vattenfall, have also independently released their respective roadmaps with all of them aiming to achieve fossil-free by 2045 in line with the national climate target (LKAB, 2022; SSAB, 2017; Vattenfall, n.d.). These individual initiatives underline Swedish steel industry's proactive commitment to achieving sustainability goals. In addition, the Swedish government has played a crucial role as an interface to bridge the industrial sector and politics to speed up the transition. For instance, the Swedish government started the Fossil Free Sweden initiative in 2015 establishing 'Fossil Free Sweden' initiative in 2015 whose goal is "to build a strong industrial sector and to create more jobs and export opportunities by going fossil free" (Fossil Free Sweden, 2021). Fossil Free Sweden collaborates with actors, i.e., companies, municipalities, regions and organizations to identify obstacles and opportunities to speed up growth. Fossil Free Sweden develops political proposals that are presented to the government and gathers stakeholders to implement measures (ibid).

In the case of Korea, a few literature on Korean steel industry were identified including POSCO's annual report, and reports that explain the overall Korea steel industry from national research institutes such as KEEI, KIET, etc., and NGOs. Despite the existence of some publications addressing various aspects of the Korean steel industry, there is a lack of an integrated and cohesive body of work that systematically scrutinizes the Korean steel industry's transition to a low-/zero-carbon economy (Respondent #1, #2 & #4). In other words, a coherent framework and structure among actors is absent, therefore, further research, networks and institutions that can bring these fragmented pieces of work and build an organic connection to comprehensively examine and support the green steel transition is a must. Recently, the Ministry of Trade, Industry and Energy (MOTIE) chaired a 'Steel Industry Development Roundtable' and announced the 'Steel industry development strategy for Transition to low-carbon Steel Production'. The meeting was attended by seven major steel companies including POSCO and Hyundai, Korea Iron & Steel Association (KOSA), Korea Steel Scrap Association (KOSIA), Korea Institute for Industrial Economics & Trade (KIET) and Yeonsei University (MOTIE, 2023). Hopefully, this initiative can contribute to a more organically harmonized steel industry green transition. This initiative by the government holds the potential to enable the organic harmonization of efforts among stakeholders, resulting in a more integrated approach towards attaining decarbonization with the Korean steel industry.

5 Findings

This chapter presents the findings and analysis of the research based on the TIS functions – knowledge development; direction of the search; and market formation.

5.1 Function 1 Knowledge development & diffusion

Knowledge development is crucial in the innovation system as it provides the necessary fuel for entrepreneurial experimentation and facilitates an understanding of how technological alternatives can be optimized for successful market outcomes (Vasseur et al., 2013). As the learning process frequently involves different actors, knowledge exchange emerges as another crucial aspect (ibid). This function captures the breadth and depth of the current knowledge base of the TIS, as well as its evolution over time, encompassing the diffusion and combination of knowledge within the system (Bergek, Jacobsson, et al., 2008). This study identifies the number of R&D projects, investment in R&Ds and knowledge sharing activities.

In Korea domestically, one respondent (Respondent #1) said that most of the HYREX project collaborations are with two government ministries – MOTIE and MSIT, and academia – POSTEC, Seoul National University, Yeonsei University, Korea University, Hanyang University, etc. There is one governmental research institute dedicated to steel in terms of alloy design, process and property control (Korea Institute of Materials Science, KIMS) but there are no governmental research institute that are specialized in ironmaking and steelmaking process (Respondent #1). The information on HYREX was available on POSCO's website and was mentioned in several policy briefings. Recently, POSCO has launched a website dedicated to HYREX[10]. However, certain information on the website is currently accessible only to its partners. Therefore, to complement and to identify the number of past and ongoing R&D projects on H-DR, two additional search engines in addition to Google scholar, were used: the National Science & Technology Information Service (NTIS) - a platform that provides information on past and ongoing national R&D (NTIS, n.d.), and the National Knowledge Information System (NKIS) – a policy information sharing platform from National Research Council and national research institutes (NKIS, n.d.).

From the NTIS, when "hydrogen direct reduced ironmaking", or "hydrogen reduction ironmaking" ("수소환원제철" in Korean) was searched, a total of 32 projects appeared. Among them, projects that included "hydrogen direct reduction ironmaking" as a keyword were extracted, in other words, nuclear hydrogen, CO2 emission reduction for Blast Furnace, scrap, etc. were excluded. It was then narrowed down to 2 projects: 1) Development of CO2 reduction type Hybrid Amplification and Reforming Technology for Reduction ironmaking (2017-2024); and 2) Fundamental study of the thermodynamics and kinetics of CO2 utilization and nitrogenation in future steelmaking for carbon neutrality (2022-2027). These two projects have produced 2 and 1 research papers[11] respectively and 19 patents solely from the former. The investment scale of these two R&D projects has been KRW 11.8 billion and KRW 800 million won, for a total of KRW 12.6 billion won (equivalent to approx. USD 9.6 million or EUR 9 million) (ibid). These two projects include hydrogen-based iron & steel making technology, however, it can be argued that they are more complementary components of a larger system rather than standalone topic. It was not until May 2023 that the H-DR became the main focus

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[10] http://www.hyrex.co.kr

[11] Namely Long-term durability of La0.75Sr0.25Cr0.5Mn0.5O delta-3 as a fuel electrode of solid oxide electrolysis cells for co-electrolysis ; Development of CO2 reduction type Hybrid Amplification and Reforming Technology for Reduction ironmaking; and Critical challenges facing low carbon steelmaking technology using hydrogen direct reduced iron

of the national project. The government has selected 100 core technologies, including POSCO's HYREX technology, to achieve carbon neutrality (MSIT, 2023). It is intended to first complete basic technology development by 2025 with the government's R&D investment of KRW 26.9 billion (equivalent to EUR 19 million) including KRW 16.9 billion for fluidized bed reactors and KRW 10 billion for electric smelting are furnace. Considering that it takes a long time to fully introduce HYREX, KRW 237 billion (equivalent to EUR 173 million), R&D investment on low-carbon fuel substitution and energy efficiency on current BFs and EAFs by 2030. This investment involves in KRW 141.4 billion by the government (MOTIE, 2023c). From NKIS, when H-DR was searched, there were a total of 10 reports that at least dedicated a chapter with H-DR. Among them, two out of ten publications specialized in the steel industry decarbonization. However, it is important to note that these reports constitute grey literature produced by a government research institute rather than collaborative research including corporates and other stakeholders.

In Sweden, SSAB, LKAB and Vattenfall have collaborated on the HYBRIT project with financial supports from the Swedish Energy Agency (SEA) and the EU's Innovative Fund. In early 2016, these three companies announced the implementation of a fossil-free steel production process in Sweden, and a pre-feasibility study was launched (Åhman et al., 2018; HYBRIT, n.d.). From 2016 to 2019, the HYBRIT initiative has received significant financial support of **SEK 599 million** (equivalent to EUR 51.5 million) from the SEA when initiating the project (Vattenfall, 2019). In 2017, a collaborative research program between industry, universities, and research institutes was established to identify possible fossil-free stages in the energy, mining, iron and steel value chain (ibid). Consequently, knowledge development on the hydrogen-direct reduced ironmaking technology has been able to be fostered by many different actors. The HYBRIT initiative has divided the work packages that is necessary for the HYBRIT project. Table 5-1 shows the HYBRIT work packages with different partners and their published research papers (HYBRIT, n.d.-a). According to Gerres et al. (n.d.), although Swedish companies have smaller steel production capacity compared to Korean steel producers and other major EU steel companies, Swedish companies have announced the largest share of investments, with a South Korean company coming in second (Table 5-3) (Gerres et al., n.d.).

Table 5-1 HYBRIT work packages and partners

Work package	Work package's partners	Number of papers
Supply of fossil-free electricity and the effects on the electricity system	LKAB, Luleå University of Technology, Swerim and RISE ETC with the support of Vattenfall and SSAB	
Production and storage of hydrogen	Vattenfall and KTH	12
Production of fossil-free iron ore pellets	LKAB, Luleå University of Technology, Swerim and RISE ETC with the support of Vattenfall and SSAB	7
Hydrogen-based reduction of iron ore	LKAB, KTH, Luleå University of Technology with the support of Swerim and RISE ETC	6

Steel production of hydrogen-reduced iron ore	by SSAB and KTH with support from LKAB and Luleå University of Technology	4
Meeting the market	Lund University, Stockholm Environment Institute (SEI) and Swerim with support from SSAB, LKAB and Vattenfall	15

Source: Hybrit (n.d)

Table 5-2 Korean national project for H-DR from NKIS

	Title	**Organization**	**Year**	**Keywords & Summary**
1	Scenario analysis of iron and steel production process for carbon neutrality	Korea Energy Economics Institute, Inha University	2022	Analysis on the cost of fuel and raw material of BF and H-DR
2	Assessment of Carbon Neutrality Potentials from Sector Coupling	Korea Energy Economics Institute, Pukyeong National University	2022	P2G technology: converting energy surplus into hydrogen
3	A study on Policies Supporting Decarbonization in Hard-to-Abate Industry	Korea Energy Economics Institute, Busan National University	2021	hard-to-abate sector, low-emission practice, policy support
5	Energy Transition Forum for Green New Deal	Korea Environment Institute	2020	Green New Deal, Industrial transition, Clean energy transition
6	Costs of Innovative Technologies for Achieving Carbon Neutrality	Korea Environment Institute	2022	Carbon Neutrality, Technology costs (EES, Hydrogen, etc.)
7	A study on Changes in Trade and Environmental Relations and Korea's Response Strategy in the Era of Carbon Trade	Korea Environment Institute, BNZ Partners, Korea University	2022	CBAM
8	A study on how to facilitate GHG emissions decoupling in major manufacturing industries	Korea Energy Economics Institute	2020	hard-to-abate sector, decoupling
9	A study on the strategies for early settlement of market driven hydrogen economy in Korea	Korea Energy Economics Institute	2021	Hydrogen economy

Source: National Knowledge & Information System (n.d.)

Numerous universities participate in national projects related to steel. However, Respondent #1 expressed that there is a shortage of master’s and PhD students in the field of iron and steelmaking process as steel is considered to be declining industry compared to semiconductor, AI and other high-tech industries. Research programs or research papers on H-DR steelmaking technology from Korean steel producers specifically was not identified neither on the NTIS platform nor the POSCO's website. Although H-DR specific R&D collaborations are not pronounced, Respondent #4 said that there is active R&D collaboration between government & academia on green hydrogen (Respondent #4).

Although it was difficult to find much active domestic knowledge development within Korea, e.g. research publications, projects etc., POSCO has actively sought cooperation internationally. In 2021, POSCO signed a Memorandum of Understanding (MoU) with Roy Hill[12] – Australia's largest iron ore mine operator, producing 60 million tons of iron ore per year (Yeonhap, 2021). The aim was to conduct a preliminary feasibility study on an optimal hot briquetted iron (HBI) production system combining POSCO's hydrogen reduction steel technology (Roy Hill, 2022). In March 2022, POSCO Group made a Heads of Agreement with Australia's Hancock group on a joint study on HBI, with plans to invest in Australia in renewable energy and water electrolysis for hydrogen production and to produce HBI (Hankyung, 2022; Sparke, 2022). In addition, POSCO has launched the first international Hydrogen Iron & Steel Making Forum (HyIS) since 2021, which has become an annual international event providing a platform for stakeholders, including steel producers, electricity utility, hydrogen producers, international organizations, steel buyers in steel industry to gather and share knowledge on decarbonized hydrogen steelmaking. Such an initiative has fostered knowledge development on a global level.

Table 5-3 Number of research and the investment

	The total number of Research paper	Total amount of initial R&D investment
Korea	26	EUR 8.2 billion
Sweden	43	EUR 20 - 46 billion

Source: National Knowledge & Information System (n.d.) & Gerres et al., n.d.

5.2 Function 2 Influence on the direction of search

For the development of a TIS, a diverse array of enterprises and other organizations must choose to enter it (Bergek et al., 2008). Consequently, it is imperative to provide sufficient incentives and/or pressures to motivate organizations to be induced to do so (ibid). The second function covers the mechanisms that impact the direction of search within the TIS, including but not limited to different competing technologies, applications, markets, business models, etc. These factors are, for instance: incentives from changing factor and product prices, growth occurring in TISs in other countries, actors' perception of the relevance of different types and sources of knowledge, regulations and policy, articulation of demand from leading customers, etc. (ibid). Among these factors, this paper investigates more into regulations and policy for the steel industry in Korea and Sweden.

Based on the interviews carried out with Sweden/EU respondents, two most frequently mentioned policies were Industrial Emissions Directive (IED) and Emission Trading Scheme (ETS). Additionally, one respondent highlighted the Ecodesign Directive as well (Respondent #7). The Korean perspective mostly emphasized the Carbon Border Adjustment Mechanism

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[12] Roy Hill is an independent iron ore operator in Western Australia's Pilbara region with four ownerships: Hancock Prospecting Pty Ltd (70%), Marubeni Corporation (15%), POSCO (12.5%) and China Steel Corporation (2.5%) (Roy Hill, n.d.)

(CBAM) and carbon pricing. In addition to CBAM, the Korean respondents did not specify a particular policy, but one respondent said that "Korea has many policies, but they are rather scattered and there is a lack of integrity" (Respondent #2).

5.2.1 Investment

In terms of investment in Korea, MOTIE announced a development strategy for the steel industry which laid out its plan on how to secure & strength scrap and R&D on low-carbon steel technology development including hydrogen reduction technology. Along with this, steel decarbonization alliance will be formed to link public-private partnerships and establish KRW 150 billion private fund (equivalent to EUR 107 million) to create scrap value chain and low-carbon iron & steel making transition (MOTIE, 2023).

Numerous articles have been published regarding the investment to Swedish hydrogen-based steel production. In 2019, the three shareholders of HYBRIT – SSAB, LKAB and Vattenfall – announced investing SEK 150 million and the SEA is contributing additional 50 million for the construction of a storage facility for hydrogen at the HYBRIT pilot plant (approx. EUR 17.3 million) (MaintWorld, 2019). In 2022, the HYBRIT was granted a total of EUR 143 million for scaling up for a complete value chain for hydrogen-based iron and steelmaking from the EU Innovation Fund[13] (HYBRIT, 2022). The grant consists of EUR 108 million earmarked for the demonstration of the hydrogen direct reduction process which involves fossil-free hydrogen production in Gällivare (HYBRIT), another EUR 30 million for the demonstration of electric melting of hydrogen-based direct reduced iron in Oxelösund (SSAB) and the last EUR 5 million for the demonstration of fossil-free DR-pellets production for the hydrogen reduction process (LKAB) (ibid).

5.2.2 Industrial Emissions Directive (IED)

The IED serves as the EU instrument regulating pollutant emissions from industrial activities (European Commission, n.d.). The IED encompasses a range of emissions, including emissions to air, water and land (originally excluding CO2 emission), generation of waste, use of raw materials, energy efficiency, noise, accident prevention, and site restoration after closure. Approximately 52,000 installations in EU – 1300 plants in Sweden (Jernkontoret, 2021) - that engage in the industrial activities are listed in Annex I[14] of the Directive and required to operate under a permit granted by the authorities in the Member States (European Commission, n.d.). The permit should contain conditions set in accordance with the principle of the 'polluter pays' and of pollution prevention (Directive 2010/75). The permit conditions, including emission limit values, are established based on the Best Available Techniques (BAT). The commission facilitates an information exchange with experts from Member States, industry and environmental organizations to define BAT and its associated environmental performance within the EU context (European Commission, n.d.)[15]. The outcome of this process yields BAT

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[13] The EU Innovation Fund is one of the world's largest funding programs that supports the demonstration of innovative low-carbon tehnologies that mitigate reduce GHG emissions (HYBRIT, 2022).

[14] Iron and Steel production is listed in the Annex I chapter 2. "Production and processing of metals".(Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control) (Recast) (Text with EEA Relevance), 2011) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010L0075-20110106

[15] This process is coordinated by the European Integrated Pollution Prevention and Control (IPPC) Bureau at the EU Joint Research Center in Seville, Spain (European Commission, n.d.)

Reference Documents (BREFs)[16] which contain the BAT conclusions (BATC)[17] that are subsequently adopted by the Commission as Implementing Decisions. The IED requires that these BAT conclusions are the reference for setting permit conditions (ibid).

The steel industry is known as the first sector to receive BAT Conclusion for iron and steel production, which means that the steel producing companies have been able to meet the emission limit value based on the BAT specified in the BAT Conclusions (Jernkontoret, 2021). The activities of the Swedish steel industry are regulated by IED, the associated descriptions of BAT and emissions limit values to be achieved (Jernkontoret, 2018). During the years 2020-2023, the IED goes through a revision in line with the European Green Deal (ibid). Some of the main proposals for revision of the Directive are: i) to extend it to cover more processes and new sectors (e.g. whether mining should be included); and ii) to include GHG emissions reduction in installation-level environmental permits, and so forth. (CAN Europe, 2022; European Commission, n.d.-b; Jernkontoret, 2021). One respondent expressed concern regarding the IED revision. This is because the Commission and other legislators want to widen and put more details into IED which may result in challenges in obtaining permits for specific steel production process. To be specific, one concern is the risk of overlapping with other legislation, such as EU Emissions Trading Scheme (ETS) and waste legislation. Another concern is the inclusion of CO2 in the IED. The steel industry is included within the EU ETS. As per the provisions of Article 9.1 of the IED, it is stipulated that the permit shall not include an emission limit value pertaining to the direct emissions of GHG (Jernkontoret, 2021). The rationale behind the IED not including CO2 was that CO2 would be already covered by the ETS. However, because of the issue of free and over allocation from the EU ETS, the CO2 emissions reduction may not be effectively achieved, as indicated by one of respondents (Respondent #7).

5.2.3 Emissions Trading System (ETS)

The Kyoto Protocol to the UN Framework Convention for Climate Change (UNFCCC) was agreed upon in 1997 and set legally binding GHG reduction targets by 2012, for 37 industrialized countries (Annex I countries) during the first commitment period (2008-2012) (European Union, 2015). This necessitated the development of policy instruments to fulfil the Kyoto commitment (ibid). Based on this need, the European Commissions presented a green paper outlining initial concepts for the EU ETS in 2000 (European Commission, n.d.). It served as the foundation for many stakeholder discussions that contributed to the system's development (ibid). The EU ETS Directive then was adopted in 2003 and the EU ETS was launched in 2005, the world's first international emissions trading system (European Commission, n.d.). In conjunction with the GHG emissions inclusion,

Under the EU ETS phase 3 onwards, a benchmarking approach is used for the free allocation of allowances (European Commission, n.d.). The free allocation for each installation is calculated using GHG emission benchmarks developed for each product, where possible and 54 benchmarks have been currently elaborated based on extensive technical work and consultations with various stakeholders. A product benchmark is based on the average GHG

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[16] BREFs refer to what is considered to be the best available techniques for a sector or part of a sector (Jernkontoret, 2021).

[17] The BATC is a chapter in BREFs. It outlines the BAT and associated emission levels (BAT-AELs) for different activities under the IED (ibid)

emissions of the best performing 10% of the installations producing that product in the EU and EEA-EFTA states (European Commission, n.d.).

The benchmark is used to determine the level of free allocation that each installation in each sector will receive. A benchmark is not an emission limit or an emissions reduction target per se (European Commission, 2015). All installations within a sector receive the same allocation of allowances per unit activity. The best performing installation, whose GHG emissions are lower than the benchmark, will receive more free allowances than they need (ibid). In other words, the principle for these benchmarks in the beginning was to look into all the sites making the same product and their emission intensity and then take the 10% best of producers in terms of having the cleanest and least-polluting facilities in each sector. These selected benchmarks serve as the starting point for setting standards and play a crucial role in offering incentives to industry to decarbonization (LKAB, 2020) (Respondent #6).

In accordance with the EU ETS, the European steel industry receives free allocation for five product benchmarks: coke, sinter, hot metal which is connected to the blast furnace process, EAF carbon steel, and EAF high alloy steel (EUROFER, 2022). These benchmarks play a key role in providing incentives to industry to decarbonize. The sinter plant is needed in a process that involves the conversion of iron ore fines into a mass, commonly known as a pellet (Jernkontoret, 2019). Conventionally, the sinter plant is situated on the same premises as the steelworks, i.e. BF-BOF. However, LKAB, a Swedish mining company and one of consortiums of HYBRIT has progressed to the next step in the value chain by including the pellet production rather than solely selling fines to steel producers (Respondent #6). LKAB is unique in its mining because its ore composition is mainly magnetite, which requires far less energy to transform it into steel than the hematite iron ore that is the main iron ore found elsewhere in the world (LKAB, 2020) (Respondent #6). Therefore, the emissions from LKAB's pelletizing process are significantly lower compared to other sinter work in Europe mainly due to the iron ore type. Despite the cleaner feature of LKAB's pellet compared to other European sinter process, they are currently not included in the sinter benchmark (ibid). The European steel industry's competitiveness in terms of reaching climate target is being negatively impacted by overcompensation, which is causing a decline in the competitiveness of those who have made significant investments in climate efficiency (ibid). The overcompensation could bring the investments in fossil-free steel, e.g. HYBRIT, a worse competitive position than the carbon-intensive traditional steel industry (ibid). Nevertheless, as one interviewee expressed, there is hope as the Swedish government has been lobbying for the inclusion of the LKAB's pelletizing process in the sinter benchmark and would anticipate favorable results in the second period of EU ETS phase 4 starting in 2026.

Korea commenced the Korean ETS (K-ETS) in 2015, the first country in East Asia to do so, based on the laws on the Green Growth and the Act on Allocation and Trading of GHG Emission in Korea (GIR, 2022), and is now in the third phase of K-ETS (2021-2025). The steel industry in Korea has been so far receiving 100% free allowances ever since the K-ETS started and is expected to receive the 100% free allowances until the third phase. The specific details regarding the fourth phase of the K-ETS have yet to be laid out. However, in 2022, the ministry of Environment created an Emissions Trading Advancement Council to discuss ways to enhance the K-ETS to achieve the country's carbon neutrality and to address the Carbon Border Adjustment Mechanism (Influence Map, n.d.). The discussion pertains to decrease in free allocation, free allocation based on benchmark in the 4th phase (2026-2030) (ibid).

Table 5-4 Timeframe of EU ETS & K-ETS

	EU ETS	**K-ETS**
Phase I	2005 – 2007 (3 years)	2015 – 2017 (3 years)
Phase II	2008 – 2012 (6 years)	2018 – 2020 (3 years)
Phase III	2013 – 2020 (8 years)	2021 – 2025 (5 years)
Phase IV	2021 – 2030 (10 years)	

Source: Korea Exchange (2018)

5.2.4 Carbon Border Adjustment Mechanism (CBAM)

The gradual implementation of the CBAM is aligned with the phase-out of the allocation of free allowances under the EU ETS to facilitate the decarbonization of the EU industry (European Commission, n.d.-a). Both the EU ETS and CBAM are complemented one another, aiming at pricing GHG emissions embedded in the same sectors and goods. This is done via the use of specific allowances or certificates. Both systems have a regulatory nature and are justified by the need to mitigate GHG emissions, in line with the binding environmental target under the EU law, set out in Regulation (EU 2021/1119, which aims to reduce the EU GHG emissions (European Union, 2023). One of main differences between EU ETS and CBAM is that EU ETS applies to installation within the EU, whereas CBAM applies to certain goods imported into the customs territory of the EU (ibid). The CBAM will enter into force in its transitional phase as of October 2023 and targets carbon intensive and at most significant risk of carbon leakage goods. i.e. iron and steel, cement, aluminum, fertilizers, electricity and hydrogen during this phase (ibid).

It is true that there are some concerned voices. In the case of Korea, for instance, the steel industry is expected to be the most affected by the EU CBAM (KEEI, 2022). It is because the average share of steel exports to the EU during the 2018-2020 period was approximately 11% (MOTIE, 2023; KEEI, 2022.). Though the Korean government recently announced the Steel Industry Development Strategy with its investment plan to address potential challenges posed by the CBAM and to lay the foundation for the domestic steel industry, no definitive response has been observed from either the government or Korean steel producers. One respondent mentioned that the majority of the discussion in terms of how to respond CBAM so far has centered on the administrative procedures (Respondent #2). The respondent also mentioned that the government support tends to focus on SMEs rather than conglomerates. Since the EU announced the implementation of the CBAM in 2019, most studies have been conducted on the potential impact of the CBAM domestically and internationally (KEEI, 2022). While there has been some research on the economic impact of CBAM, however, there are relatively few studies on domestic measures on how to respond to CBAM (ibid). These few studies have focused on the SME perspective on how to respond to the CBAM, which shares the concern of one of the respondents about government support (ibid) as well as additional costs for the administrative process of CBAM.

5.3 Market formation

Bergek et al. categorizes three market phases for an emerging TIS market formation: nursing – in the very early stage, bridging – when volume increased and finally mature phase. For a TIS in a transformation phase, markets may not be fully formed (Bergek et al., 2008). In terms of the hydrogen-based steelmaking technology it was Sweden that first successfully piloting hydrogen-based steel production in 2018 and heading towards demonstration phase, thereby indicating the absence of current market for the large-scale hydrogen-based steelmaking technology. Therefore, the author perceives the current market for the hydrogen-based steel is nursing phase, or in other words, a niche market. To understand the sequence of the formation of markets, Bergek et al. suggested scrutinizing both actual market development and what drives market formation, for instance, the timing, size, and type of markets that have actually formed (ibid). Since the market size is still nursing phase, in order to investigate the market formation, demand signals, drivers of market formation are identified in the chapter.

The industrial sector is taking significant steps toward transition (IEA, 2022a). Many market research reports estimate the global green steel market was beyond USD 182 million in 2022 and is projected to grow rapidly ((Precedence Research, 2023; Vantage Market, 2023). The rising demand for low- to zero-emission steel is driven in part by climate targets set by consumers of steel producers such as construction and automotive, and others who seek to reduce their scope 3 emissions (IEA, 2022a). In addition, many automotive & construction companies, e.g., Lendlease, Skanska, Hyundai, Toyota, Ford, BMW, and others, announced their net zero target by 2050 at the latest. Given this widespread industry trend, the demand for low- emission steel will be high (ibid). This strong demand signal coming from steel offtakers has incited steel producers to react accordingly.

Moreover, there's a global initiative to drive global demand for green steel such as the SteelZero, the First Movers Coalition and etc. For example, SteelZero was launched by the Climate Group[18], in collaboration with ResponsibleSteel, which is the first global initiative aimed at driving a demand signal for green steel (Green Steel World, 2023). In order to become a member, organizations need to make a public commitment to use, procure and specify 50% low-emission steel by 2030, with a long-term target of using 100% green steel (ibid). As of present, the current membership count of SteelZero amounts to 36 companies, including 4 Swedish companies namely Skanska UK, Vattenfall, ViaCon Group, Volvo Cars (SteelZero, n.d.). There are currently no Korean companies that are part of the SteelZero (ibid). In terms of policy to support this demand signal, NGOs and some other actors – but not necessarily coming from government side – discussing Green Public Procurement (GPP) as a tool to accelerate the market for green steel. In Sweden, or EU in broader term, is working on Eco Design Directive as a demand side measure (Respondent #7).

In case of Sweden, though the country has just passed the pilot stage and heads towards the demonstration stage meaning there is no current existing market for hydrogen-based steel, discussion on creating a market for decarbonized steel is actively on going. The HYBRIT project is aiming to scale up to a demonstration plant and to commission to make fossil free steel available to the market in 2026 (HYBRIT, n.d.). It has a plan to produce 1.2 Mt of crude steel per year, which represents 25% of Sweden's total production, and has the potential to reduce 14.3MtCO2eq of GHG emissions during the first ten years of operation (ibid). The production facility in Gällivare estimates to use 500 MW electrolyser capacity powered by fossil-free electricity. The project will enable to facilitate the replacement of two blast furnaces at SSAB with an electric arc furnace which would use the sponge iron as the feedstock to produce high-quality steel (HYBRIT, n.d.a). It is worth noting that the domestic market is gradually gaining recognition in Sweden. In 2021 summer, the first 100 tons of sponge iron from the pilot plant in Luleå were delivered to SSAB, which was then able to supply fossil-free steel to Volvo (HYBRIT, 2021b). SSAB and Volvo Group have signed an agreement to collaborate on

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[18] Climate Group - located in London, New York, New Delhi, Amsterdam and Beijing - is an international non-profit organization founded in 2003 working with governments and business to achieve net zero emissions by 2050 especially high-emission sectors including energy, industry, transport and etc. ((Climate Group, n.d.).

research, development, serial production and commercialization of the world's first vehicles manufactured from fossil-free steel (SSAB, 2021). In 2022, SSAB made another progress in the development of fossil-free steelmaking and delivered around 500 tons of fossil-free steel to SSAB's customer. Volvo Construction Equipment (Volvo CE) became the first company in the world to deliver a construction machine using SSAB fossil-free steel to its customer, NCC[19].

With respect to Korea, hydrogen-based steel production technology has not been piloted, however, in July 2022, POSCO signed a joint engineering business agreement with Primetals, a British plant construction company, to start designing the demonstration plant for hydrogen-based steel making HYREX (POSCO, 2022d). The reason POSCO can leapfrog to demonstration stage for hydrogen-based steel plant is that POSCO is currently operating a FINEX[20] facility that uses reducing gas containing 25% hydrogen that shares the basic principle with HYREX but uses full 100% hydrogen coming from renewable energy (ibid). HYREX follows the method of reducing iron ore by directly with hydrogen in a powdery state and can skip the pelletizing process and use relatively low-grade ore (ibid). POSCO aims to advance its H-DR technology by incrementally raising the hydrogen concentration in the two Pohang-based fluidized bed reactors to 1.5 million tons and 2 million tons per year, respectively (POSCO, 2021b). No specific companies have agreed to purchase hydrogen-based steel as an end-product, however, there has been active business-to-business interaction on hydrogen. POSCO and Hyundai Motor, for instance, signed a business agreement on hydrogen business cooperation. In principle, only one steelmaker's materials are used for one type of part, but different parts may contain materials supplied by different steel producers. Thus, Hyundai Motor's vehicles do not only use steel from Hyundai Steel, but it is known that steel from a wide variety of steelmakers is used in a single vehicle. Moreover, POSCO has its affiliated construction companies (Donga, 2021).

In February 2023, the Korean Ministry of Trade, Industry and Energy announced the strategy for the steel industry for low-carbon steelmaking transition and its plan to establish a fund worth 150 trillion won, equivalent to USD 116 million or EUR 105.3 million, to support steelmakers' transition to a low-emission production structure and to boost competitiveness (MOTIE, 2023; Yeonhap, 2023). This is almost the very first government's official support to the steel industry. In the last year 2022, MOTIE and the Korea Iron & Steel Association held the Iron Day celebration event and reached a business agreement to establish a steel ESG fund to support SMEs with ESG certifications. POSCO, Hyundai Steel and IBK Corporate bank that contributed a total of 150 billion won - 50 billion won, 20 billion won, and 80 billion won respectively (MOTIE, 2023; Chosun, 2022), but no government financial support for hydrogen-based iron & steelmaking technology was specified. In line with the ESG fund, this strategy set out 150 trillion won (equivalent to EUR 105.3 million) with the establishment of a private-public alliance involving major Korean steel companies, MOTIE, and Korea Iron & Steel Association as well as the development of a roadmap for low-carbon steel production roadmap in coming years. The strategy also set out its countermeasure for the Carbon Border Adjustment Mechanism, however, according to one interviewee, a specific roadmap that outlines specific plan will have been published in a couple of years since the announcement (Respondent #2).

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[19] NCC is a Swedish construction company that set climate neutral target by 2045 (NCC, 2022)

[20] FINEX is a method that uses iron ore and coal in powder form without the sintering and coking process which make raw materials into lumps that POSCO commercialized FINEX in 2007 (POSCO, 2022)

In case of Sweden, the HYBRIT was granted financial support of SEK 599 million (approx. EUR 52 million) by the Swedish Energy Agency through the Industriklivet initiative[21] (Vattenfall, 2019) and continuously has received investment for a research and technology development. The three shareholders of HYBRIT - SSAB, LKAB and Vattenfall – have also spent and committed to invest SEK 1.1 billion (ibid). The Swedish Energy Agency has granted HYBRIT an additional investment of SEK 250 million via the Industriklivet initiative, for another example, for building a rock cavern storage facility for fossil-free hydrogen gas on a pilot scale next to the current HYBRIT's pilot facility for direct reduction in Luleå (SSAB, 2021). In addition, the project received in total EUR 143 million for scale-up a complete value chain from mine to fossil free steel from the European Union Innovation Fund[22] (HYBRIT, 2022b).

It is clear that the demand for a reduced emissions for steel products is growing, but steel producers' efforts need to be complemented by government and policy actors at an early stage. One of the main concerns about hydrogen-based steel products mentioned by some of interviewees was the additional premium cost and the willingness to bear the cost. Two potential policies that are under discussion as complementary measures for creating a market for green steel is Green Public Procurement (GPP). GPP is a policy instrument whereby public organizations seek to procure goods that have a reduced environmental impact throughout their lifecycle compared to similar goods that perform the same function (European Commission, 2016; Hasanbeigi & Bhadbhade, 2023). Government-funded construction and infrastructure project accounted for around 11% of total steel demand in Korea in 2019, and the government can use its purchasing power to stimulate demand for green steel products (Hasanbeigi & Bhadbhade, 2023).

Table 5-5 Comparison between Korea & Sweden

	Korea	**Sweden**
Actors	Large, multinational firms	Large firms, start-up
Institutions	Inconsistence push & investment from government	Large amount of investment from government
Networks	Strong international learning network Emerging political networks Weak network	Strong domestic learning network Strong political network Organic cross-cutting network with all public-private sectors

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[21] Industriklivet is a Swedish national initiative launched in 2017 with the aim of providing support for measures to mitigate Swedish process-related GHG emissions from the country's industrial sector as a step towards achieving the national net-zero target. It offers funding for research, development and demonstration (Stockholm Environment Institute et al., 2022). Industriklivet is undertaking numerous projects in the Swedish industry sector including 25 projects in the steel industry (Industriklivet, n.d.).

[22] The EU Innovation Fund has allocated a budget of approximately EUR 20 billion (subject to carbon prices) for financing the commercial demonstration of innovative low-carbon technologies over 2020-2030. The funding comes from the EU ETS and can support up to 60% of the additional CAPEX and OPEX of large-scale project. For smaller project, only CAPEX is eligible for coverage (Stockholm Environment Institute et al., 2022)

Knowledge development and diffusion (R&D, investment)	- 13 R&D and study reports - EUR 8.2 billion	- 43 R&D and study reports - EUR 20-46 billion
Guidance of the search	Policy: Carbon pricing, ETS, CBAM	Policy: IDR, ETS
Market formation	Active B2B	Moderate B2B

Source: Author's own

6 Discussion

6.1 Comparison of the Korean and Swedish H-DR innovation systems

6.1.1 Discussion to RQ1: How has knowledge development and diffusion been supported in Korea VS Sweden?

The current level of knowledge development and diffusion in Korea for Green H-DR has been relatively low domestically in terms of the number of research papers, R&D, as well as the amount of investment for the R&D. Until the government designated POSCO's HYREX technology as a national R&D project in May 2023, it was mainly POSCO was responsible for paving path for Green H-DR without specific governmental support. However, the number of national projects which contain "H-DR" as a keyword was 2 and 3 research papers were derived from the national projects ((Kim & Sohn, 2022; Kwon et al., 2019; Park et al., 2020). These three research papers are of scientific and technological aspects which involve electrolysis, solid oxide fuel cell, porous carbon, poly (vinylidenefluoride), which are important parts of hydrogen-reduction iron & steelmaking technology. However, research papers that overarchingly focus on H-DR technology diffusion in Korea that is publicly available were lacking. More comprehensive ones – i.e. steel industry decarbonization - were found from some grey literature from government research institutions, such as KEEI, KIET, Korea Institute of Energy Research (KIER), and a few reports from NGOs. With regards to the international knowledge sharing activities, on the other hand, POSCO has shown proactive approach to international cooperation - i.e. a joint study with Roy Hill & Hancock, the Australian mining company, hosting the international HYIS forum, and etc. - have been observed more frequently. For H-DR related R&D in Korea started with equivalent to 21 million EUR investment including recent government announcement.

One reason why the Korean domestic knowledge network has been weak, especially public-private, according to **a respondent 1** from Korea, is that national projects are mostly driven by public-academia, which resulted in limited corporate engagement. However, when it comes to formulating carbon neutral strategy, large corporates participation is a must in order to identify demand for a certain technology and to determine the direction of technology and business, especially considering that large corporates play significant role in the Korean economy. In response to this need, corporates, including steel producers have expressed their interest to participation in national projects coordination, and their interest was received positively. However, respondent 1 expressed concern that this dialogue has not been consistent and may be subject to change depending on which political party take presidency (Korean respondent 1). Another reason, according to a **respondent 2** from Korea, could be explained that the government's tendency to provide more support to small and medium-sized enterprises (SMEs) while remaining relatively indifferent towards conglomerates. The respondent also noted that, in turn, conglomerates are hesitant to share their data with the government (Korean Respondent 2). As climate target is our collective goal that needs concerted efforts, therefore, regardless of which political party take presidency, climate target should remain consistent so that corporates can really concentrate on their low-emission transition. Furthermore, corporates need to improve their data transparency, while also establish a comprehensive and detail roadmap.

In the case of Sweden, domestic knowledge development has been well established. Following the Paris Agreement, three main project phases were set: pre-feasibility study (2016-2017), feasibility study Pilot stage (2018-2024) and demonstration plant stage (2025-2035) (HYBRIT, 2017). In terms of R&D, a four-year (2017-2021) research program was launched with the support of the Swedish Energy Agency (HYBRIT, n.d.). It was observed during the interview that the three shareholders of the HYBRIT – SSAB, LKAB and Vattenfall - and the steel association approached universities to collaborate in the HYBRIT project. It was mentioned by **three Swedish respondents** commonly that it is natural for corporates to approach academia for the purpose of such partnership in Sweden. The HYBRIT project was started with the EUR 51.5 million investment from SEA, and has resulted in 44 research papers. Domestic (or Scandinavian) network was strong, however, international knowledge network was not identified from HYBRIT. It is noteworthy initiative and groundbreaking milestone that Sweden has shown the world that green H-DRI is feasible technology. However, technology to decarbonize the steel industry is not only about one company or one country gaining competitive advantage over another but also about a collective effort to tackle climate change and decarbonize the world's most polluting industry. Therefore, this dialogue and cooperation should be expanded to more international dimension.

6.1.2 Discussion to RQ2: How has the guidance of search been supported in Korea and Sweden?

Despite the positive perception and recognition of the urgent need for the Green H-DRI, the technology transition in Korea has been relatively slow. One reason could be that each time there is a change in which party holds the presidency, the climate target and support also slightly changes based on the stance of the administration. For example, the current administration - President Yoon Seokyeol - announced the government's draft of the first National Carbon Neutrality and Green Growth Basic Plan (2023-2042) in 2022. It is the first sectoral GHG emissions reduction targets that the Yoon administration put forward. Under this plan, the GHG reduction target for industry sector has been set at 11.4% reduction by 2030, which is 3.1% less than the Moon administration's goal (14.5%) (Yeonhap, 2023). Respondent 1 mentioned that under the previous administration, carbon neutrality was more accelerated. Thus, according to the prevailing government's direction, POSCO announced its carbon neutral roadmap in 2021 and brought all energy intensive industry, all national projects together to commit to carbon neutral. Numerous corporates, including POSCO have put effort to prepare to this end. However, due to the government leadership change last year, this plan was postponed. The current administration has decreased the level of government pressure on both corporate entities and governmental investment with regards to carbon neutrality, in contrast to the previous administration. This raises another concern as the industry sector, including POSCO need to comply with the Nationally Determined Contributions (NDC) by 2030. Therefore, depending on the next government, steel producers could face significant pressure (Respondent 1). This clearly shows that inconsistency of government support for not only steel industry but for all corporates to reach climate targets presents not encouraging environment for corporates to accelerate their low-emission transition especially Green H-DR requires extensive support from all actors especially government.

In terms of regulation and policy, CBAM was the policy most frequently mentioned by interviewees as affecting the Korean steel industry. One interviewee expressed concern about CBAM saying that this is beyond corporates' capacity and requires government-to-government negotiation to respond CBAM. In February 2023, a roundtable discussion was held to discuss the steel industry's development strategy in response to CBAM (MOTIE, 2023). In the event, MOTIE, steel association, 7 steel producers including POSCO and Hyundai Steel agreed on creating a KRW 150 billion (EUR 107 million) fund to promote low-carbon steel production. CBAM also brought Korea and Japan together to cooperate with (MOTIE, 2023; Korean Herald, 2023). It is true that CBAM raised a concern of possibility of encouraging protectionism, however, it has finally brought government's attention to decarbonize the giant steel industry and support them that used to be absent. Watching Sweden leading in fossil-free steelmaking, and European Commission putting forward Carbon Border Adjustment Mechanism (CBAM) to prevent carbon leakage, it might have given a pressure to the Korean government to take decarbonized transition to green steelmaking more seriously. (NEWSIS, 2022). What is more, it brought Korea and Japan together who have very sensitive diplomatic relation to cooperate.

In Sweden, three policy instruments were mentioned during the interviews: Industrial Emission Directive (IED), the Emission Trading Scheme (ETS) Directive and the Eco-Design directive. Starting with the IED, **respondent 1** expressed concern about the revised IED that it wants to set stricter emission limits without a thorough understanding of the differences between companies, sites and product types. Especially when making advanced products, the revised IED may not be advantageous in terms of energy efficiency and resource efficiency. The Swedish steel industry aims to produce advanced products of high quality as they are in the end better in terms of longer lifespan with less corrosion. **Another respondent (Respondent #2)** stated that IED and ETS are complementary. IED does not consider CO2 because it assumes that ETS takes it into account. But, due to free allocation and so on, it hasn't reduced CO2 emissions significantly. However, as the EU ETS is phasing out free allocation, legislators really need to make sure that these policy instruments do not double regulate the steel industry to shift to more advanced decarbonized technology.

6.1.3 Discussion to RQ3: How has the market formed for the green steel in Korea and Sweden?

Globally speaking, many networks are being formed to attract buyers in the green steel space, and promote market formation for green steel e.g. SteelZero, FirstMover Coalition, etc.. However, currently there are no Korean companies that are members of the international green steel coalition while those of Sweden have been identified. Along with this international initiative, the B2B contract is commonly recognized. For example, Korea, notably POSCO, signed MOUs with Hyundai Motors, while Swedish company SSAB has signed contracts with Volvo cars, Volvo Construction Equipment (Volvo CE), NCC, and etc.

In Korea, one respondent raised a concern about the additional premium cost associated with green steel as well as the lack of clarity related to consumer's willingness to purchase at an augmented cost. Some say that green steel will be 30% likely to be more expensive than conventional steel (Global Economic, 2023; Next Group & SFOC, 2022). However, some argue that as long as the green hydrogen can be produced with low price, green steel can remain similar cost range or cheaper (KEEI, 2022; Hydrogen Insight, 2023).

In Sweden, one respondent (Respondent #7) said that it is true that the bulk material industry, such as the steel industry, does not get incentives under the EU ETS to decarbonize, to change their process, when making advanced products in high quality. However, if there's a demand for green steel, steel industry is likely to answer that demand. Therefore, the respondent mentioned that the proposal for a new Ecodesign for sustainable product regulation (ESPR) is under discussion in the EU institutions as a demand side measure. Existing Ecodesign directive only applies to household energy using appliances, e.g. dishwasher, washing machine, etc., but the proposal tries to include intermediary products such as steel, to improve their circularity, energy performance and other environmental sustainability (European Commission, n.d.). This is to encourage consumers and businesses to make informed choices when purchasing products and improve transparency about life cycle impacts of products on the environment (ibid). If iron and steel are included, it will be part of product requirements applied to iron and steel products (Respondent #2). Though a clear instrument from EU or the government is not pronounced, a demand side measure for green steel in the market is currently on the discussion table among the EU institutions.

Several non-governmental organizations have proposed policy recommendations for green steel market through e.g., Green Public Procurement policies, but the Korean government have not yet publicly considered nor announced GPP as a tool to stimulate the market for green steel (Hasanbeigi & Bhadbhade, 2023). The same is true with Swedish government. One study on GPP at EU-level from the Stockholm Environment Institute says that the current implementation of GPP among EU member states remains below the target set by the EU Commission and the recent data is only available up to 2012 (Stockholm Environment Institute et al., 2023). And no discussion on GPP for green steel could be identified by the Swedish government nor respondents other than the Ecodesign Directive. GPP in Korea was first introduced in 2005, has grown fourfold from KRW 3.8 trillion to KRW 175.8 trillion by 2020, with civil engineering and building materials accounting for the largest share (46.1%) ((Next Group & SFOC, 2022). However, steel products are not included in the minimum green standard of the GPP product list (ibid). The public sector plays a key role in influencing and supporting the market formation for green steel as steel is one of the fundamental materials in all sectors, including the construction sector. Therefore, implementing policy support like GPP can provide reassurance to steel producers by sending a strong market signal for green steel.

Moreover, to diffuse this type of more sustainable and decarbonized technology, policy support is essential. The energy sector, for instance, to increase the deployment of renewable energy in 2000s, policy instrument such as the Feed-in-Tariff, significantly helped countries to increase the production of electricity from renewable sources in the initial stages. To be more specific, the first German Feed-in Tariff (EEG in German) was introduced in 2000 and contributed to the initial stage of increase in renewable energy deployment from 6.2% in 2000 up to 28% in 2014 (Future Policy, 2015). Although this example pertains to a different context, it demonstrates the necessity of policy instruments in promoting the adoption of new sustainable production technology in energy-intensive sectors like the steel industry. Therefore, the government involvement to facilitate the market for green steel especially in the early stage, is crucial.

6.2 Reflection on my study

The first and most important reason to choose this topic and delve into it was because I encountered much news about Sweden's success in piloting green H-DRI, whereas I came across many reports that the Korean steel industry emission reduction has been stagnated, and it is by far the most emitting industry in Korea and has been shielded from government's regulation such as free allocation. This made me ponder on why Korea is at a slow pace reducing GHG emissions contrary to its net zero target. However, this research has revealed that there are so many non-publicly spoken efforts within corporates to achieve decarbonization. And CBAM has accelerated in bringing the dispersed effort and consolidated even more where the effort used to be dispersed has now been brought attention from many different actors and network in Korea. Every country has its unique set of strength and weakness in order for technology diffuse, which can be influenced by factors such as political dynamics, trade advantages, geopolitical positioning, etc.. These factors can create advantages for some countries in specific areas, while others may face certain challenges. Based on the overall reflection, the following section presents the relevance of the study, selected methods, more specifically.

6.2.1 Methodological and analytical choices

The choice of a qualitative method with semi-structured interviews has allowed this research to provide an overarching insight into the challenges and trend of green H-DRI technology diffusion in the Korean and Swedish steel industries. The interview with steel producers, who are directly related to green H-DR, allowed me to understand the challenge that the practitioners' concerns. Also, the interviews with NGOs helped me grasp some other aspects that are still significantly relevant but have not been actively brought to the surface such as the network in the steel sector, policies and perspectives of civil society and people of the area where steel plants are located. Using the TIS as a theoretical and analytical framework was appropriate as green H-DR is an emerging technology that succeeded in piloting stage that needs to be scaled up. As a theoretical framework, the TIS has laid the foundation for understanding the process of technological innovation and dissemination within a socio-technical system. It pointed to the interplay between technological, social, economic, and policy dimensions. Simultaneously, TIS as an analytical framework, it offers a various set of indicators to analyze each function on how the technology has diffused guiding the research to explore the role of key actors, institutions, networks. By examining knowledge development, policy interventions, and market interactions, I gained a comprehensive understanding of how both internal and external dynamics influence the adoption and scaling up of technology in distinct ways in each country's context. The TIS framework enabled me to reveal the complex interaction between external influences and internal capacities in driving the spread of H-DRI technology in the steel industry.

6.2.2 Legitimacy

The research questions that were formulated by using functions and indicators of the TIS was legitimate as green H-DR is an emerging technology that succeeded in pilot stage and needs to be scaled up. It is true that the TIS is sometimes criticized by its lack of attention to overall context, i.e. geographical issues, international relations, and marginal importance in politics and technology diffusion (Markard et al., 2015). Nevertheless, the TIS framework was the right choice to start as it provides more perspectives, i.e. economic and political aspects to analyze which allowed me to observe more than just technological perspective.

Further research could investigate the remaining functions of the TIS and integrate them into a comprehensive analysis. Moreover, as scaling up renewable electricity as well as green hydrogen production will play a pivotal role in green H-DRI, future research could investigate hydrogen governance, including trade dynamics, renewable electricity generation to produce hydrogen, its contribution to the electricity system and its implications/impact for the steel industry.

7 Conclusions

The steel industry is considered a hard to abate sector. However, HYBRIT project showed that steel industry is possible-to-abate using hydrogen though there's a mile away to scale up. This paper compared steel industry in Korea and Sweden in terms of green H-DR technology transition analyzing three functions in the technological innovation systems: 1) knowledge development, 2) guidance of search and 3) market formation. Figure 7-1 depicts a summary of the domestic and international collaboration levels observed in Sweden and Korea. The study reveals that Sweden exhibits robust domestic collaboration but limited international cooperation. Conversely, Korea demonstrates a strong international cooperation and a weak domestic cooperation.

Sweden identified relevant actors and formed a strong domestic network initiated collaborated R&D with universities, research institutes etc. Sweden already published the steel industry roadmap to decarbonize in 2019. There has been EU-level policies that impacted the steel industry decarbonization and Sweden itself is known for its high carbon price. There hasn't been explicit support to foster demand and formation of market for green steel, however, there has been active B2B contract with green steel companies and vehicles and construction companies. The main message from the Swedish case is that a successful TIS needs stable institutional conditions (Swedish Energy Agency & the EU Commission), where actors are supported to obtain knowledge and skills from experimenting with the technology, form strong networks (universities, research institutes, corporates, etc.) that have an impact on learning process and policy making with consistent investment.

Korea has a strong international position, and this has been observed through 1) POSCO's international network for its supply chain with Australia and Oman, and 2) POSCO creating an international platform for knowledge development networking, e.g., HYIS forum. However, domestic knowledge network is weak green H-DR technology that POSCO was trying to promote did not gain much attention until recently. ETS is the most relevant policy that affects the steel industry in Korea, however, ETS has not been successfully reduce the GHG from steel industry. Instead, CBAM really gathered all actors in industry sector in Korea to support the steel industry decarbonization to maintain the competitiveness. The international market appears to be more attractive since there is no explicit domestic demand, other than one Korean vehicle company, nor market for green steel. As cost is the main competitiveness of Korean steel, therefore it is the matter of who would buy increased cost of green steel. For the Korean steel industry has suffering from inconsistent policies, investment and commitment depending on the presidency. In foreign markets, CBAM was once concerning but it has accelerated domestic actors to engage especially government's support. International knowledge exchange appears to be important for Korean R&D in order to stay in a leading position worldwide with respect to research. International markets appear to be just as attractive for the Swedish steel companies, but B2B contract is already made in the domestic market.

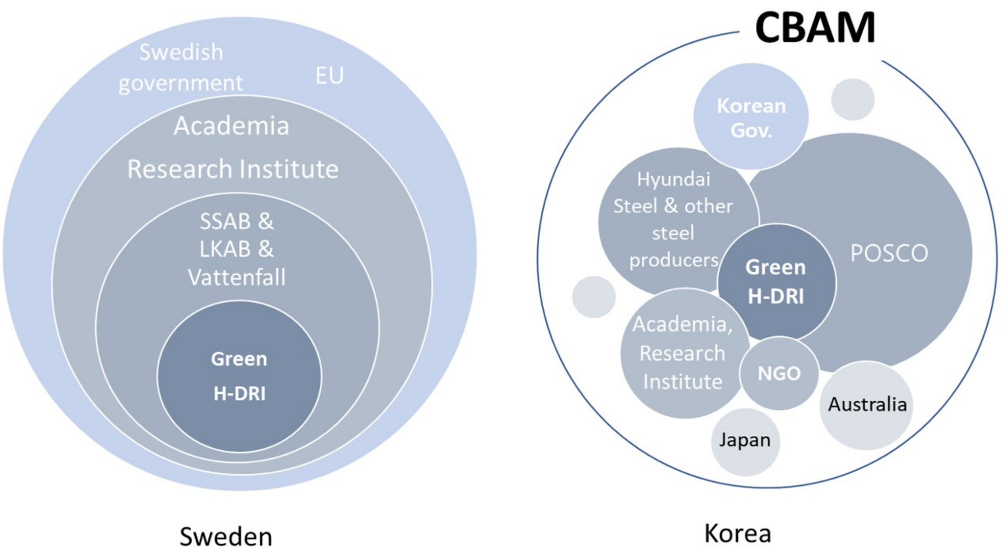

Figure 7-1 Comparison H-DR TIS between Sweden & Korea

Source: Author's own

7.1 Recommendations for future research

Based on the findings through this research, this section will delineate some recommendations for future research.

Strengthen alliances

As CBAM and Inflation Reduction Act (IRA) from the US are expected to bring about reducing greenhouse gas in energy-intensive industry, however, there is a potential risk of protectionism. Therefore, it's a worth consider for Korea to cooperate with neighboring countries and create and strengthen alliances. The recent initiatives in meeting with Korea and Japan governmental higher-ups as well as active trade with Australia shows positive move on this front. Thus, establishing an Asia-Oceania steel alliance could facilitate steel industry decarbonization globally.

Enhance international cooperation

Building upon the previous recommendation, beyond compartmentalizing efforts by region, the global steel industry should foster cooperation to collectively address environmental and climate challenges together. A unified approach across the industry will be more effective in achieving meaningful and sustainable decarbonization goals. The green steel networks and the HYIS forum are good examples.

Policy support, e.g., Green Public Procurement

The research found out that neither Korea nor Sweden have not yet actively considered GPP for green steel promotion in the market. Recognizing the significant influence do not actively consider GPP for green steel. As the public sector has a strong purchasing power to the market, countries need to revisit their GPP policy and foster the demand for green steel in the market.

Continuous investment R&D – consistent with university and private and pulic

The research found out one concern in Korea was that depending on which party taking the presidency, the pressure on meeting climate targets and the amount of investment have been inconsistent. Another Korean respondent in the research mentioned that government's support tends to be biased towards boosting SMEs growth, giving less attention to conglomerates. However, although green steel transition is dominantly led by conglomerates, consistent government engagement and support is a must to reach industrial and national climate target. Therefore, consistency in governmental support and investment is a must regardless of the political party in power.

Conduct Interdisciplinary Research

Steels are used everywhere ranging from, white home appliances to building materials, ships, wind turbines. Steel, from the production process to the finished products, has so much impact on society and people's daily life. For example, conflict with local communities over the construction of wind farms and the rights of the indigenous Sami people has caused controversy. Therefore, green steel transition needs a more interdisciplinary approach that goes beyond technological aspects and integrate socio-economic, socio-political and various other dimensions.

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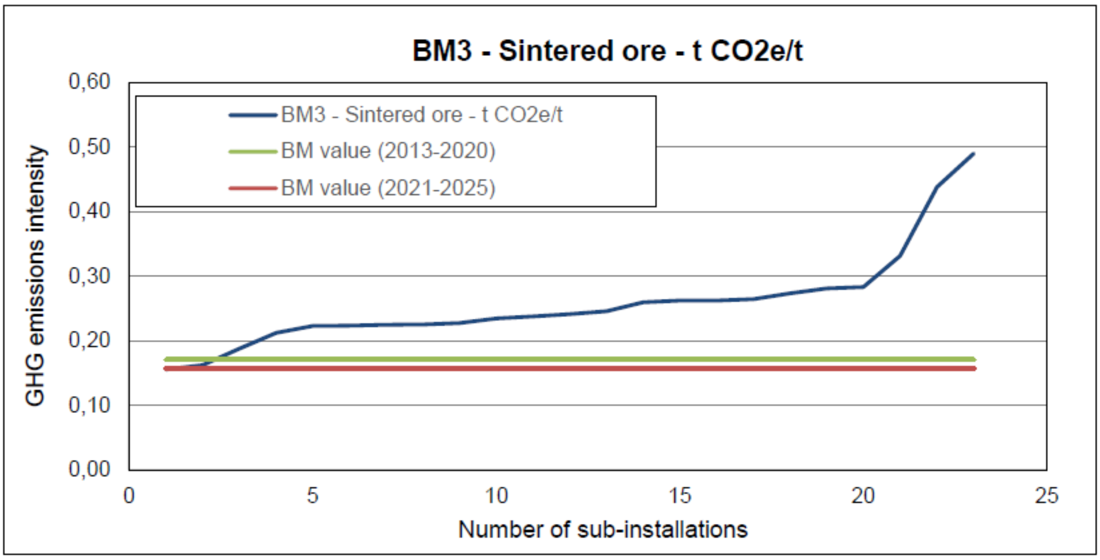
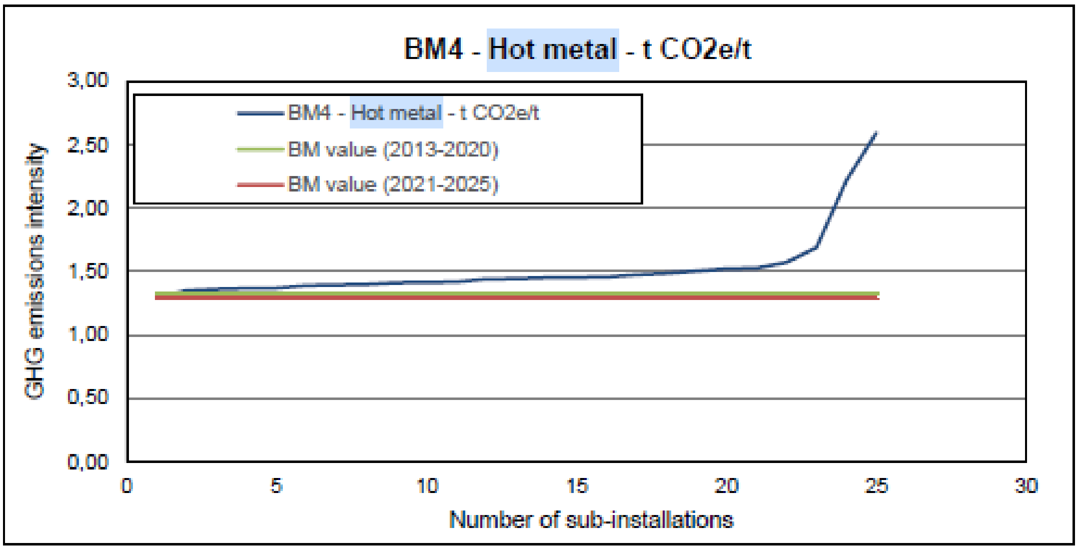
Appendix

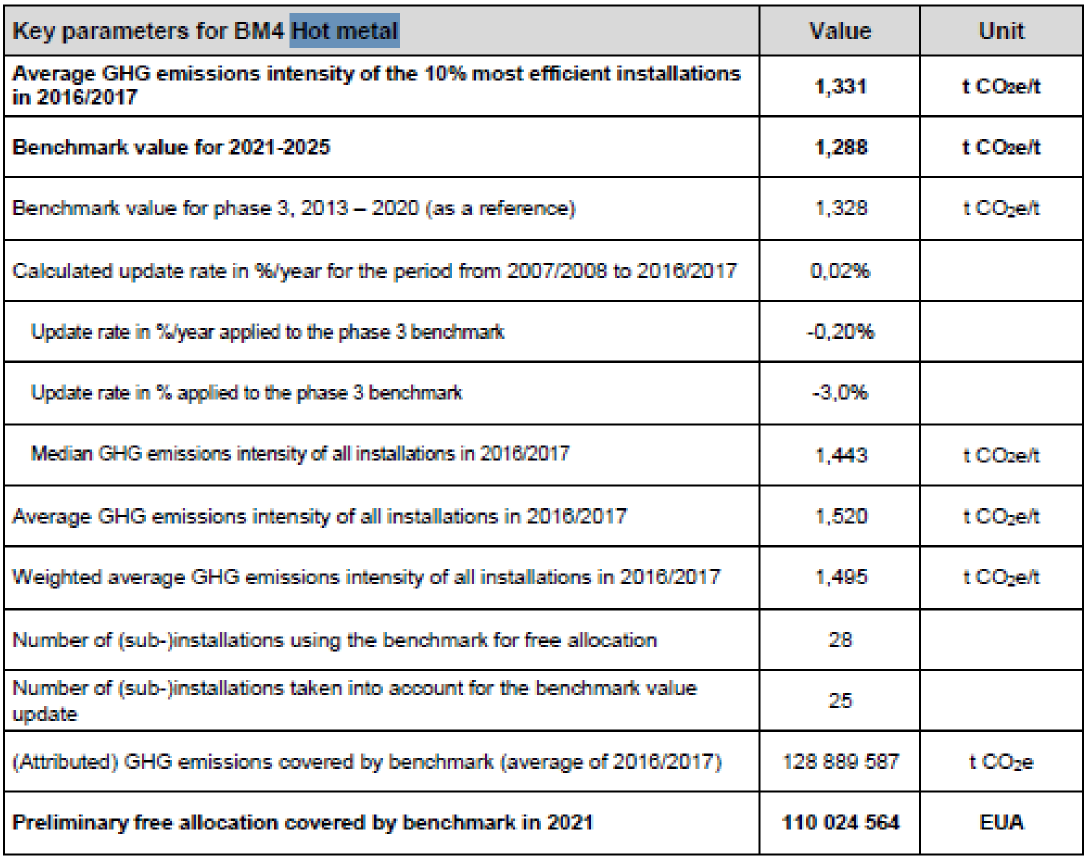
Appendix 1. Benchmark value for sinter (Source: European Commission, 2021)



Key parameters for BM3 Sintered Ore	*Value*	*Unit*
Average GHG emissions intensity of the 10% most efficient installations in 2016/2017	0.163	t CO2e/t
Benchmark value for 2021-2025	0.157	t CO2e/t
Benchmark value for phase 3, 2013-2020 (as a reference)	0.171	t CO2e/t
Average GHG emissions intensity of all installations in 2016/2017	0.259	t CO2e/t
Weighted average GHG emissions intensity of all installation in 2016/2017	0.248	t CO2e/t
(Attributed) GHG emissions covered by benchmark (average of 2016/2017)	23 154 801	t CO2e/t
Preliminary free allocation covered by benchmark in 2021	14 393 515	EUA

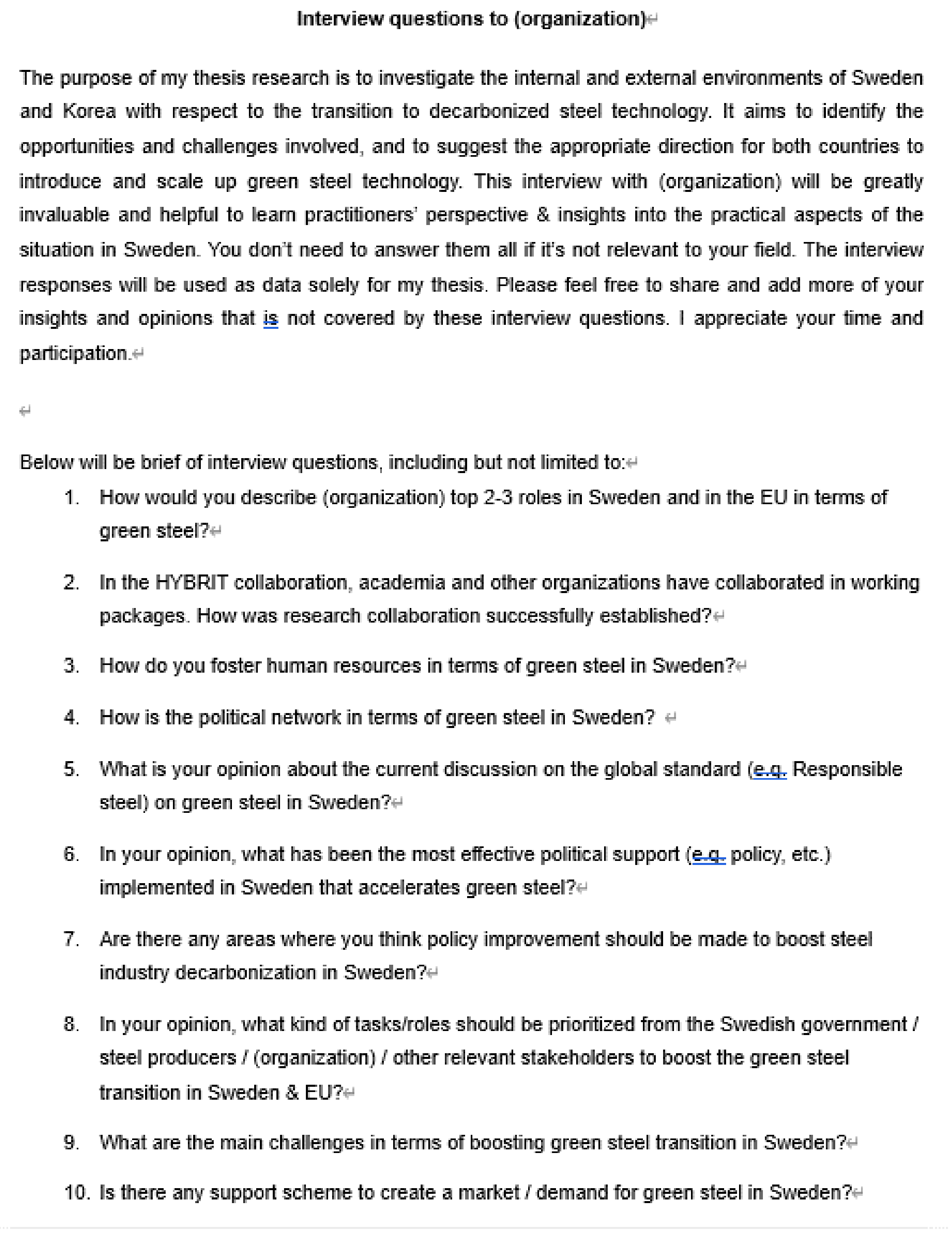
Appendix 2. Benchmark value for hot metal (Source: European Commission, 2021)





Key parameters for BM4 Hot metal	Value	Unit
Average GHG emissions intensity of the 10% most efficient installations in 2016/2017	**1,331**	**t CO_2e/t**
Benchmark value for 2021-2025	**1,288**	**t CO_2e/t**
Benchmark value for phase 3, 2013 – 2020 (as a reference)	1,328	t CO_2e/t
Calculated update rate in %/year for the period from 2007/2008 to 2016/2017	0,02%	
Update rate in %/year applied to the phase 3 benchmark	-0,20%	
Update rate in % applied to the phase 3 benchmark	-3,0%	
Median GHG emissions intensity of all installations in 2016/2017	1,443	t CO_2e/t
Average GHG emissions intensity of all installations in 2016/2017	1,520	t CO_2e/t
Weighted average GHG emissions intensity of all installations in 2016/2017	1,495	t CO_2e/t
Number of (sub-)installations using the benchmark for free allocation	28	
Number of (sub-)installations taken into account for the benchmark value update	25	
(Attributed) GHG emissions covered by benchmark (average of 2016/2017)	128 889 587	t CO_2e
Preliminary free allocation covered by benchmark in 2021	**110 024 564**	**EUA**

Appendix 3. Interview Questions



Interview questions to (organization)

The purpose of my thesis research is to investigate the internal and external environments of Sweden and Korea with respect to the transition to decarbonized steel technology. It aims to identify the opportunities and challenges involved, and to suggest the appropriate direction for both countries to introduce and scale up green steel technology. This interview with (organization) will be greatly invaluable and helpful to learn practitioners' perspective & insights into the practical aspects of the situation in Sweden. You don't need to answer them all if it's not relevant to your field. The interview responses will be used as data solely for my thesis. Please feel free to share and add more of your insights and opinions that is not covered by these interview questions. I appreciate your time and participation.

Below will be brief of interview questions, including but not limited to:

1. How would you describe (organization) top 2-3 roles in Sweden and in the EU in terms of green steel?
2. In the HYBRIT collaboration, academia and other organizations have collaborated in working packages. How was research collaboration successfully established?
3. How do you foster human resources in terms of green steel in Sweden?
4. How is the political network in terms of green steel in Sweden?
5. What is your opinion about the current discussion on the global standard (e.g. Responsible steel) on green steel in Sweden?
6. In your opinion, what has been the most effective political support (e.g. policy, etc.) implemented in Sweden that accelerates green steel?
7. Are there any areas where you think policy improvement should be made to boost steel industry decarbonization in Sweden?
8. In your opinion, what kind of tasks/roles should be prioritized from the Swedish government / steel producers / (organization) / other relevant stakeholders to boost the green steel transition in Sweden & EU?
9. What are the main challenges in terms of boosting green steel transition in Sweden?
10. Is there any support scheme to create a market / demand for green steel in Sweden?