UNIVERSITY OF GOTHENBURG

DEPARTMENT OF POLITICAL SCIENCE
CENTRE FOR EUROPEAN STUDIES (CES)

A EUROPEAN (NO) COAL AND (GREEN) STEEL COMMUNITY?

A Technological Innovation System case approach in the fossil-free steel sector

Hannes Wigerfelt

Master's thesis:	30 credits
Programme:	Master's Programme in European Studies
Level:	Second Cycle
Semester year:	Spring 2021
Supervisor:	Roman Martin

Abstract

The EU has committed to reaching carbon neutrality by 2050 and thereby heavily reducing the emissions of greenhouse gases. Policymakers and scholars have pointed out the development of fossil-free technological energy innovations as crucial in reaching these objectives. In line with this, hydrogen as a fossil-free source of energy is being increasingly explored and invested in, corresponding to a crucial part of achieving emission reductions and are depicted to have substantial potential. However, the developments of hydrogen-technology projects are in its infancy and are conveniently operationalized as early innovation processes in transition. In line with this, a few actors in the European steel industry, that are responsible for a substantial part of the carbon-emissions, have committed to utilizing hydrogen to produce fossil-free 'green' steel. A particular project that has been portrayed as a potential European frontrunner in green steel production using hydrogen is the company Hybrit, initiated in Northern Sweden by a consortium involving three companies. This interdisciplinary case study has applied the theoretical framework of Technological Innovation System to Hybrit to examine the overarching aim of studying potential bottlenecks and possibilities for fossil-free hydrogen in the steel sector. More specifically, the structural elements and the system functions were elaborated on Hybrit to analyze the matureness of the system by conducting a combined methodological study of semi-structured interviews and document analysis. Moreover, Swedish and European policy instruments related to hydrogen in the steel industry were additionally analyzed. The outcome of this study demonstrates that Hybrit is in regard to the theoretical framework fairly mature, with a few but critical hurdles. Findings from the study further revealed that the Swedish and European policy instruments are fostering hydrogen developments but have opposing tendencies in terms of coherence.

Master's thesis:	30 credits
Programme:	Master's Programme in European Studies
Level:	Second Cycle
Semester year:	Spring 2021
Supervisor:	Roman Martin
Keywords:	Green steel, HYBRIT, Hydrogen, Technological Innovation System
Word count:	20 030

Acknowledgements

This thesis is dedicated to my nephew Hugo, who came to this world during my thesis-writing and has been a great company of mine during days of adversity.

I would like to extend my sincerest gratitude to everyone who has helped me to complete this thesis. My supervisor Roman Martin who has contributed with insights and guided me through the process. The interviewees for contributing with their valuable time and dedicational knowledge. To my supportive friends and family, in certain regards to my dear girlfriend Emma, who has put up with me constantly talking about hydrogen and green steel for months. Without all you heroes, this thesis would not have been able to accomplish.

Thank you!

Content

1. Introduction 1
1.2. Aim and scope 2
1.3. Contributions, limitations and delimitations 3
1.4. Thesis outline 3
2. Background 5
2. 1. Hydrogen – the renewable silver bullet? 5
2. 2. Hybrit and the industry it operates within 6
2. 3. Presenting the relevant EU policies and regulations 7
2.3.1. Key Hydrogen policies in Europe 7
2.3.2. EU – Emission Trading System 8
3. Literature review 9
4. Theoretical framework 13
4. 1. Socio-technical approach through innovation 13
4. 2. Technological Innovation System 14
4.2.1. Structural elements 15
4.2.2. Functions of a technological innovation system 16
5. Method and material 19
5.1 Research design and approach 19
5.2 Case selection – Hybrit 20
5.3 Collection of data 21
5.3.1. Semi-structured interviews 22
5.3.2. Document analysis 24
5.4 Quality of the research 25
5.4.1. Ethical considerations 25
5.4.2. Validity 26
5.4.3. Reliability 26
5.5 Operationalization of central concepts 27
5.6 Data analysis 29
6. Results and analysis 30
6.1 Mapping the structural elements 30
6.1.1. Actors 30
6.1.2. Institutions 32
6.1.3. Infrastructures 33
6.2 System functions analysis 34
6.2.1. F1 Entrepreneurial activities 34
6.2.2. F2 Knowledge development 36

6.2.3. F3 Knowledge diffusion 38
6.2.4. F4 Guidance of the search 39
6.2.5. F5 Market formation 41
6.2.6. F6 Resource mobilization 43
6.2.7. F7 Legitimacy creation 45
6.2.8. System function’s performance summary 48
6.3 Analysis of Swedish and EU policy instruments 48
7. Conclusions 52
7.1 Concluding the research questions 52
7.2 Discussion and suggestions for future research 54
References 57
Appendix 68
Appendix 1 – Interview guide – *Hydrogen utilization in Hybrit – Company representatives* 68
Appendix 2 – Interview guide – *Hydrogen utilization in Hybrit – Researchers* 71

1. Introduction

"Two weeks ago in Sweden, a unique fossil-free steel pilot began test operations. It will replace coal with hydrogen to produce clean steel. This shows the potential of hydrogen to support our industry with a new, clean, license to operate"
– Ursula Von der Leyen, President of the European Commission,
(European Commission, 2020c).

The unique, clean steel-producing project Von der Leyen is referring to in her speech for the state of the Union is the fossil-free steel project Hybrit, initiated by the Steel producing company SSAB, the mining company LKAB and the energy company Vattenfall, situated in northern Sweden. The project is envisioning the EU:s commitment to reaching carbon neutrality by 2050 through the European Green deal and the Paris agreement's zero pollution objective (Abe et al., 2019; European Commission, 2021c; Hybrit, 2021a). Today, the steel sector alone stands for 7% of the European CO_2-emissions and is currently heavily dependent on fossil fuels. However, a transition towards fossil-free 'green steel' production, within Europe is forthcoming, and the Swedish project Hybrit has taken a leading role in this change (EN:former, 2019).

Recently, hydrogen has gained rapidly increased attention; Scholars, policymakers, and corporations have addressed the potentials of this source of energy. Fossil-free hydrogen has several perceived areas of benefit, such as decarbonizing the industry sector and serve as a constant source of energy without being dependent on, for example, weather conditions. Still, there are noticeable obstacles regarding implementing this source of energy, such as underdeveloped hydrogen-infrastructures, storage issues and it is currently seemingly expensive energy (Otto et al., 2017).

However, hydrogen-technologies are in its infancy and a common perception among scholars and policymakers is that scaling up this transition of technological developments in sustainable and green solutions through innovation is crucial (e.g., European Commission, 2020c; Hydrogen Europe, 2020; Gielen et al, 2019). This makes the hydrogen transition within the carbon-intense industry of European steel production fruitful to be analytically studied through a theoretical socio-technical innovation in transition. This technological innovation transition can be exemplified in the steel producing project of Hybrit, which will be the unit of analysis in this thesis case study. Furthermore, hydrogen has recently been pointed out as a cornerstone in several EU policies and strategies, such as the EU hydrogen strategy and the EU industrial strategy (European Commission, 2020b; 2020c). This illustrates the importance of addressing the policy and regulatory frameworks that apply to hydrogen and the steel industry, which will further be conducted in this thesis through the case of Hybrit.

1.2. Aim and scope

The overall aim of this thesis is to study potential bottlenecks and possibilities for fossil-free hydrogen in a European context. More specifically, this fossil-free source of energy is regarded as technological innovation and is therefore analyzed through the theoretical framework of a 'Technological Innovation System', approach in an interdisciplinary manner.

Two research gaps could be identified in the findings from the research review. Firstly, a research gap among innovation approaches of hydrogen studies has been highlighted by several scholars (e.g., Friedmann, et al. 2019; Santos et al., 2013), which has pointed out the importance of further research. Secondly, a research gap regarding policy incentives and instruments within the field of hydrogen became salient by examining the research. Further research on policy approaches on hydrogen has been pointed out by scholars (e.g., Bader & Bleischwitz, 2010; Van den Hoed &Vergragt, 2004) as crucial. Therefore, this thesis aims at addressing these two research gaps.

In order to narrow the aim of this thesis, the scope of this study is to target the Swedish steel project 'Hybrit' in regard to its utilization of hydrogen in steel production. Furthermore, relevant European and Swedish policy instruments will be examined by emphasizing possibilities and bottlenecks for the developments of hydrogen in the steel-producing project Hybrit. To study this aim, two research questions have been formulated.

1) *How mature is the Technological Innovation System in Hybrit's green steel production?*
    - *Which structural elements can be identified and how do the system functions perform?*

2) *Which possibilities and bottlenecks in regard to Swedish and European policy instruments can be identified?*
    - *What policy actions are needed to foster the development of hydrogen?*

The first research question is theoretical by nature. The second research question has been constructed in a rather practical manner.

1.3. Contributions, limitations and delimitations

The contributions of this thesis can be divided into three themes, consisting of one theoretical and two practical contributions. In terms of the theoretical contributions, it aims to further expand the research field of socio-technical transitions by utilizing the theoretical concept of 'Technological Innovation System'. This by studying the early innovation stages of an energy technology in transition by analyzing the structural elements and system functions (Jacobsson & Bergek, 2011; Suurs et al., 2009; Hekkert et al., 2007). Secondly, the practical contribution is twofold. On the one hand, this thesis seeks to address the research gaps that have been identified from the research review in order to expand the field of hydrogen research. The practical contribution further implicitly includes providing new insights and knowledge regarding Hybrit's steel, produced by hydrogen.

An initial limitation of this research is that it primarily focuses on hydrogen energy as a fossil-free energy, implying that it is limited to analyze the hydrogen-technologies made from fossil-free energy and excluding hydrogen made of fossil energy sources. Following this direction, the focus of the outcome is on the hydrogen project Hybrit; thusly the thesis is delimited to a Swedish and European context. This further limits the possibilities to draw generalizations based on the results but does instead enable in-depth analysis. However, the development of hydrogen technology projects could be considered universal and applicable globally as there is increased global demand for fossil-free energy, possibly making the analytical findings of this thesis through an innovation theoretical approach on the topic interesting in a wider sense. Lastly, an apparent limitation of this research is the timeframe of the conducted study, which spanned between January and May 2021.

1.4. Thesis outline

The thesis is structured as the following outline. After the previous presentation of the introduction, thesis aim, contributions and limitations, a general background of this thesis topic will be presented in chapter two. This includes brief presentations of hydrogen, Hybrit and, relevant EU policy- and regulatory frameworks. In chapter three, a research review regarding different aspects of hydrogen is conducted. The theoretical framework of this study is presented in chapter four. Chapter five treats the methodological aspects and considerations of this thesis. In chapter six the analysis of the gathered material will be presented. Lastly, the conclusions of the findings from the results of the research questions will be drawn, followed by a concluding discussion and suggestions for future research presented in chapter seven.

2. Background

This chapter will present an outline of hydrogen as a source of energy, including brief discussions of relevant technological aspects amongst the most common hydrogen-technologies, as well as presenting certain fields of usage. However, in line with the objectives and limitations of this thesis, the focus is to provide knowledge and analyze the hydrogen-technology projects through the theoretical framework of technological innovation systems in Europe, and therefore technological aspects will be kept brief. Next, a presentation of the analytical project of this thesis case study, Hybrit, will be presented. Lastly, brief presentations of relevant EU policies and regulations will be given. The aim of this chapter is to provide a broader understanding of this dissertation's topic and the frameworks it operates within.

2. 1. Hydrogen – the renewable silver bullet?

Approximately 90 percent of all atoms are made of hydrogen. To produce hydrogen gas[1], hydrogen atoms must be decoupled from other elements in which they occur, for example, water or fossil fuels. This initial decoupling phase is what determines the hydrogen's sustainability level (i.e., the amount of CO_2 released in the atmosphere) (Friedmann, et al. 2019; Santos et al. 2013). Hydrogen as a source of energy has numerous perceived benefits as a component in the sustainable energy transition. It can be used in several ways, such as in replacing carbon-intense fueling in aviation, shipping, rail, and heavy road transports; decarbonizing the industry sector; as well as serving as a feedstock for carbon capture (Abe et al., 2019; Markusson et al., 2011). Hydrogen can further be used as a constant source of energy, while other renewables can experience seasonal variations in energy demand (Irena, 2018). In line with the EU-objective of reducing the GHG-emissions, it is due to these reasons public investments in hydrogen have experienced a massive increase lately[2].

Even though the focus in this thesis is the notion of hydrogen as a renewable and carbon-free source of energy, it is important to highlight that hydrogen can be produced in other ways, such as made from fossil fuels, and resulting in higher carbon emissions. In sustainability lingual, hydrogen is usually categorized into three subgroups, labeled; 'grey hydrogen'; 'blue

[1] Henceforth referred to simply as "hydrogen"

[2] Such as through the European Commission's €420 billion investment in the hydrogen strategy (European Commission 2020c).

hydrogen'; and 'green hydrogen' (Gielen et al., 2019; Santos et al., 2013). Most of the hydrogen used today is produced through a process called steam methane reforming, which can be understood as a steaming process of methane gas resulting in hydrogen, although this process also produces carbon monoxide and a small amount of carbon dioxide. This process is labeled *grey hydrogen* due to the fact that the process results in GHG-emissions. However, if the carbon emissions produced from the steam methane reforming process are instead captured and stored elsewhere, the procedure is labeled *blue hydrogen*. Thus, blue hydrogen does not induce GHG-emissions but is still made from fossil fuels. Finally, *green hydrogen* is completely free from fossil fuel and CO_2-emissions by being produced through the electrolysis of water, only leaving oxygen as a bi-product. The electrolysis process can simply be explained as a technological process in which water and electricity are separated into hydrogen and oxygen through an electrolyzer. If the electricity involved in this process is produced from renewable energy, the result of such hydrogen production is entirely CO_2-free, which can be further applied to fuel-cells technologies in, for example, vehicles and industry (Capros et al., 2019; Gielen et al., 2019; Santos et al., 2013).

2. 2. Hybrit and the industry it operates within

The steel production industry is today responsible for roughly 7% of the global CO_2-emissions and is predicted to grow by 25-30% until 2050 with the current production standards and a market rise in demand. Thus, the steel sector is among the largest CO_2-emitters (Holappa, 2020). The European context is representative, Hybrit is located in Sweden, which is among the prominent steel producing member states of the EU, and the industry alone stands for roughly 10% of the Swedish CO_2-emissions. "Hybrit" is an acronym: 'Hydrogen Breakthrough Ironmaking Technology'. It is a steel producing decarbonization project in Northern Sweden, launched in 2016 with the aim of becoming the world's first fossil-free steel producer, omitting carbon footprints (Hybrit, 2021a). The project consists of a consortium of different actors, including the steel producer company SSAB, the mining company LKAB, as well as the energy company Vattenfall, and the two latter companies are owned by the Swedish state. In Sweden, SSAB stands for more than 90% of the national CO_2-emissions in the steel production industry, and most of the emissions originates from iron ore reduction. The direct reduction means that iron ore, which mainly consists of iron oxides, is reduced to a solid product of iron called sponge iron, and the reduction process involves removing oxygen from the iron ore. Traditionally, this was used in a blast furnace done by using carbon or coke, but the Hybrit technology instead use fossil-free hydrogen. This process is called Hydrogen-direct reduction (H-DR) (Hybrit, 2021b). The steel produced through this H-DR process is referred to as *green steel*, due to its diminished climate impact.

This strive to achieve climate neutrality is in line with the ongoing developments of the Hybrit-project through the usage of hydrogen. Fischedick et al. (2014) and Arens et al. (2017) suggests that in order to reduce the CO_2-emissions in the steel industry, deployment of alternative technologies is of utter need. Hydrogen was pointed out as one of these crucial energy technologies in the sector. This have been embraced by Hybrit and the project aims to continue until 2045, and it is estimated to include investments of a total of €30-40 billon. The initial phases, such as the current development of the pilot facility includes investments of 1.4 billion SEK (€ 130 million), of which 35% is Swedish state funding and the remaining 65% of the investment is shared equally between the three consortium companies (Energimyndigheten, 2020; Hybrit, 2021a). Hybrit's H-DR production process is divided into three phases, including the completed pre-study that took place 2016-2017. This is followed by the second phase, developing and testing the production in the pilot study, 2018-2024. In the third phase, set to take place 2026-2035, testing in demonstration facilities will be conducted before commercializing the H-DR steel production with Hybrit. After the pre-study in phase one, the joint Venture-company Hybrit Development AB was created by the three companies SSAB, LKAB and Vattenfall.

2. 3. Presenting the relevant EU policies and regulations

This sub-chapter will provide brief presentations of the most relevant EU policies, strategies and regulation that are affecting Hybrit and its consortium-companies. This is in order to provide understanding of the conditions and framework that Hybrit is operating within.

2.3.1. Key Hydrogen policies in Europe

The EU has as committed to reaching carbon neutrality by 2050 through the European Green Deal and the Paris agreement's zero pollution objective (European Commission, 2021c; Unfccc, 2016). A crucial part of the GHG-emitters can be found within the energy and industry sectors, and the integration of hydrogen has been pointed out as a potential solution in reducing the emissions (Capros et al., 2019). This has in turn been highly promoted by the EU, which, during an informal energy ministers meeting in 2018, launched an EU-wide hydrogen initiative which was approved by 25 member states (Rosengren, L., 2018, September 19). Even though this was a non-binding symbolic declaration, the EU Commission later launched the "European Clean Hydrogen Alliance" which is an alliance among different actors in the strive to encourage the development and usage of hydrogen in Europe, consisting of both political actors such as member states and regions but as well of companies and interest organizations (European Commission, 2021a). Furthermore, the EU commission have launched several policy-initiatives and strategies in order to promote hydrogen. The most significant strategies can be noted in the 'EU hydrogen strategy' (European Commission, 2020c), the 'EU Industrial Strategy' (European Commission, 2020b), the 'European green recovery package' (European Commission, 2021b), which demonstrates the willingness and enthusiasms in developing hydrogen energy in Europe.

2.3.2. EU – Emission Trading System

A particularly relevant EU-regulation system for fossil free steel production through hydrogen is the European trading system (EU-ETS), which can be described as a system that regulates and limits the emission cap amount of greenhouse gases, referred to as a cap-and-trade based scheme, which applies to European companies. The system is controlled and monitored by the EU through its "EU allowances", consisting of limited caps in different sectors, and companies that emits more than the applied cap must buy allowances from other companies or reduce their emissions. The main purpose behind the EU-ETS is to reduce the GHG-emissions, making it costly for companies to emit GHGs in line with the Polluters pay principle. The system is periodically divided into different phases, with the first phase being initiated 2005 and the most recent phase being 2013-2020 (European Commission, 2014; Joltreau & Sommerfeld, 2019). Currently, companies within the European Steel industry such as the companies involved in Hybrit (SSAB and LKAB) receives a number of free allowances (European Commission, 2021d). Further, some European sectors that are particularly exposed to competition receive free allowances. This has been criticized for distributional issues from several scholars, e.g., Jordan and Tosun (2013) and Ellerman et al. (2016). Nonetheless, the free allowances have by other scholars, e.g., Joltreau and Sommerfeld (2019) and Verde et al. (2019), been considered necessary incentives to further develop a European climate-neutral industry. The EU-ETS is currently being revised and it's a debated topic whether the usage of fossil free hydrogen in the steelmaking process should be included or not in the next phase of the system (Fossilfritt Sverige, 2021).

3. Literature review

This chapter covers relevant hydrogen research with a particular focus on innovation approaches. However, due to the limitations of this thesis, research on technological details will to some extent be omitted. The literature review will provide an overarching presentation that covers hydrogen-research, of which certain focus areas have been identified and will therefore be structured and highlighted throughout this chapter as follows: Hydrogen technology; Hydrogen economy; Hydrogen storage; as well as innovation aspects of hydrogen research. Furthermore, due to the European focus of this thesis, including the project of analysis, a European approach structures the literature review.

Most of the conducted research on hydrogen is within the fields of technology and engineering. A common trend amongst such scholars is that they tend to focus on hydrogen applications in fuel cells technology, such as studies conducted by Ehret & Bonhoff (2015), Hardman et al. (2015) and Van den Hoed and Vergragt (2004). Other hydrogen research, still within the area of technology, has examined the potential implementation of hydrogen in vehicles (e.g., Hardman et al., 2015; Wilberforce et al. 2017). Another technological field that has been explored is hydrogen related to house and facility heating (Dodds et al., 2015). It appears that most hydrogen-technology-based research often expresses positive and hopeful conclusions in terms of developing and implementing hydrogen in a wide range of technologies. Although, in their research, Ustolin et al. (2020) highlighted the potential dangers of losses of integrity in hydrogen technological systems, presenting modest criticism towards that further developments are required to prevail such safety issues.

A trend in hydrogen research, apart from examining the technical aspects of hydrogen, can be found in studies of economic aspects. These are commonly based on evaluations of a potential transition towards a system where hydrogen is a significant energy carrier, in research frequently referred to as ‘the hydrogen economy’, which is a field that has been explored by several scholars, such as Abe et al. (2019), Bader and Bleischwitz (2010) Maisonnier and Perrin (2007), Sahaym and Norton (2008), Veziroglu (2012) Niaz et al. (2015). The concept of ‘hydrogen economy’ comprehends solutions to interconnected societal problems confronting the world today, including climate issues, securing energy, and a growing world population, suggesting that successfully developing hydrogen economies could lead to crucial solutions of these challenges (Veziroglu, 2012).

Bader and Bleischwitz (2010) have examined potential opportunities and obstacles in a European transition towards a hydrogen economy by analyzing EU policies. Findings from their study concluded that the EU policies do not foster hydrogen development but neither do they hinder it. They further highlighted that in order to successfully develop a technological hydrogen transition in Europe, this would require further research and evaluations of regional-specific dimensions due to that differing conditions between European regions. This potential research gap has in fact been examined on behalf of the European Commission through a study that was conducted by Maisonnier and Perrin (2007). They examined regional aspects of hydrogen within the EU by evaluating the, at the time, current usage levels of hydrogen. However, even though this study to some extent brings valuable aspects to hydrogen research, the developments of hydrogen have experienced a rapid increase lately and the research is therefore somewhat outdated (Abe et al., 2019; Andersson & Grönkvist, 2019; European Commission, 2020c).

Furthermore, an identified trend among hydrogen energy research can be found within the infrastructural concept of 'energy storage', examined by scholars such as Abe et al. (2019), Andersson and Grönkvist (2019), Ehret & Bonhoff (2015), Gielen, et al. (2019), IEA (2019) and Widera (2019). IEA (2019) points out that taking energy storage into account is of crucial importance when developing a hydrogen energy system, both at a political level as well as of relevance for researchers and companies. In line with previously mentioned research on technological aspects of hydrogen, technological development is again considered key in enabling successful hydrogen developments also within energy storage (Andersson & Grönkvist, 2019). Further on, making hydrogen storage lucrative policymakers would have to deepen their economic incentives which could include initial subsidies (ibid).

In their research, Ehret and Bonhoff (2015) and Widera (2019) evaluated potentials and obstacles within hydrogen energy storage, and both concluded a rather positive view of how-to storage the energy. Widera (2019) highlights the importance but also challenges of storing hydrogen, proposing to solve this problem by building massive storage-facilities, still struggling with the issue of how-to find incentives to develop such investments. Interestingly, Ehret and Bonhoff (2015) see huge potential in storing the energy, proposing a notable solution to the issue: "Hydrogen could be competitively produced from excess wind power by large-scale wind-hydrogen-system and stored in caverns, to later provide energy for both the transport and stationary sector" (Ehret & Bonhoff, 2015: 5532). These positive approaches could be questioned regarding whether storing the hydrogen in either caverns or huge facilities are sustainable and effective measures, especially if infrastructurally conducted at a European level – It is plausible that caverns are absent in many regions and that constructing storage-facilities implies high costs. Nonetheless, findings from the literature disclose a positive view of hydrogen-storage while economic incentives and again, technological development, are the most crucial obstacles to overcome.

Reviewing previous research from the theoretical approach of this thesis, namely innovation point of view, the field appears to be unexplored - this constitutes that a research gap became salient. Most of the research on innovation and hydrogen has been strongly connected to specific technological aspects, such as the previously mentioned fuel cell technology (Suurs et al., 2009; Andreasen & Sovacool, 2015) as well as regional innovation aspects (Madsen and Dannemand, 2010). However, in line with the objective of this thesis, carbon-neutral and renewable-based hydrogen as an energy source is the primary focus of the limited innovation research. Santos et al. (2013) points out that there is a high potential for establishing such renewable hydrogen, but further argues that research and innovation efforts are crucial in order to accomplish this. Nevertheless, a vast majority of the hydrogen energy that is used today is produced by fossil fuels, as Andersson & Grönkvist (2019) argue, this is primarily a matter of costs due to the fact that producing green hydrogen is to a great extent more expensive than production by fossil fuels. In opposition to this, Santos et al. (2013) contend that the case of expensive hydrogen prices will most likely experience a shift, due to a wide uncertainty regarding the reserves of fossil fuels, which could impact the energy costs of such sources.

Madsen and Dannemand (2010) have examined geographical aspects related to hydrogen innovation-developments within Europe, by focusing on regional clusters. They pointed out that hydrogen was (at the time) relatively poorly developed and skewed towards northwestern Europe. They argue that there is a great opportunity for innovative regions that consist of strong representation of chemical, energy, manufacturing, automotive, etc. to successfully establish hydrogen systems. Notably, a research dichotomy appears in this matter when examining the study from IEA (2019: 177), which highlight greater opportunities in industrial clusters and areas with already existing natural gas infrastructures, rather than in innovation hubs. Thus, the research dichotomy appears whether which geographical and regional conditions would benefit the most by investing and establishing in hydrogen technologies; Innovation-hub regions or rather traditional gas infrastructure and pipelines developed regions.

Besides the previously presented challenges and the safety-concerns raised by Ustolin et al. (2020), the research on renewable hydrogen is not free from critique. This has been raised towards that hydrogen can be noticed in terms of energy-efficiency losses as well as disputes regarding the carbon capture and storage (CCS) technologies needed for blue hydrogen specifically (Markusson et al., 2011). Friedmann, a researcher at Columbia University's center on global energy policy, argues in line with this perception, pointing out that in order to reduce the price of green hydrogen, targeted public support and incentives for innovation developments is crucial (Friedmann, et al., 2019: 52).

To conclude, two research gaps based on the findings from the literature review can be found in terms of research on hydrogen. Firstly, a gap of innovation studies related to hydrogen was identified. Several scholars (e.g., Friedmann, et al., 2019; Madsen & Dannemand, 2010; Santos et al., 2013; Widera, 2019), highlights the importance of filling this gap by further conduct innovation-approached research on hydrogen. This can be found within all the hydrogen-categories of this research review. Secondly, a research gap regarding policy incentives and instruments within the field of hydrogen became salient. Further research on policy-approaches related to hydrogen was by several scholars (e.g., Bader & Bleischwitz, 2010; IEA, 2019; Van den Hoed &Vergragt, 2004) pointed out as crucial, both in terms of national-support but as well in regard to the European Union. Thus, with this background, this thesis aims at filling the research gaps that became salient from this literature review.

4. Theoretical framework

In this chapter, the theoretical framework that has been utilized in this thesis will be presented, with the intention of interlinking the analysis theoretically and clarifying what the empirical analyses and conclusions are based upon. A general presentation of socio-economic perspectives will be presented in section 4.1, which lays a guiding theoretical foundation. In section 4.2, the Technological Innovation System theoretical concept that has been applied in this case study analysis will be presented. Section 4.2.1. will elaborate on the structural elements of a technological innovation system, followed by a presentation of the seven functions in such a system in Section 4.2.2.

4. 1. Socio-technical approach through innovation

Innovation can be considered crucial in enabling sustainable technological solutions in societies, such as combating climate change, as argued by Hekkert and Negro (2009) and Jacobsson and Bergek (2011). Hydrogen as a renewable energy transition technology, can be perceived to be part of a strive towards an increased sustainable society. However, sustainability is a contested area that often includes not only political action but also involving other actors, such as companies, NGOs, and civil society (Geels et al., 2011: 25-26). Scholars such as Rotmans et al. (2001), Van den Hoed and Vergragt (2004), and Smith et al. (2005) have labeled such societal-technical changes as socio-technical transitions, which entails focusing on economic-technical factors, as well as political, allowing to theoretically examine such transitions. In line with this, Geels et al. (2017) and Van Bree et al. (2010) argues that sustainability transitions have extraordinary complex characteristics due to that the benefits are often motivated by collective goods; thus, the individual user benefit might be less apparent. Instead of observing innovation systems through separated innovation-level steps as the reductionist innovation theory utilize, the socio-technical approach rather emphasizes the observed system as a dynamic process (Edquist & Johnson, 1997). Furthermore, within the socio-technical approach, different theoretical frameworks have emerged, where the ‘technological innovation system’ (Hekkert et al., 2007) will be further explained and elaborated on due to that it is fruitful in analyzing emerging innovation technologies as in the case of this thesis, development, and usage of green hydrogen. Furthermore, it enables theoretical examinations of public policy instruments, thus the theory is considered relevant and applicable in order to answer the research questions of this thesis.

4. 2. Technological Innovation System

The appearance of new technological innovation systems (TIS) is generally perceived as complex processes, taking several aspects into account, often including a variety of actors as well as through different stages. [3] Deriving from the Schumpeterian tradition, TIS has been approached through seemingly different theoretical approaches, but a frequent perception among scholars is that such systems undergo different phases, taking off at an initial formative phase, followed by a growth phase, next comes a maturity phase and finally a declining phase (Abernathy & Utterback, 1978; Bergek et al., 2005; Carlsson & Stankiewicz, 1991; Malerba, 2006). The formative phase can be illustrated by uncertainty in terms of technological development and its applications, as well as market and regulation aspects. The TIS is evolving in this phase which includes adaption from networks and institutions (Jacobsson & Bergek, 2004). The growth phase covers the timeframe from the initial technological invention to the point at which investments and initial developments have been made. At this phase, the goal of the technological invention can be perceived to experience rapid growth, including showcasing a competitive and effective impact. The third phase, maturity, is characterized as the new innovation-technology have gained acceptance by a general population and among its competitors, meaning that the innovation becomes normalized. Lastly, the declining phase corresponds to that the value of the innovation-product begins to decline by reduced investments and perhaps even out beaten by new competing innovations (Malerba, 2006; Jacobsson & Bergek, 2004).

Technological innovation theoretical concepts involve a variety of scholars and perceptions, whereas a key figure among such theoretical frameworks can be found by the economist Joseph Schumpeter, which stressed the innovation processes from the emerging technology's birth, followed by the maturity and finally its destruction through his framework of business cycles (Schumpeter, 1943). Innovation research later evolved towards an interdisciplinary field, including inquiry from fields such as economics, engineering, research, and politics (Lundvall, 1985). From this, three related theoretical innovation perspectives emerged, namely national innovation systems (Freeman, 1987), regional innovation systems

[3] A technological innovation system (TIS) has been defined as 'network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology' (Carlsson & Stankiewicz, 1991: 21).

(Cooke, 1996), Sectoral innovation systems (Malerba, 2004), and technological innovation systems (Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997). While these innovation systems share many similarities, such as their focus on innovation and diffusion process as a collective and individual act, the systems can still be perceived as independent from each other (Markard & Truffer, 2008). Technological innovation systems can further be perceived through two conceptual aspects, consisting of the initial *structural elements*, which take into account the structures in which the system is involved, followed by the *functions,* which can be understood as dynamic criteria in the assessment of the TIS.

4.2.1. Structural elements

Although, while traditional technological innovation entails such processes as linear developments (Godin, 2006), vital is that TIS rejects this perception, which rather emphasizes the continued interaction among the involved actors, allowing for development-bolstering between research, market, and politicians throughout the different phases (Suurs et al. 2009). Hekkert, et al. (2007) further underlines the theory of TIS as a dynamic process as new regulations, technological developments and new political approaches tend to emerge. However, it is worth noticing that alternative theoretical concepts with similar features as the 'technological innovation system' exist, such as the 'regime shifts' (Kemp et al. 1998) and the 'multi-level perspective' (Geels, 2002). Nonetheless, the theoretical framework of this thesis is primarily based on the Technological innovation system theory (Hekkert et al., 2007) and operationalized in the method chapter 5.

The structural elements that will be applied in this thesis involve the components of *Actors, Institutions, and Infrastructures (*Jacobsson & Bergek, 2011; Suurs et al., 2009). The initial element, **Actors,** corresponds to all involved actors with technical, financial and/or political power to influence and partake in the technological development processes. These could for example be the actors involved in, for this thesis topic, a hydrogen project, or a governmental organization that regulates or give funding to such projects. Mapping the element ‘actors’ further include networks in which the actors are involved and can be perceived as knowledge-sharing groups which involves both market-based networks, which could be profitable for individual actors, as well as non-market-related actors, such as involving interest organizations.

Institutions are seen as the influencer of the norms and rules regarding the technological innovation. The institutions are referred to as "the rule of the game" (Edquist & Johnson, 1997: 46), which includes formal rules such as laws and regulations, but as well informal rules, such as norms and cultures. Their roles vary due to that they could for example influence the connectivity in such systems, structure potential demands as well as enabling industrial innovation clusters (Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997; Jacobsson & Bergek, 2011; Suurs et al., 2009). Lastly, a third structural element has been included in some TIS studies, **Infrastructure** (e.g. Woolthuis et al., 2005; Wieczorek & Hekkert, 2012**,** which will be applied in this thesis analysis as well. Building on Wieczorek and Hekkert (2012), infrastructure within the TIS encompasses mapping and evaluations of infrastructural components, such as physical and financial aspects. In a TIS analysis related to energy transitions such as Hybrit, this structural element can for example include roads, energy accessibility, financial programs, etc. To include the infrastructural component was considered essential due to the findings that were covered in the research review (see Ehret and Bonhoff (2015), whereas infrastructural challenges were pointed out as crucial.

Furthermore, it is worth noticing that occasionally in some TIS approaches, such as by Malerba (2004) and Suurs et al. (2009), a fourth component is included among the structural elements, namely the component of 'technology' which includes examinations of technological artifacts. However, due to the findings from the research review and to the limitation of this study to not analyze the technology in-depth, the technology-element can be considered irrelevant, and the important technological aspects will be included in the mapping of the fourth element 'infrastructure'. Therefore 'technology' will not be included in the analysis of this thesis.

4.2.2. Functions of a technological innovation system

For emerging technological systems to develop, by conducting a TIS analysis of such technologies provides insights into the dynamics of how to perceive such a large-scale development, by applying and evaluating a set of seven key criteria's, named 'functions' by Hekkert et al. (2007). The establishment of the seven system functions included in a TIS (See table 1 below) derives from insights of years of innovation research (Suurs et al., 2009: 9641) and can be understood as mutual determine the chances of developing a successful TIS within a specific technology by evaluating classes of activities tied to contributions of development, diffusion, and the use of technological innovations. Moreover, as mentioned previously, TIS approaches have been applied and pointed out as particularly useful by scholars in analyzes of technological energy transitions, such as by Hekkert and Negro (2009), Markard (2020) and Jacobsson and Bergek (2011), and in addition, the theoretical assumptions of TIS can further lead to fruitful theoretical results in the hydrogen analysis through the interviews and content analysis.

Table 1. Functions of a Technological Innovation System. Table inspired by Hekkert et al. (2007) and Suurs et al. (2009).

System Function	Description	Event types associated
F1. *Entrepreneurial Activities*	The role of the entrepreneur is to translate knowledge into business opportunities, and eventually innovations. The entrepreneur does this by performing market-oriented experiments that establish change, both to the emerging technology and to the institutions that surround it.	Projects with a commercial aim, demonstrations
F2. *Knowledge Development*	This function involves learning activities, mostly on the emerging technology, but also on markets, networks, users etc. Learning activities relate to both learning-by-searching and learning-by-doing. The former concerns R&D activities, whereas the latter involves learning in a practical context.	Studies, laboratory trials, pilots
F3. *Knowledge Diffusion*	Innovations occur most where actors of different backgrounds interact and result in interactive learning. A special form of interactive learning is learning-by-using, which involves learning based on the experience of users.	Conferences, workshops, alliances
F4. *Guidance of the Search*	This function refers to the activities that shape the needs, requirements and expectations of actors with respect to their (further) support of the emerging technology.	Expectations, promises, competition, policy targets, standards, research outcomes
F5. *Market Formation*	Emerging technologies cannot be expected to compete with incumbent technologies. To support innovation, it is usually necessary to create artificial markets.	Niche-markets, product demands, market regulations, tax exemptions
F6. *Resource Mobilisation*	This function refers to the allocation of financial, material and human capital. The access to such capital factors is necessary for all TIS developments.	Subsidies, investments
F7. *Legitimacy Creation*	The rise of an emerging technology often leads to resistance from actors with interests in the incumbent energy system. In order for a TIS to develop, other actors must counteract this counteracting.	Lobbies, advice

By studying the seven functions of a TIS, they should be understood as cycles of interpretation in the dynamics of the system, whereas fulfilling any functions can lead to positive and negative feedback loops (Suurs et al., 2009: 58). As an example, success in fulfilling the first function, entrepreneurial activity, could later result in test-failing of a particular product, which then would induce that the product did not fulfill the second function, knowledge development, thus a negative feedback loop has occurred (Suurs et al., 2009). It is moreover important to take into regard that the functions may be fulfilled in various ways and that they should be tailored to suit the specific examined topic of analysis, hydrogen in this case of this thesis. An adaption and operationalization will therefore be presented in chapter five, section *5.5 Operationalization of central concepts.*

5. Method and material

In this chapter, the chosen methods for conducting the research of this thesis are presented and argued for in order to guide the reader through the methodological considerations that has been done. In section 5.1 the general research approach and design of this thesis will be presented in order to clarify what scientific methodologies that has been used to analyze the topic of this thesis. In section 5.2, the case selection of this thesis will be presented and argued for. Section 5.3 Presents and discusses the material that has been chosen and used in the analysis as well as how it was gathered. Subsequent in section 5.4, the quality of the research will be presented, thus enhancing the scientific considerations regarding this thesis. Section 5.5 presents and elaborates on the chosen path of operationalizations of central concepts, including connecting and concretization of the theoretical framework to fit the topic of this thesis. Lastly, the construction of how the analysis of the material in the next chapter was done will be presented in section 5.6.

5.1 Research design and approach

In this thesis, complex issues regarding hydrogen developments in a European steel company through the theoretical concept of 'Technological Innovation System' was studied. This was methodologically done through qualitative research and the chosen research design was case study. In order to approach this thesis topic, mixed methods were utilized through semi-structured interviews and document analysis.

The case study design was considered the most relevant research methodology due to that it enables to conduct the study through an in-depth contextual understanding, as well as that the field of research can be considered to be in its infancy (Yin, 2014). Moreover, by overviewing the status quo of H-DR in steel production, establishment of such systems are rarely existing today which erased the possibility to collect hard data from previous project-establishments, which further illuminated that the selection of conducting a qualitative study the most fruitful option (Marshall & Rossman, 2016). Furthermore, in line with the objectives of this thesis and the utilization of the theoretical framework of 'Technological Innovation System' (TIS), scholars within the theoretical field (e.g., Bergek et al., 2008; Hekkert et al., 2007) inclines that such methodological approach is suitable in examining TIS-technologies.

The research approach conducted in this thesis can be argued to have a hybrid approach with influences from both exploratory but as well explanatory character. It is on the one hand exploratory in the sense that a relatively newly developed and unexplored technological innovation was examined. It is on the other hand explanatory in the sense that it sought to elaborate on how the Hybrit-involved actors, as well as researchers that has conducted studies on Hybrit, perceive the H-DR technology as well as relevant political instruments (Yin, 2014). This in turn lead to a deductive approach due to that the theory has been centralized in the analysis, which established the analytical framework that was applied on the topic of this thesis. However, even though this deductive approach has been conducted with the theory based on previous research, the operationalization of the theory was, as will be discussed in the section 5.4 'operationalization of central concepts', adapted to fit the particular case of this thesis, Hybrit (Marshall & Rossman, 2016; Yin, 2014).

Furthermore, based on the findings from the research review, several fields of research appeared to be crucial in an examination of hydrogen (e.g., social science, economy, environmental science, engineering). In addition, the fact that the theoretical framework of TIS includes assessment of perspectives from multiple fields, made the choice to conduct an interdisciplinary approach fruitful. By conducting the interdisciplinary approach, it enabled the utilization of concepts and ideas from several academic disciplines. In line with Shmelev and Shmeleva (2012), such interdisciplinary approaches can often be found particularly appropriate when analyzing socio-technical transitions due to that, as in the case of this thesis, has multiple intertwined challenges. Thus, without including, for example economic factors, the political nor infrastructural potentials and bottlenecks concerning the TIS applied to Hybrit would not be successfully analyzed.

5.2 Case selection – Hybrit

The case selection of this thesis, the steel producing project company Hybrit, was decided as the unit of analysis for several reasons. Firstly, findings from the research review uncovered that a research gap within hydrogen existed in terms of innovation and policy approaches. In line with this, the second reason was that, as presented in chapter *2.2,* the steel industry stands for a large part of the GHG-emissions, representing roughly 7% of the global and 10% of the Swedish CO_2-emissions, which makes it a particular interesting sector in terms of combating climate change. Thirdly, the very current policies and investments by the EU (see chapter *2.3)* into the development and deployment of hydrogen, which can be understood as a technological innovation due to its seemingly small usage today but still pointed out to be crucial. This was therefore in line with the findings of the research gaps, innovation and policy aspects. Therefore, the development and integration of hydrogen in the steel producing sector (H-DR steel production) in Europe was considered interesting and a need to address the previously identified research gaps.

However, case-limitations had to be done in order to examine this technological innovation in-depth. Hybrit (including the consortium companies) was chosen as the project of analysis due to the fact that Hybrit have been pointed out as the European leader in this hydrogen transition. This has been done by the involved actors themselves (e.g., Hybrit, 2017; Energimyndigheten, 2020) but as well by the President of the European Commission (European Commission, 2020c). Second, Hybrit and its consortium actors was found to be involved in and affected by Swedish national- and EU regulations and policies, as well as participating in European partnerships and receives public funding. All these factors made the case of Hybrit an interesting choice and clearly a part of European, hydrogen-technological innovations. Therefore, Hybrit was chosen as the analytical case unit of study. Lastly, the limitational choice of focusing this thesis to one case, Hybrit, was considered rational since it allowed the author to examine the project in-depth. Nevertheless, a broadening of the study to include other European similar projects would have been interesting and probably developed into interesting comparative results.

5.3 Collection of data

The information gathering was mainly conducted in two ways, one consisting of semi-structured interviews with Hybrit-representatives, as well as with researchers that have conducted research related to Hybrit from different fields of angle. Second, empirical data was further gathered through research reviews, largely consisting of different sorts of publications from actors of research institutes, interest organizations, policy documents, webpages as well as Hybrit-company publications. This two-way course of action in terms of data-collection was chosen due to that it opened up for broader information and knowledge gathering, as the scholar Denscombe (2014) argues, combining such material-collecting is fruitful when conducting case studies. Lastly, data from public databases has been used in order to gather complementary data.

5.3.1. Semi-structured interviews

The interviews were conducted semi-structured with representatives involved in Hybrit, as well as with researchers involved in Hybrit-related research. The choice of conducting semi-structured interviews was considered a valuable methodological tool due to that it enables and focuses the interviews on the respondent's own knowledge and experiences (Brinkmann & Kvale, 2015), which empowered an openness for new perceptions and paths exterior to the prepared questions.

The interviews were conducted through two courses of action, where the first two interviews were conducted with representatives involved in the Hybrit project. The interviewees were discovered through overviewing Hybrit and its consortium-companies webpages and requests regarding participation as interviewees in this thesis was sent through e-mails. Savonen at LKAB and Kansbod at SSAB accepted and was in the first course of action interviewed by the author. The second course of action was conducted through research overviewing regarding this thesis topic, which enabled to discover researchers from different disciplines involved in Hybrit research. Several was contacted through e-mails. This resulted in that interviews with the researchers Lundmark, Luleå University of Technology, Cornell and Grönkvist, KTH Royal institute of Technology, and Olsson, Stockholm Environment Institute, were held. Further details are presented in table 2 'interview mapping' below. All the interviews lasted for 45-60 minutes and was conducted through the videotelephony software Zoom. All of the interviews were conducted in Swedish, which was recorded and transcribed, and finally translated by the author.

Table 2. Interview mapping

Name/date	Company/Institution	Title	Other information
Savonen, Stefan 2021-03-25	LKAB – Mining company	Senior V.P. Energy and Climate	Involved in the Hybrit project
Kansbod, Jesper 2021-03-29	SSAB – Steel producing company	Head of gov. relations.	Involved in the Hybrit project
Lundmark, Robert 2021-04-22	Luleå University of Technology (LTU)	Professor	Research on effects on regional markets related to Hybrit

Cornell, Ann & **Grönkvist**, Stefan 2021-04-23	KTH Royal institute of Technology (KTH)	Professors	Conducting research on Hydrogen and Hybrit
Olsson, Olle 2021-04-29	Stockholm Environment Institute (SEI)	Researcher	Conducting research on Hybrit

The creation of the two **interview guides** was made by the author, strongly based upon the operationalization of the theoretical concept of TIS (presented in section *5.5* in this chapter), in line with the first research question of this thesis. This enabled analyzes of the 'structural elements' and the 'system functions' applied to Hybrit. The interview guides furthermore included questions regarding Swedish national and European policy instruments, in line with the second research question. The interview guide that was utilized in the first course of action, with the company representatives, is presented in **Appendix 1.** The interview guide that was utilized through the second course of action, with the researchers, is presented in **Appendix 2.** The choice of separating the two interview guides was simply due to that in the first course of action, the questions was addressing the representatives as actors that operates within Hybrit, and the second one instead addressed the actors through an outside perspective.

Although, gathering and examining the empirics through interviews, the issue of subjectivity and bias in the information is imminent and should be noted throughout the analysis chapter (Brinkmann & Kvale, 2015). This was kept in mind during the interviews and to mitigate potential bias, the research questions and the theoretical framework structured the interviews. However, the subjectivity aspects could also be considered an advantage in the analysis of this thesis due to that it enables different perspectives to be examined.

Finally, the author acknowledges that conducting an interview with the third partner-company of Hybrit, the energy company Vattenfall, could have brought up new perspectives and useful information in the analysis of this thesis, but representatives from Vattenfall did not agree to an interview due to time-reasons. However, even though this could have been useful, the publications from Vattenfall were still analyzed and as mentioned in the previous section, the main interest of this thesis is to examine the steel producing companies involved in Hybrit, thus the conducted interviews with SSAB and LKAB can be considered relevant and scientific in line with the research questions of this thesis.

5.3.2. Document analysis

Regarding the empirical document-data that was examined in the analysis chapter mainly consisted of publications, policy papers, scientific research as well as information gathering from webpages. This was conducted in order to broaden the material of analysis as well as increasing the various perspectives in the analysis of the thesis topic. The material derived from a variety of actors, such as including publications from Hybrit (e.g., Hybrit, 2021a; 2021b), the pre-feasibility study of Hybrit development by the Swedish Energy Agency (Energimyndigheten, 2018; 2020), and a study concerning Hybrit conducted by the researchers at Stockholm Environment Institute (Olsson & Nykvist, 2020), etc. The choice to include information from the various documents was considered necessary due to this thesis interdisciplinary approach, which was fruitful in filling information gaps that was not able to be gathered from the conducted interviews. It furthermore enabled examinations of potential ambiguities regarding Hybrit and hydrogen, which was useful in this thesis analysis chapter.

Furthermore, occasionally, membership lists of European hydrogen and green steel related collaborations were overviewed and presented in the analysis to provide supplementary material in the assessment of the structural elements and functions of the asses Technological Innovation System, Hybrit. One example of this can be found in the EU hydrogen alliance list (European Commission, 2021a). Lastly, publications and websites from certain European competing companies was also gathered and examined, to enable fruitful comparisons to Hybrit. Nevertheless, it should be noted that this study was not a comparative study of structural nature, but the choice of including these sources was considered necessary due to that the theoretical framework of the analysis sporadically includes competitive aspects. To mention two examples of such gathered data from competitors can be found in ArcelorMittal (2020) and H2GreenSteel (2021).

5.4 Quality of the research

5.4.1. Ethical considerations

In terms of ethical considerations, inspired by the scholars Bryman (2008) and Mohd Arifin (2018) regarding ethical considerations in interviews within qualitative research, the interviews of this thesis were conducted through requesting upon consent of participation. The interviewees were also provided with adequately information of the thesis topic, research aim and the theoretical frameworks that was utilized in the analysis of the material. This is referred by Bryman (2008) as 'the information requirement' which was used as a guiding tool through the interview-processes, which was considered to be fulfilled by the openness and providing of information. Another requirement which was upheld during the interview process was 'the consent requirement' (Bryman, 2008), whereas clarifications were made with the respondents that they have the power of freedom to choose not to participate or to answer any particular question by any reason. Furthermore, 'the utilization requirement' (Bryman, 2008) was also taken into account due to that the information collected by the respondents was and will in the future only be used in this research.

Regarding the interviews, lastly, respondent's validation (Bryman, 2008; Silverman, 2014) was conducted and is usually considered an essential aspect in interview studies-processes, which in this thesis was considered particular important due to that the individuals was presented by their names, titles and organizations as was therefore conducted. Thus, the information gathered from the interviews, including the interpretations that was made by this thesis author in the analysis/results, was emailed to all the respondents before the publishing of this dissertation. This was made in order to give the respondents the possibility to check for fact accuracy, potential misquoting's as well as the interpretive claims that was made in the analysis by the author.

Regarding ethical considerations of the examined documents, publications and wepages: All the documents, webpages, and databases, are consisting of public material and is therefore accessible for anyone. The documents did not include any company secrets nor confidential information and was therefore not required to be utilized extraordinary careful. However, it was nonetheless considered very important that interpretations and citations were conducted adequately.

5.4.2. Validity

The concept of research-validity, which by scholars (e.g., Bryman, 2008; Yin, 2014) have been described as a measurement of whether one examines what is methodologically intended to be examined. The validity of the conducted research in this thesis was pursued by safeguarding that the analyzed material, containing both findings from semi-structured interviews and through different publications, were aligned with the stated aim and research questions. Furthermore, due to that the interview guides and its questions were formulated and delimited to coherence with this thesis aim and research questions, which includes the operationalization of the theoretical framework of Technological Innovation System, this thesis maintained a high validity.

5.4.3. Reliability

The discussion regarding the reliability of a study is among scholars usually portrayed as being fulfilled if the study and its results is replicable by other researchers (e.g., Bryman, 2008; Silverman, 2014). However, as Bryman (2008) argues, in a qualitative study, especially with the methodological choice of conducting semi-structured interviews, such as the structure of this thesis, achieving the same analytical interpretations and results is seemingly hard and subjective, and was not considered the goal of this study. Due to the fact that the interviews were conducted semi-structured the information gathering was dynamic, given the time and space they were held. Furthermore, the fact that the authors pre-understanding and selection of material, as well as the author's associations of particular concepts from the findings of the interviews are subjective which accordingly makes it hard for other researchers to connect the same results as in this thesis' analysis. Although, the interviews were recorded and analyzed several times as well as transcribed to get truthful and adequate results, which, increased the reliability of this study due to that the opportunity to "return" to the findings was then made possible. Lastly, the reliability of this study was considered increased due to the fact that the theoretical framework in this thesis was based upon previous theoretical innovation research, which laid the foundation in the making of the operationalization of the theoretical concepts to address and fit the topic of this thesis.

5.5 Operationalization of central concepts

In this section the connection between the theoretical framework and the empirical data used for analysis will be presented. These operationalized connections lay a fundamental base throughout the following analysis due to that it contextualizes and reduces the gap between the theoretical perspective and the empirical cases.

Hydrogen is conceptualized throughout the analysis as a source of energy, focusing on the technological process of electrolyzes (green hydrogen), which as presented earlier makes it a CO_2–emission free energy. However, is it worth noticing that the green hydrogen technologies might differ amongst each (Friedmann, et al. 2019) but has in this thesis been operationalized and treated as more of an umbrella-labelling, referred to as hydrogen technology. Moreover, as presented in chapter 2, section *2.2,* the hydrogen integration of Hybrit in its green steel production is through hydrogen-direct reduction (H-DR), which will be presented as H-DR technology throughout the analysis. The H-DR technology is additionally conceptualized as an innovation due to that it can be observed as being an innovator in early adoption stages, as well as its applications is currently being explored in a variety of industries and areas (Capros et al., 2019). The steel produced from H-DR processes is referred to as *green steel* throughout the analysis chapter.

As previously presented, the analysis section has been based on the theoretical framework of a 'Technological Innovation System', developed by scholars such as Hekkert et al. (2007) and Suurs et al. (2009). This has been applied through mapping and analyzing the structural elements, defined previously, and the functions of the TIS. However, due to that the functions can be perceived in a general manner, applicable to suit different sorts of innovation technologies, an operationalization of the functions was therefore necessary. This laid a theoretical foundation of the functions-examination in the analysis, presented in table 3 below.

Table 3. Operationalization of the functions of the Technological Innovation System. Table created and case-tailored by the author, inspired by Hekkert et al. (2007) and Suurs et al. (2009).

System Function	Performance indicator
F1. ***Entrepreneurial Activities***	How does the actor innovate with their technologies, in certain regards to hydrogen Existence of entrepreneurial experiments Diversification of incumbent companies into the hydrogen sector
F2. ***Knowledge Development***	Increased amount of published scientific research related to hydrogen and green steel Investments in hydrogen R&D
F3. ***Knowledge Diffusion***	Participating in- and hosting workshops / events Membership participation in alliances and organizations, such as trade organizations Sharing findings from new developments with different actors
F4. ***Guidance of the Search***	Incentives for technological transition Circumstances in relation to competitors Identified public targets for use of hydrogen (EU and national levels)
F5. ***Market Formation***	Existence of hydrogen niche markets (artificial markets) Identified product demand
F6. ***Resource Mobilisation***	Availability and accessibility financial capital for the hydrogen sector Identified economic investment incentives Subsidies or policy incentives for hydrogen
F7. ***Legitimacy Creation***	Examples of successfully achieved targets of lobbying Resistance and or support from other actors in the innovation developments

5.6 Data analysis

To proceed by utilizing the operationalizations previously discussed, this section will present how the analysis was conducted. The analysis was divided into three sub-chapters. In the initial section, the structural elements within the TIS system in focus, Hybrit, was examined and mapped out in line with the theoretical framework based on Hekkert et al. (2007) and Suurs et al. (2009). The mapping of the structural elements consisted of *actors, institutions* and *infrastructures,* to establish the state of play for Hybrit in the forthcoming analysis of the functions. Furthermore, the analysis and assessment regarding the performance indicators of the seven system functions applied on the project of analysis was presented. This was made to measure the matureness of the TIS in accordance with the operationalization of the functions. This was followed by a summary of the system functions. Lastly, the third sub-chapter presents an examination of National and EU policy instruments, including identifying its beneficials and bottlenecks.

The gathered material in this thesis were applied throughout the analysis. However, the main focus has been to analyze the material that was considered the most relevant in every section, based on the research questions and the theoretical framework, given that some of the material discuss particular areas and others do not. This study was therefore not a thematic analysis but rather conducted by concentrating the discussed material in matters of relevance, and the material was in an academic manner referred to. Therefore, only the material that was highlighting a particular assessment was presented. To illustrate, when a document or interviewee did not discuss a particular issue that was examined, they were not presented in the issue.

6. Results and analysis

In the initial phase of this thesis' analysis chapter, a mapping of the structural elements within the technological innovation system of Hybrit will be conducted. This is crucial in order to provide an analytical background and establishing the state of play of the Hybrit-project, in line with the research aim and the TIS theory. This will be followed by an analysis of the seven TIS functions applied to Hybrit, in order to assess how mature the TIS involving Hybrit transpires. This will be followed by a brief summary of the results in the functions-analysis, whereas European policy instruments will lastly be analyzed. To reiterate, the results chapter will also introduce the sources used for the analysis.

6.1 Mapping the structural elements

For a TIS to evolve successfully, which also applies to this case study that involves the hydrogen technologies utilized by Hybrit, the matureness of the functions that will later be assessed must be sustained by the structural elements (Hekkert & Negro, 2009). Therefore, a mapping of the structural elements will be deployed at this sub-chapter, which includes the *'Actors', 'Institutions' and 'Infrastructures'* of the Technological Innovation System.

6.1.1. Actors

The actors involved in the hydrogen-steel project Hybrit consists of a consortium of the three companies SSAB, LKAB, and Vattenfall (see chapter 2, section *2.2*. for further details). Furthermore, another prominent actor involved in Hybrit is the Swedish Energy Agency, which is funding roughly a fourth of the Hydrogen-investments (Hybrit, 2021a; Energimyndigheten, 2020). It is further important and analytically fruitful to additionally identify other relevant actors (Jacobsson & Bergek, 2011), such as companies within the sector, but as well policymakers and regulators, given that they might have impacts on the developments of the Hybrit project and the structural system it works within. Thus, another actor worth mentioning in this TIS analysis is Jernkontoret, which is the Swedish iron and steel producers' association which both SSAB and LKAB are members of (Jernkontoret, 2021). Apart from the Swedish public authority involvement in Hybrit, another relevant actor that can be found at a policy level is the European Commission, which plays an important role in the development of hydrogen in steel production through its Hydrogen strategy (European Commission, 2020c) and Hydrogen in the green recovery plan (European Commission, 2021b), as well as the EU-ETS (European Commission, 2021d).

The structural element '*Actors'* further involves mapping competitors involved with similar technologies as the analyzed TIS, Hybrit, as well as the actor's-related collaborations of knowledge-sharing groups or market-based networks (Jacobsson & Bergek, 2011). Accordingly, in this effort to mapping out relevant European Hybrit-competitors, the research project "green steel tracker" which is led by Stockholm Environment Institute (SEI) with multiple universities and research institutes (LeadIt, 2021), provides information regarding the developments of green steel among different companies, which therefore was overviewed in this mapping of European competitive companies. Findings from the website reveal that some other prominent hydrogen-in-steel-production projects that are currently being developed within the steel industry can be found in the companies ArcelorMittal, Voelstalpine and Thyssenkrupp. The strive to develop a carbon-free steel production is further demonstrated in assessing company-reports such as ArcelorMittal (2020), Thyssenkrupp (2019) and Voelstalpine AG (2020). These three companies all share similarities to Hybrit due to that they are likewise developing technological integration of hydrogen in the reduction of iron ore (i.e., H-DR processes), hence they can be considered competitors to Hybrit and consortium companies. Furthermore, findings from the interview with Grönkvist at KTH, there is a new company in Northern Sweden that, in line with Hybrit, aims at producing green steel through hydrogen, namely H2 Green Steel (H2GreenSteel, 2021).

In terms of collaborations, whereas Hybrit and its partner companies are participating in several networks, in which sector cooperation can be identified in many of them with a variety of companies involved. One European major network that the Hybrit companies are participating in can be found in the 'Hydrogen Alliance', which is a cooperation initiated by the European Commission (European Commission, 2021a). This network gathers for instance actors consisting of several EU member states and regions, research institutes as well as companies, whereas the latter can be identified to cover a majority of actor-memberships. Albeit that they are competitors, the previously mentioned company Thyssenkrupp is also a member of this alliance (Ibid.).

6.1.2. Institutions

As presented in the theoretical framework chapter, the institutions encompass the formal and informal rules and norms, which is setting the rule of the game (Edquist & Johnson, 1997: 46; Suurs et al., 2009). In this effort to initially mapping the jurisdictional (formal) rules that applies to the Hybrit and its consortium companies, legislation and legal bodies can be found at different jurisdictional levels, including global, European and Swedish regulations. Globally and nationally, the 2050 zero-carbon emission objective until 2050 in the Paris Agreement and the European climate law, as well as the zero-carbon emissions objective until 2045 in Sweden influences actors, such as Hybrit, to reduce carbon-emission in line with these EU- and Swedish climate targets. In line with these objectives, Hybrit aims at achieving a carbon free steel production by 2045 (Hybrit, 2021a).

Furthermore, findings from the interviews with Savonen at LKAB and Kansbod at SSAB regarding the institutional rules, several systems that applies to the hydrogen processes of Hybrit was highlighted. Regarding relevant EU-regulations, the Carbon border adjustment mechanism, Industry emission directive, as well as the EU Taxonomy was highlighted. Moreover, highlighted as the conceivably most crucial regulating system is the EU- ETS (see chapter 2, section *2.3.2*) under which both SSAB and LKAB currently obtains CO_2 permit allocations. Which will be further discussed in the section 6.3. due to that this is predominantly a mapping of the structural element '*institutions'*.

By mapping the informal and norm-setting structures of Hybrit, it is relevant to couple back to the Paris Agreement and global climate movements, pressure from public opinion could have an impact on developments and investments of the steel industry, including investments into H-DR in Hybrit. The fact that the steel industry is the largest emitter in Sweden, which alone stands for 10% of the CO_2 emissions, while only a minor part of the Swedish work force is involved in the sector, as for 2018 merely 0.4% (SCB, 2018), could underlie dissatisfaction in such investments. Although, whether this potential public discontent regarding steel industry investments will occur is still to be seen, whereas the notion of Hybrit's commitment of taken a leading role in producing fossil free steel could avoid such criticism or even lead to supportive public reactions.

6.1.3. Infrastructures

In line with the findings from the research review (see chapter 3) regarding the infrastructural potential and challenges, the production and storage of hydrogen was pointed out as particular crucial. Thus, these aspects will hereby have a certain focus in this mapping of the third and last structural element '*infrastructure'*. Findings from the IVL study concerning a climate neutral industry in Sweden (Klugman et al., 2019) reveal that the deployment of hydrogen in steel technologies (i.e., H-DR processes) in the context of Hybrit faces infrastructural challenges that needs to be accomplished for a successful green steel production:

> In order to replace the Swedish blast furnaces with hydrogen – DRI, a vast hydrogen production is necessary which involves a high demand of electricity and capacity for hydrogen storage […] a prerequisite for the DRI-Hydrogen process, is that the electric grid capacity is strengthened to the production sites (Klugman, et al., 2019: 19).

Klugman, et al. (2019) further point out that more technological development is required, given the fact that the hydrogen production that would be required in order to produce the quantities of green steel that Hybrit aims at achieving in the future, have not yet been seen in the world at such big scale. However, the infrastructural challenges concerning hydrogen storage have also been brought to the attention of Hybrit themselves, and they have currently started a construction of a hydrogen storage facility in a rock-shelter in the cavern 'Svartöberget', outside of the city Luleå, which aims to be operational between 2022 – 2024 (Hybrit, 2021c). Based on the interview with Savonen at LKAB, Savonen recognized that there are challenges with being the world first in developing the H-DR technologies in Hybrit in terms of storage capacity in rock shelters, for which Savonen stated:

> It would be easy to storage hydrogen for a week's production, but if we would storage hydrogen for a year's steel production, we are talking millions of tons of hydrogen that would require gigantic and highly costly storage facilities.

Challenges regarding hydrogen storage was also highlighted in the interview with Kansbod at SSAB, but according to him, Hybrit also have great confidence that the hydrogen storage development will turn out successfully. Nevertheless, this was problematized in the interview with the researcher Grönkvist at KTH, who on the one hand have conducted research connected to storing hydrogen in caverns (i.e., rock-shelters) and agreed to its potential, but on the other hand argued that the huge amount of fossil free energy and hydrogen that would be required in the green steel production of Hybrit is massive and a big challenge. Cornell from KTH agreed in the interview about the storage-challenge, whereas she further argued: “If Vattenfall in addition to the hydrogen storing in the steel production also wants overproduction to balance the electricity-grid, a lot more hydrogen will be needed”. In line with this designated storage-challenge, Grönkvist notably responded in the interview regarding infrastructural bottlenecks that: “The hydrogen production and storage is a big bottleneck itself”.

The presented results from this mapping of the *‘infrastructural element’* indicates that developing electric grids and hydrogen storage are crucial challenges. Perhaps remarkably, in contrast to previous concerns discussed (see chapter 3) regarding storage hydrogen in caverns, this solution seems to be a fruitful way of storing hydrogen and is under development. However, based on the results, it shows signs of that Hybrit and its consortium-actors are well aware of these both infrastructural challenges and strives to prevail over these.

6.2 System functions analysis

This sub-chapter intends to assess and analyze the matureness of the seven functions in the TIS applied to Hybrit. By deploying the operationalization of the theoretical framework, the performance indicators will be elaborated on, based on the gathered material in this thesis. This will be followed by a summary of the performance-indicators in section *6.2.8.*

6.2.1. F1 Entrepreneurial activities

This section will, in line with the operationalization of the performance indicator of *‘entrepreneurial activities’* (F1), analyze the matureness of how Hybrit innovate, as well as conducting entrepreneurial experiments (Suurs et al., 2009). The entrepreneurial activities involving Hybrit exhibits grand entrepreneurial and innovative ambitions and goals, perhaps envisaged by the goal of being the world’s first fossil free steel producing actor (Hybrit, 2021a; Vattenfall, 2021). Findings from the interviews with Kansbod from SSAB and Savonen at LKAB displays a determined and thoroughly worked out pathway forward, with the goal of becoming the world first in commercializing the H-DR green steel. Findings from the interviews reveal that the reasons behind this hydrogen transition can be understood as twofold.

On the one hand, the strive to become the world's first fossil free steel producer is motivated by concerns regarding the climate change itself and a will to reduce the CO_2 emissions, but on the other hand, internal calculations and streamlining-projections that was mainly conducted in the companies around 2016-2017, resulted in economic and profitable incentives in integration hydrogen in the direct-reduction process. Kansbod stated that:

> We [SSAB] thought that we either continue developing emission-reduction in coal-based solutions or change the technology completely. Here we chose the latter choice to develop fossil-free hydrogen technologies in our steel production. With Hybrit's owners ambitious investments and timeframes, we are aiming to become the world's first to deploy the H-DR technology at a commercialized scale.

Attributing to taking a world-leading role in this transition can certainly be considered to have great entrepreneurial aspirations in line with the performance indicator of the *'entrepreneurial activities'* (F1) (Suurs et al. 2009). This "experimentation by the entrepreneurs" (Hekkert et al., 2007: 421) falls in line with a typical example of when an actor within a TIS is diversifying and opening for new technological advantages in their business strategies. The diversification of the company can also be found in terms of cooperation, due to the fact that Hybrit is based on three companies, which, in line with the F1 of the TIS, might further be a strengthening aspect given that entrepreneurial activities can be driven from three different actors. Another example is that the Swedish Energy Agency has invested in the project, for example 22 million SEK in research towards the establishment of a demonstration facility (Energimyndigheten, 2020). If Hybrit would not be a consortium of the three relatively big companies and their unique competencies, the question could be raised as to whether the funding would have been to such extent if the three companies would have applied for their own production themselves.

Lastly, in terms of entrepreneurial activities applied to Hybrit, the development of the H-DR technology itself can be considered a huge innovative change, as Cornell at KTH pointed out: "Currently, it is cheaper to produce hydrogen from fossil energy, but the fossil-free hydrogen is developing fast". Grönkvist from KTH also argued in line with this: "Because the pilot facility is on the way, that is definitely a big technological development". The results of the '*entrepreneurial activities' (F1)* disclose in line with the TIS-conceptual framework that based on the analyzed material, Hybrit is innovating in several ways. Therefore, Hybrit can be noted to perform high on the performance indicator of the first function.

6.2.2. F2 Knowledge development

By continuing to the second function in this TIS-matureness analysis, '*Knowledge development' (F2),* this section will explore whether and to what extent research regarding Hybrit and hydrogen have been conducted, are experiencing an increase, as well as identifying potential ongoing research-partnerships. Jacobsson and Bergek (2011: 47) refer to this function as the heart of an innovation system, considering that it captures and measures the breadth and depth of the knowledge base of the TIS. Thus, an initial measurement regarding the dimensions of new scientific research within the topic of this thesis, including the utilization of hydrogen in steel production with certain regards to Hybrit will be explored.

During the interview with Savonen at LKAB and Kansbod at SSAB, they both pointed out that there are currently numerous ongoing studies regarding Hybrit and that there are wide networks of researchers involved in the Hybrit developments. By examining this track, it can be observed on LTU's webpage (LTU, 2020) that extensive research has been conducted related to Hybrit, including scholars within a variety of fields, for example economics, process-metallurgy, and energy engineering. In line with this, findings from the pre-feasibility study conducted by Swedish energy agency (Energimyndigheten, 2018), reveal that several research cooperations among multiple universities are going on, often in cooperation with the Hybrit actors, as well as including research institutes such as Swerea MEFOS and Stockholm Environment institute (Energimyndigheten, 2018).

Furthermore, Olsson from SEI pointed out in the interview that SEI has conducted research regarding Hybrit with researchers from Lund University, focusing on Hybrit through a broader perspective (i.e., interdisciplinary). Whereas Olsson stated:

> Hybrit is very interesting, it has developed at a rapid speed. We [SEI] started to conduct Hybrit-related research in 2017 in cooperation with Lund University by examining different social-benefits scenarios with the green steel. When we were approaching the publication deadline of our report regarding the demonstration plant, the Hybrit actors had decided to initiate one.

This provides indications that the TIS applied to Hybrit is, so far, performing well regarding F2 and a lot is occurring on the research-agenda. The Hybrit actors are involved in several studies and research collaborations, as well as independent ongoing research is taking place related to hydrogen and fossil-free steel production.

Additionally, by taking an observational step outside of the national borders of Sweden, namely by examining related research conducted at a European level, Hybrit is involved in several European collaborations. To mention one example, Hybrit is through the consortium-company LKAB together with the University LTU participating in the EU-funded research network 'Eit Raw Materials', which conducts research regarding raw material and innovation. Within the research project, an innovation Hub (CLC North) is located in LTU science park, and LKAB is also a member in its board (Eitrawmaterials, 2021; LKAB, 2021).

So far, the results point towards that research on H-DR and targeted Hybrit-research is being conducted to a high extent, at different levels, and among different actors. Findings from the interviews with the researchers Lundmark at LTU and Cornell at KTH both pointed out in the separate interviews that hydrogen research in general, as well as hydrogen usage in the steel industry, have seen an uprise lately. However, perhaps remarkably, they both explained that the hydrogen research is cyclic, clarified that it has had upturns before. As an example, in the 90s, hydrogen research experienced a previous upturn followed by a decline in conducted research in between these last years described in the interview by Lundmark as: "hydrogen research seems to come and go in periods". Nonetheless, both Lundmark and Cornell highlighted that the current increase of hydrogen studies might be here to stay due to developed technological innovations that have happened recently and that reducing the CO_2 has gained higher attention in the past years could be another explanation in that regard. Lundmark pointed out: "It is possible that there have been more fundamental changes and more mature technology - but many challenges remain with hydrogen".

Clearly, the presented results indicate that a comprehensive amount of research is going on related to Hybrit within several fields connected to the value chain of green steel production. In line with the F2 in the TIS theoretical concept (Hekkert et al., 2007), this is an important measurement that can be considered fulfilled. Although, concerns could be raised whether research on hydrogen and the green steel is cyclical, but findings from the interviews point towards that it seems to begin to establish itself and is possibly here to stay. On the performance indicator of F2, Hybrit performed high.

6.2.3. F3 Knowledge diffusion

As presented in the previous function, '*Knowledge development'*, The Hybrit actors are involved in European research collaborations, such as the mentioned research project Eit Raw Materials. This is already an indication of well-performance in the third TIS-function '*Knowledge diffusion'(F3),* which measures the extent of knowledge-sharing interactions among actors with different backgrounds (Hekkert et al., 2007). To further measure whether Hybrit is conducting knowledge-sharing activities, Kansbod from SSAB stated:

> We started a research project in 2016 together with several universities and research institutes, such as Lund University, KTH, Sverim etc. The project is very exciting and will be finished in 2021.

This implies that, in line with the results in the previous function regarding research collaborations, Hybrit-involvement in knowledge-sharing activities can be found. As the function *'Knowledge diffusion'* was operationalized in the performance indicator, membership in networks and alliances is an important part of the measuring of the matureness of TIS on Hybrit. An observation of the EU hydrogen alliance membership list was therefore made, where all the three Hybrit-consortium actors LKAB, SSAB and Vattenfall appeared as members (European Commission, 2021a). This implies an initial well performance on the F3-indicator in this examination.

Continuing the European knowledge-sharing perspective, it is substantial to examine whether other actors, such as competing companies, are participating in similar knowledge-sharing activities (Jacobsson and Bergek, 2011). Examples of this can be found in the companies ArcelorMittal (2020) and Thyssenkrupp (2019). These companies are members of the European Green Steel Association (Eurofer, 2021), which conducts studies and knowledge-sharing experiments related to prospects of replacing fossil feedstocks in blast furnaces with hydrogen in steel production. By overviewing the Eurofer membership list, neither Hybrit nor its consortium actors can be found as members. However, Jernkontoret, the previously presented Swedish iron and steel producers association, obtains a membership in the collaboration. This signifies that Hybrit is, at the minimum formally, an indirect member (Eurofer, 2021). Although, this does not reveal any specific numbers of knowledge-sharing partnership activities which makes it hard to draw inferences in that regard. Therefore, a further examination of this knowledge-sharing among Hybrit and European collaborations was made through the interview with the LKAB representative Savonen. He stated that:

> LKAB, together with our Hybrit partners, has a strive to basically participate in as many European and international collaborations as possible. To mention one example, I am involved in Green Steel Europe where there is an exchange of experiences. Still, we do occasionally face time- and resource difficulties to participate in all the networks.

The results indicate that Hybrit and its consortium actors are participating in some research collaborations. Still, there exist some opportunities for improvement, meaning that there are European collaborations which Hybrit is not participating in. However, it can be noted that Hybrit and its partnership companies have a strive to develop further knowledge-sharing collaborations. The ambitions are clearly there, but the performance is not completely fulfilled. Therefore, Hybrit performed moderately on the F3 indicator.

6.2.4. F4 Guidance of the search

As an important part of measuring the matureness of the TIS in transition, an initial step in the fourth function '*Guidance of the* search' (F4) is to examine the transition process itself (Jacobsson & Bergek, 2011). Thus, analyzing why and how this transition is taking place and its incentives were considered crucial in grasping this process shift. The operationalization of the F4 also included, inspired by Hekkert et al., (2007), how Hybrit performs in relation to competitors, which will be highlighted too.

Something that was stressed in the interview with Olsson at SEI regarding Hybrit is that the internal processing time, from decision-making to initiating demonstration facilities, has occurred in a rapid speed, which he portrayed as high ambitions from the partner companies involved. Olsson highlighted that this transition has several explanations, whereas one can be found in climate action ambitions, which, according to him, a general shift (at basically all levels in European society) had occurred, whereas the goals of net-zero emissions have been recognized in general. He further described that the steel industry recognized this as well, in line with what the interviews with the company representatives Savonen at LKAB and Kansbod at SSAB depicted. Another aspect that was discussed by Olsson at SEI and Cornell at KTH is that developing hydrogen in the direct reduction of steel has been made possible due to that the price has gotten lower on fossil-free electricity. The location of Northern Sweden, where Hybrit is located, was pointed out as a particularly good condition for such energy. The fact that iron ore also exists in the region makes the potential even brighter, according to Olsson. Thus, concerns in climate change, advantageous regional conditions, and goal-oriented companies seem to be the catalyst in this green steel transition. Olsson further developed his argument regarding Hybrit as a potential transition-frontrunner could be due to the political will from most political parties in Sweden, i.e., a state that is backing up sustainable transition within the steel industry.

By further analyzing the frontrunner topic, Hekkert et al., (2007) describe that competitional aspects are a relevant aspect in the F4 analysis, which will be elaborated on. Based on the interview question regarding European competition, most of the interviewees referred to hydrogen but also green steel as a new trend in Europe. Savonen at LKAB argued that what differs Hybrit from its competitors is that:

> While the other European companies are investigating a potential hydrogen transition in their steel production, it is currently only at the sketch tables. Hybrit on the other hand, have pilot facilities up and running and started trials at the pilot plant.

This is in line with what can be found in the Hybrit pre-feasibility study (Hybrit, 2017: 5):

> As a demonstration of science and innovation, HYBRIT has the potential to sustain Europe's leading position in fighting climate change while strengthening competitiveness.

By examining this track further of Hybrit as a potential frontrunner, Olsson at SEI stated in the interview:

> There are other similar (green steel) projects in Europe, but these are being developed at smaller scales. What is particularly interesting with Hybrit is that they [the company] established business plans early on, including long-term goals and strategies. They take this transition seriously.

Grönkvist expressed in the interview a similar approach regarding the transition process, although, he had a more mitigated perception of this, concerned about Hybrit might be too ambitious in terms of obstacles that could occur, stating that:

> Huge upscaling is needed to achieve the targeted goal. The fact that Hybrit aims at commercializing in 2035 sounds ambitious itself. We have not experienced such extensive industrial investments in Sweden since the 1970s. Now there is also H2 Green steel, which seems like a serious actor although they have very ambitious, perhaps too ambitious, timeframes scheduled.

Grönkvist mentioned something noteworthy, there is a new company in Northern Sweden that aims at producing green steel through hydrogen, namely H2 Green Steel. Regarding the frontrunner perspective as a performance indicator, the following can be read at H2 Green Steels webpage (H2GreenSteel, 2021):

> An important source of inspiration for the initiative is the groundbreaking HYBRIT project and its founders SSAB, LKAB, and Vattenfall. H2GS looks forward to a close collaboration with the HYBRIT-founders, sharing the vision to position Sweden at the forefront of fossil-free steel production.

This further indicates that Hybrit is inspirational, even among competitors. By assessing the presented results, Hybrit is performing high regarding the *'Guidance of the search'*.

6.2.5. F5 Market formation

The fifth function in this TIS-analysis entails of examining the '*Market formation'* (F5), operationalized in chapter 5. Suurs et al. (2009) address the functionality of the F5 as enabler and supporter of technological innovations in transitions, and it is usually necessary to create artificial markets for such innovations. Hence, this analysis of the F5 will start by examining whether a niche-market, defined by the scholars Smith and Raven (2012: 1025) "as a protective space where path-breaking, radical innovations, such as in the case of this thesis low-carbon technologies, are produced and developed", exists related to the Hybrit-technologies. Therefore, this analysis will initially examine the potential existence of niche-markets, taking off by analyzing the summary of the Hybrit pre-feasibility study (Hybrit, n.d.: 5, 9). Recognition of niche-markets tendencies becomes salient:

> Sweden offers favourable conditions for HYBRIT to contribute to these national targets, such as high-quality niche production of iron-ore pellets, a specialized and innovative steel industry, and an abundant supply of fossil-free electricity […] A viable business case may be dependent on carbon dioxide instruments, as well as development of niche markets for fossil-free iron and steel.

This implies that Hybrit has outspoken acknowledgments and ambitions that their business operates within niche markets, as well as the project called to be seemingly dependent on political carbon instruments. By studying the research papers, findings from the SEI report (Olsson & Nykvist, 2020) points out that niche markets in the steel sector have in general developed in the last two decades, originating from the over-capacity of steel in the 1990s, which forced companies either to consolidate or seek out niche-markets. Regarding whether Niche markets applies to Hybrit, following can be read: "In the case of HYBRIT, SSAB produces a wide range of steels from commodity steels to niche products characterized by a strong focus on customer relationships" (Olsson & Nykvist, 2020: 19).

However, SEI further highlight in the Hybrit-study (Olsson & Nykvist, 2020: 19-20) that a crucial aspect whether Hybrit, in a future of full-scale H-DR steel production, still exists within a niche-market, is due to what the price premium for "green steel" would be in comparison to the incumbent blast furnace produced steel. By taking a notice of this highlighted aspect, namely the premium price in relation to customer aspect of the green steel, this is in line with this thesis' operationalization of the '*market formation* (F5)' – whether there exists a product demand. To analyze this track, examining reports from independent research institutes will be initially conducted.

The Swedish foundation for Strategic Research states in their report (SSF, 2019: 26) that forecasts show that a global demand of steel will increase until 2050, highlighting the importance of to producing it fossil-free in order to reach the climate targets and that Hybrit stands for that solution. Furthermore, based on the IVL study (Klugman et al., 2019) it is highlighted that in the commercialized phase, the production cost of Hybrit's HD-R steel is estimated to increase to 20-30 percent compared to the cost of today's blast furnace productions in SSAB, which would increasingly affect the costumer-price of the steel. This could raise concerns regarding whether there will be a demand for Hybrits' green steel from the costumers. Projections of the premium price in relation to demand was further raised in the interviews with the company representatives and the researchers. In contrast to the potential concerns whether there would be a demand for the more expensive green steel, Kansbod from SSAB and Savonen from LKAB contends that the consumers would pay the higher price in order to reduce their own CO_2 emissions. Further findings from the interviews with the researchers Lundmark at LTU and Olsson at SEI points towards the same direction, namely that if Hybrit succeeds with producing the green steel, costumer would pay for the increased “premium price” due to the same rationale as argued by Kansbod and Savonen.

Thus, based on the analyzed material which includes both the research publications as well the information gathered from the interviews, Hybrit and its products are part of niche-market(s). The fact that all the interviewees from their different knowledge and point of views more or less agreed upon this strengthens that assumption. Furthermore, it appears that a demand for the green steel products, including a potential premium price increase is projected to be of customer interest and purchase willingness. Therefore, the result of this analysis indicates that Hybrit is performing well in the fifth function *‘market formation (F5)’* of this TIS-analysis.

6.2.6. F6 Resource mobilization

Another critical aspect to examine whether how mature the TIS applied to Hybrit is, is by measuring the sixth function, *Resource mobilization*, which, according to the theoretical framework of Hekkert et al. (2007) refers to the allocation of financial, material, and human capital. Concretized, it is critical to identify whether economy and investments can be found within the hydrogen direct reduction business of Hybrit. While the former function, F5, examined the market formation which lays a financial boost and foundation, analyzing the F6 rather focusing on the tangible investments and future prospects.

It was highlighted in the interviews with both the company representatives Savonen and Kansbod, as well as the researcher Lundmark at LTU, that motivations for carrying through these seemingly massive investments are due to market incentives. This is also in line with the results from the previous function analysis of ‘*Market formation’ (F5),* that future customer demand for green steel can be identified. However, potential obstacles can still be identified, such as by analyzing the SEI report on matters regarding commercialization processes (Olsson & Nykvist, 2020: 12) it is stated that:

> "It is highly likely that there will be issues linked to the process, the supply chain or the business model that remain unresolved until the full commercial facility is up and running".

Moreover, with the aim to facilitate a deeper comprehending regarding the investments made into Hybrit, a brief contrasting perspective to other comparable hydrogen-in-steel-production companies was considered useful, to grasp the TIS in a wider European perspective and will therefore be discussed. Findings from the decarbonization roadmaps of the previously mentioned European competitors ArcelorMittal (ArcelorMittal, 2020) and Thyssenkrupp (Thyssenkrupp, 2019) demonstrate heavy investments are being made to similar steel produced by hydrogen-technologies as Hybrit. ArcelorMittal estimates that by integrating hydrogen in the iron ore reduction processes, the costs would induce investments of around €30-40 billion, while Thyssenkrupp is planning on investing €10 billion until 2050. While these are estimated projections and could possibly be subject to change in the future, clarifying the investment into Hybrit is not quite clear, and a reason for that is that the consortium comprehends three different companies, which, all should be calculated for. However, it is estimated that the total amount of investments will end up at around €30-40 billion (Hybrit, 2021c; Håkansson, L., 2020, November 23) However, findings from these roadmaps in terms of planned investments into hydrogen disclose that the roadmaps, in line with Hybrit, requires public incentives and investments in order to accomplish this climate-neutral steel-production.

Findings from the interview with Olsson at SEI, a similar approach was highlighted. He asserted a notable comparison between these current hydrogen developments to the developments of solar power in Europe in the last decade, whereas massive price reductions have been made possible due to boost from European states, according to Olsson. He developed this argument in the case of solar power in Germany:

> They [solar power companies] needed a public push that bought the expensive solar powers, which the German state executed which in turn decreased the prices of both the technology itself but also the energy from it.

According to Olsson, due to these initial public subventions, the solar power industry was then made self-reliant without further interference from the German state. Olsson stated that the EU has indicated a similar approach in the hydrogen economy.

The emphasized need for subventions and public procurement is in line with the performance indicator of the F6 in the TIS (e.g., Hekkert et al., 2007), which, can be identified to be occurring and fulfilled at a national level. The fact that the Swedish government, through the Swedish Energy Agency, invests 35% of the Hybrit pilot-production plant (Energimyndigheten, 2020) but also through different research programs (see *function 2, 'knowledge development')* provides evidence that subventions are taking place. These results imply that resource mobilization in terms of capital exists. However, this F6 analysis includes another resource that has been elaborated and discussed on previously in this TIS analysis, namely the resource of accessing electricity in order to produce the hydrogen used in the green steel production. Nonetheless, the electricity demand is projected to be substantial, which, based on the Hybrit feasibility report (Energimyndigheten, 2018) assumes that between 2028 and 2032, 3 TWh per year would be needed for the production, continuing to 9 TWh/year from 2038-2040. Furthermore, findings from the interviews with Cornell and Grönkvist from KTH regarding the energy demand of Hybrit, was referred to enormous and the researchers indicated that this is a huge bottleneck, involving not only the consortium companies but also other companies and public actors.

To conclude the assessment of the matureness concerning the F6, in regard to the presented results, the financial mobilization seems to be in place, including subventions, but the fact that the electricity-resource faces challenges can be assumed to be not quite mature, yet. Thus, Hybrit is considered to perform moderate in the '*resource mobilization' (F6).*

6.2.7. F7 Legitimacy creation

The last function (F7) measures the '*legitimacy creation'* of the TIS, meaning that a technological innovation faces uncertainty and therefore requires legitimacy from actors to enable implementations and investments. Emerging technological innovations often tend to face resistance from incumbent actors, whereas creating legitimacy and support from other actors such as policymakers is crucial (Suurs et al., 2009). Regarding Hybrit, measuring the support from policymakers as well as lobbying engagement will hereby be examined in line with the operationalization of the F7.

Concerning whether Hybrit experience received support from the politics in Sweden and Europe, Savonen at LKAB argued in the conducted interview:

> The Swedish government and parliament support us [Hybrit], including the Swedish Environmental Protection Agency and the Swedish Energy Agency. However, in a European context, it is problematic that Sweden is the frontrunner in this transition. To get real EU support it would probably be useful if bigger member states would be in the same development phase.

This provides indications that legitimacy from politicians can be found. By continuing the examination of this track, Olsson at SEI argued in regards to legitimacy from politicians:

> Basically, all Swedish political parliamentarian parties seem to be in favor of the transition of fossil free steel, very few criticize this transition […] Hydrogen has exploded as a phenomenon recently. Only a few years ago, the Hybrit idea of conducting the H-DR fossil-free steel production was questioned, but a paradigm shift has occurred, and a lot has developed recently.

By further measuring lobby activities, findings from the interviews with the Hybrit-companies' representatives, Kansbod pointed out that SSAB is not actively conducting lobbying to policymakers but highlighted that they are following several EU policies and directives. Savonen at LKAB indicated a similar approach but pointed out that they are involved in planning UN Climate summits. However, even if seemingly little effort is made into lobbying from the Hybrit-consortium, they still get international attention from policymakers. For example, SSAB presented at the Meeting of the European Gas Regulatory Forum 2020 (SSAB, 2020). Savonen further described in the interview that:

> We experience that the EU wants to show us as a good case of the fossil-free transition, but it would be good if they could support us in other ways.

However, a measurement regarding lobby activities related to Hybrit can be found in the LobbyFacts.eu database (Lobbyfacts.eu, 2021), which is a joint project by Corporate Europe Observatory and LobbyControl which computes lobbying activities towards the EU institutions. A summarization is presented in Table 4 below, which sums up the presented number of lobbying expenditures and numbers of lobbying meetings in regards to Hybrit, as well as the three consortium companies. A first check was made for Hybrit as an own actor, which revealed seemingly low expenditures (less than €9,999) in lobbying, whereas the three Hybrit-companies on the other hand spent substantially more, with Vattenfall on the top with its €900,000 - €999,999 expenditures. However, the expenditures and amount of lobby activities do not necessarily illustrate that the errands are related to Hybrit and the green steel production, it can be assumed that the companies have other lobbying-interest though. It should also be noted that Vattenfall is among the biggest electricity and heating company in Europe with businesses in several European countries, which is not the case for the other actors. Neither does the LobbyFact data cover informal meetings nor other sorts of arrangements.

TABLE 4. Lobbying expenditures and activities

Actor & year	Lobby expenditures	Number of meetings
Hybrit, 2019	Less than €9,999	2
SSAB, 2019	Between €100,000 - €199,999	1
LKAB, 2020	Between €200,000 - €299,999	1
Vattenfall, 2020	Between €900,000 - €999,999	24

To widen the perspective of lobbying-activities of Hybrit and its consortium actors, in comparison to the competitor ArcelorMittal, Lobbyfacts.eu exposes that the company spent between €1,250,000 - €1,499,999 in lobbying expenditures and have had 89 meetings with the European Commission (Lobbyfacts.eu, 2021).

To determine the performance assessment of the function '*Legitimacy creation'(F7)*, it appears that Hybrit has received a seemingly high amount of legitimacy from policymakers, especially at the national arena. However, the second F7 indicator examined lobby activities, which seems to be quite vague. There is still a lot to be seen in the future regarding the legitimacy creation. Therefore, Hybrit is considered to perform moderate in the F7.

6.2.8. System function's performance summary

Based on the previously assessed matureness of the TIS-functions, a summary of the performance indicators is presented in table 5 below, determined on a three-level scale, ranging between low, moderate and high performances. Based on the findings from the analyzed system functions, the TIS applied to Hybrit performs fairly mature, with a few but critical impediments. As presented in table 5, a majority of the system functions performed high in the analyses, the remainders performed moderate, and none performed low.

TABLE 5. Summary of TIS performance indicators, Hybrit

Function	Observation
F1 – Entrepreneurial Activities	High
F2 – Knowledge Development	High
F3 – Knowledge Diffusion	Moderate
F4 – Guidance of the Search	High
F5 – Market formation	High
F6 – Resource mobilization	Moderate
F7 – Legitimacy Creation	Moderate

6.3 Analysis of Swedish and EU policy instruments

This sub-chapter seeks to analyze the second research question of this thesis, which includes to examining the benefits and bottlenecks in EU- and National policy instruments, based on the gathered material consisting of both the publications as well as the interviews. Although it has been discussed to some extent in the previous analysis of the seven TIS-functions, this analysis-section anticipates a more in-depth problematization regarding the issue.

In terms of Swedish-national legal and political frameworks, support in Hybrit can be found from the state in terms of funding investments for the H-DR transition as well as targeted, publicly funded research (Energimyndigheten, 2018; 2020). However, the most frequently recurring issue that can be identified from studying the material regarding the national level, is that the timespan of permit-processing within Sweden is a persistent highlighted regulatory bottleneck. Findings from the SEI report concerning Hybrit (Olsson &

Nykvist, 2020) highlights these bottleneck risks in the regulatory processes concerning permitting issues. Connected to both the actual industrial sites but also the power transmission, Olsson and Nykvist (2020) further emphasize that Swedish authorities should raise attention to swifter the processing procedures, but as well that the companies focusing on these processes. Perhaps remarkably, the Swedish energy agency whom, as presented previously, is financing parts of the Hybrit project, does in their Pre-feasibility report (Energimyndigheten, 2018: 8) also argues in line with a similar viewpoint concerning issues within the regulatory processes. However, they further underscore in the same report that the location that the H-DR pilot-plant was placed at, the 'NJA-Pier' within the SSAB industrial area, are in regard to permit-processing an advantage due to that the environmental and construction permits already were in place for previous detail-plans (Ibid). This is further in line with the findings from the interviews with both the company representatives Savonen at LKAB and Kansbod from SSAB, the latter argued:

> The process from obtaining a permit, including ordering electrical connection effects to the electricity until it will be de facto switched on, can take around 10 years. But the Swedish politics have stated that they have ambitions of halving this processing time, which is welcomed by SSAB.

Regarding the issue of permit-processing timespans, Cornell and Grönkvist at KTH also highlighted in the interview that this could become a potential bottleneck, but, as Cornell further mentioned: "The Swedish state is backing this transition up". Furthermore, Olsson at SEI also pointed out in the interview that it could be a potential obstacle with the processing-time, but additionally underscored that:

> It is further important to take all societal aspects into regards. Hybrit should be seen from a sustainable point of view, not only as a climate solution. Permitting power lines for the fossil-free steel production includes taking into account several aspects, such as the minority group of Sami people's reindeer herding, as well as interests from the Swedish armed forces. However, I am certain that Hybrit and the public authorities are well aware of this.

Perceptions of a supportive Swedish State and public authorities can be notified in the presented results; however, the underscored obstacle of long permit-processing timespans is clearly highlighted in the different sources of the analyzed material, but the findings disclose that awareness of keeping the processes within legally adequate frameworks is as well emphasized. The contestation between accelerating the permit-processing time but at the same time conducting it legally- and socially adequately seems to be a challenging puzzle.

Furthermore, changing the focus to the EU by examining the possibilities and bottlenecks among its policies, strategies, and regulations, findings from the interviews reveal a seemingly general positive viewpoint regarding the EU Hydrogen policies and strategies in a general matter, as argued by Kansbod:

> In general, the EU strategies are good, such as the hydrogen- and industrial strategies, and the EU Innovation fund. These are putting hydrogen on the map, which shows that the ambitions are in place. However, it is important that EU regulations do not remove the incentives for frontrunners, such as SSAB and the Hybrit-cooperation.

Regarding the EU- policy instruments, Lundmark at LTU said in the interview that there already exists several political instruments that aim to support clean energy transitions such as the H-DR developments of Hybrit, but further argued:

> In my opinion as an economist, there should be a market failure for the politics to step in and support a particular sector. There are several market failures within the energy sector that needs to be addressed, but at the same time, it is important that the policy instruments are solution-oriented, which might always be the case. There are different forces that are pulling in different directions and this makes it difficult to assess - You do not always know where you end up as there is a lack of coherence between the means of control.

By taking a notice of Lundmarks' problematization regarding a potential lack of coherence among the EU policies and regulations, Savonen at LKAB argued in the interview with a similar approach by stating that:

> The EU-hydrogen strategies are a good start, but if the EU now has these strategies in place, they should adjust the other regulatory frameworks to enabling that the strategies can be implemented in practice.

The presented results can be interpreted as indications that the EU-hydrogen policies are received and considered beneficially for Hybrit and the developments of hydrogen energy in general, although it discloses potential obstacles in the interdependency between the policies and regulations. One EU regulation that is particularly relevant for Hybrit can be found in the EU-ETS, which is a system that regulates and limits the emission cap of greenhouse gases through its "free allowances" (presented in chapter 2 of this thesis, section *2.3.2.*). The EU-ETS is currently being revised for the next phase and it is a debated topic whether the usage of fossil-free hydrogen in the steelmaking process (H-DR) should be grouped within the same category as other blast furnace producing steel companies or not (European Commission, 2021d; Fossilfritt Sverige, 2021). Findings from the interview with Savonen at LKAB regarding the EU-ETS, underscores criticism:

> The regulatory framework [EU-ETS] is beneficial for companies that make the green transition at the speed as we are supposed to do, but it seems that the European Commission [which governs the regulation] has not really realized that this transition is about major process changes. The system is not made for actors that make such big transitional leaps as LKAB and Hybrit intend to do.

Furthermore, Olsson at SEI argued in a similar approach:

> There has been a shift from the EU in combating climate change, whereas until recently, a focus has been on taxes, such as carbon taxes, but now the focus has altered towards innovation policies and investments, such as the EU-innovation fund, which is used to push the technological transitions. Regarding the EU-ETS, the system is operating within the former system […] I don't know really know what I think is the best solution. On the one hand, it is good to have a higher price on CO_2, which is suitable for incremental changes. On the other hand, it is less suitable for radical changes such as H-DR transition that Hybrit is developing.

The presented results indicate that the EU policies and regulations both foster hydrogen development but as well leading to bottlenecks. The EU-hydrogen strategy and the industrial strategy seem to be considered beneficial for Hybrit's development, in particular, due to that they provide increased attention to hydrogen and the H-DR technology in Europe. However, two bottlenecks were identified. One can be found in a potential lack of symbiosis among the different EU policies and regulations. The second one is within the EU-ETS system, which, the results point towards seems to have flaws due to that it is more or less approximately outdated, and a sense of injustice could be recognized.

7. Conclusions

This last chapter will in section 7.1 present the conclusions of the research aim and question of this thesis that was analyzed in the previous chapter. More specifically, this includes conclusions of the mapping of structural elements of the TIS applied to Hybrit, followed by conclusions of the system functions and concluding the findings of the Swedish and EU policy instruments. This is followed by section 7.2. which consists of a concluding discussion, followed by suggestions for future research.

7.1 Concluding the research questions

The overarching aim of this thesis was to study potential bottlenecks and possibilities for hydrogen in a European context. This was externalized by analyzing the Swedish steel project Hybrit in regard to its utilization of hydrogen in the steel production through a Technological Innovation System (TIS) approach. The first guiding research question of this thesis entailed measuring the matureness of the TIS applied to hydrogen in the steel production of Hybrit. Therefore, an examination of the structural elements and the system functions was conducted. The results reveal that the TIS applied to Hybrit is fairly mature, with a few but crucial deficiencies. A majority of the system functions performed high in the analyses, the remainders performed moderate, and none performed low.

To conclude the mapping of the structural elements, that consisted of mapping out the *actors, institutions and infrastructures* related to Hybrit, it discloses several aspects. A variety of networks, competitors and policymakers was mapped out. The institutional frameworks related to Hybrit, consisting of both formal and informal rules, were mapped out and elaborated on. Lastly, the mapping of infrastructures revealed knowable flaws.

The analysis of the system functions highlighted various aspects of possibilities and bottlenecks. Hybrit is providing entrepreneurial activities by innovating in several ways, such as diversifying its business strategies and striving to become the world’s first fossil-free steel producer. The results further indicate that an increased amount of research is being conducted, both in the field in a wider perspective but also that are addressing Hybrit specifically. It emerged that the actor is participating in some, although not all, research cooperations. However, it can be noted that Hybrit and its consortium-actors have a strive to develop further knowledge-sharing. Findings from the analysis indicate that Hybrit is a global frontrunner, which inspires other actors. In terms of market prospects, the results indicate that ambiguities of whether a fossil-free steel market can be created or not is present. The premium price of the green steel retains uncertainties, and it could be necessary to create niche-markets through policy instruments. The results reveal that public procurement has previously occurred in other energy technologies in development phases. This was suggested to be an additional solution to decrease the potential issues of the premium price of the green steel. Also, the results point towards that there is a high probability that customers will pay the premium price in order to reduce their own CO_2-emissions. The results reveal that heavy investments are flowing into Hybrit, both internally but as well externally, including state support. Lastly, the results suggest that Hybrit is receiving a seemingly high amount of legitimacy from policymakers, but still has advancements to be made in terms of lobbying activities.

The second research question of this thesis addressed possibilities and bottlenecks of the Swedish and European policy instruments regarding hydrogen-produced steel of Hybrit. To conclude the assessment of bottlenecks and possibilities in a Swedish context, approximately all the interviewees agreed upon that the Swedish state provides support in the developments of the H-DR steel production of Hybrit. Similar tendencies were revealed in some of the analyzed documents (e.g., Energimyndigheten, 2020). Investments can be identified both in terms of Hybrit-targeted research and experiments, as well as direct-funding into the developments of the company. This can be considered a noteworthy facilitator for hydrogen developments in regard to Hybrit. Nonetheless, the results also expose criticism. Significant concerns regarding regulatory processes of the timespan in permit-processing are a highlighted bottleneck. A relative consistency among the studied material can be found in this regard, but the different perspectives somewhat disintegrate in regard to which extent the permit-processing obstructs the developments. It seems that both the Hybrit actors and the governing authorities have reached a consensus in the recognition of this issue and therefore aim to accelerate these processes.

By concluding the assessment of the European policy instruments, the results point towards that several EU policies is endorsing the developments of Hybrit and the utilization of a hydrogen-produced steel in Europe. The EU hydrogen strategy, EU industrial strategy as well as the EU innovation fund was in this regard highlighted. However, the results advocated that the EU policy instruments conceivably have counteracting tendencies. Regarding the EU-regulations, it emerged that a particularly relevant and contested EU-regulation is the EU-ETS. Findings from the results point towards that the system might be obsolete in regards of industrial transitions, such as in the analyzed project in this thesis, Hybrit's H-DR production of steel. The dispute of whether actors that are producing steel through this process should in the system be grouped with other steel producers that operate with blast furnaces or not is crucial. However, the results further suggest that innovation-based policy frameworks might be a more adequate enhancement in these industrial transitions. An example of such an instrument that was brought up in the analysis can be found in the currently existing EU Innovation fund.

7.2 Discussion and suggestions for future research

While the Hybrit H-DR-technology faces relatively predictable risks, by analyzing the infrastructures, economics, and perhaps predominantly the innovation- and policy aspects, potential bottlenecks and possibilities were in this thesis identified and studied. The case of Hybrit is a novelty in the sense that Hybrit strives to become the world's first in profoundly transitioning from being among the most intense carbon-emitters to zero-emissions through technological innovation. By applying the theoretical framework of TIS was in this regard a fruitful theoretical approach to analyze Hybrit due to that the different analytical aspects were included. However, the author acknowledges a minor shortcoming of applying the theoretical framework; occasionally, the system functions could be fruitfully analyzed in interlinked without separating them. Although, this is by the author also considered a useful aspect in the sense that it enables the analysis to assess the different system functions in-depth.

The result of this dissertation exposes a need to map and assess the European hydrogen transition, such as Hybrit, from an interdisciplinary approach due to the complexity in this energy- and industrial shift. Even though the findings in this thesis might not be considered generalizable due to that conditions among H-DR steel producers might differ, it still highlights important discoveries. For example, this domain can, most humbled by the author, be exploited by European and Swedish policymakers to create accurate policy instruments and regulations that most likely are appropriate in other projects too. Another contribution is that this study can provide deeper knowledge of an energy source in a radical transition in Europe, both within the fields of research but also for the general public. This thesis revealed that Hybrit is characterized by a window of opportunities and obstacles that will probably have long-lasting effects on the Swedish and European steel industry in the future. Moreover, transitioning the steel industry to fossil-free productions might play a decisive role in whether Sweden and the EU will accomplish the climate neutrality goals. This is delightfully illustrated in the following quote:

”There is no future for grey steel in Europe.
But an incredible future for green steel and hydrogen.”
- Executive Vice President, Frans Timmermans, (European Commission, 2020d).

However, this study has some limitations which could potentially be overcome by future research. First, it is based on a single case study by examining Hybrit, which on the one hand facilitated to analyze in-depth, but comparisons with other similar European projects could bring interesting and different results. In line with this, extending the list of interviewees to also include representatives from Swedish and European policymaking and regulating would most certainly lead to interesting and comparative findings and perhaps contradictions.

Second, even though an interdisciplinary research approach was conducted and considered fruitful in order to analyze the case of hydrogen in the steel industry, Hybrit, which develops the H-DR technology, could require further research focus on the technological aspects in order to understand the innovation technology. This could for example elaborate further on measuring the storage- effectiveness, as well as solving crucial infrastructural obstacles. However, findings from this thesis demonstrates that multiple scholars within the engineering and technological fields are currently conducting research on Hybrit and one can expect interesting results in a near future.

Third, integrating hydrogen in the direct-reduction processes in the steel industry can be considered and was in this thesis treated to be in a premature and developing phase. This also applies to the recent establishment of EU Hydrogen-policies, such as the new implementation of the EU hydrogen strategy as well as the Hydrogen Alliance. Perhaps even more crucial is that the revision of the contested EU-ETS is still ongoing. Future research within this area could bring new and important insights that could further affect the future of policy pathways related to developing and integrating hydrogen in a variety of sectors.

References

Abe, J., Popoola, P., Ajenifuja, E., & Popoola, O., (2019). Hydrogen energy, economy and storage: Review and recommendation. *International Journal of Hydrogen Energy*. Vol. 44.

Abernathy, W. J., & Utterback, J. M. (1978). Patterns of Industrial Innovation. *Technology Review*, 80(7), pp. 40-47.

Håkansson, L., (2020, November 23). LKAB planerar Sveriges största industriinvestering någonsin. *Affärerinorr.* [Accessed]: https://affarerinorr.se/nyheter/2020/november/lkab-planerar-sveriges-stoersta-industriinvestering-naagonsin/ [Retrieved]: 2021-04-28

Andersson, J. & Grönkvist, S., (2019). Large-scale storage of hydrogen. *International journal of hydrogen energy*, 44(23), pp. 11901–11919.

Andreasen, K.P. & Sovacool, B.K., 2015. Hydrogen technological innovation systems in practice: comparing Danish and American approaches to fuel cell development. *Journal of cleaner production*, Vol. 94, pp.359–368.

ArcelorMittal, (2020). *ArcelorMittal Europe to produce 'green steel' starting in 2020*. [Accessed]: https://corporate.arcelormittal.com/media/news-articles/arcelormittal-europe-to-produce-green-steel-starting-in-2020 [Retrieved]: 2021-04-02

Arens, M.; Worrell, E.; Eichhammer, W.; Hasanbeigi, A.; Zhang, Q., (2017). Pathways to a low-carbon iron and steel industry in the medium-term—the case of Germany. *Journal of Clean Productions*, 163, pp. 84–98.

Bader, N., Bleischwitz, R., (2010). Policies for the transition towards a hydrogen economy: the EU case. *Energy policy*, 38(10), pp. 5388-5398.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A., (2005). Analyzing the dynamics and functionality of sectoral innovation systems- A manual. *Paper presented at the DRUID Tenth Anniversery Summer Conference Copenhagen, Denmark.*

Brinkmann, S., Kvale, S., (2015). *InterViews: Learning the Craft of Qualitative Research Interviewing*. ed., 3. London: SAGE Publications Inc.

Bryman, A., (2008). *Social research methods*. ed., 3. Oxford: Oxford University Press.

Capros, P., Zazias, G., Vita S., Evangelopoulou, S., (2019). Energy System Modelling of Carbon-Neutral Hydrogen as an Enabler of Sectoral Integration within a Decarbonization Pathway. *Energies*. Vol. 12(13).

Carlsson, B., & Stankiewicz, R., (1991). On the Nature, Function and Composition of Technological Systems. *Journal of Evolutionary Economics*, 1 (2), pp. 93-118.

Cooke, P., (1996). Regional innovation systems: an evolutionary approach. In: Baraczyk, Cooke, P., Heidenreich (Eds.), *Regional Innovation Systems*. London: University of London Press.

Denscombe, M., (2014). *The Good Research Guide: For Small-scale Research Projects*. Ed., 5. Maidenhead, Berkshire: McGraw-Hill Education.

Dodds, P.E., Staffell, I., Hawkes, D.A., Li, F., Grünewald, P., McDowall, W., Ekins, P., (2015). Hydrogen and fuel cell technologies for heating: A review, *International Journal of Hydrogen Energy*, Volume 40, Issue 5, pp. 2065-2083.

Edquist, C. and Johnson, B., (1997). Institutions and organizations in systems of innovation, in Edquist C. (ed.) *Systems of Innovation: Technologies, Institutions and Organizations*, pp. 41-63. London: Pinter.

Ehret, O. & Bonhoff, K., (2015). Hydrogen as a fuel and energy storage: Success factors for the German Energiewende. *International Journal of Hydrogen Energy*, 40(15), pp. 5526–5533.

Eitrawmaterials, (2021). *Partners.* [Accessed]: https://eitrawmaterials.eu/about-us/partners/ [Retrieved]: 2021-04-14

Ellerman, A.D., Marcantonini, C. & Zaklan, A., (2016). The European Union Emissions Trading System: Ten Years and Counting. *Review of Environmental Economics and Policy*, 10(1), pp. 89-107.
EN:former, (2019). How hydrogen can change the face of steel production as we know it. [Accessed]: https://www.en-former.com/en/hydrogen-revolution-steel-production/ [Retrieved]: 2021-01-18

Energimyndigheten, (2018). *Hybrit Pilot plant – pre-Feasibility Study*. [Accessed]: http://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?projectid=26948&fbclid=IwAR1naXR8zzt77E-TlzsFgW3LSMpVU4VsL3Dj69h_jsqlvXfkIo4pZnrIZww [Retrieved]: 2021-03-24

Energimyndigheten, (2020). *Energimyndigheten stöttar nästa steg för HYBRIT*. [Accessed]: https://www.energimyndigheten.se/nyhetsarkiv/2020/energimyndigheten-stottar-nasta-steg-for-hybrit/ [Retrieved]: 2021-02-04

Eurofer, (2021). *Members of the European Steel Association*. [Accessed]: https://www.eurofer.eu/about-steel/members/ [Retrieved]: 2021-04-07

European Commission, (2014). Questions and Answers on 2030 Framework on Climate and Energy, *European Commission Memo 14/40*. [Accessed]: https://ec.europa.eu/commission/presscorner/detail/en/MEMO_14_40 [Retrieved]: 2021-02-24

European Commission, (2020a). *State of the Union Address by President von der Leyen at the European Parliament Plenary*. September 16, 2020. [Accessed]: *https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_20_1655* [Retrieved]: 2021-01-28

European Commission, (2020b). A New Industrial Strategy for Europe. [Accessed]: https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en.pdf [Retrieved]: 2021-01-28

European Commission, (2020c). *A hydrogen strategy for a climate-neutral Europe.* [Accessed]: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf [Retrieved]: 2021-01-28

European Commission, (2020d). *Opening remarks by EVP Timmermans and Commissioner Simson at the press conference on the 2030 climate target plan*. Press corner. [Accessed]: https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_20_1692 [Retrieved]: 2021-04-06

European Commission, (2021a). *European Clean Hydrogen Alliance Members.* [Accessed]: *https://ec.europa.eu/docsroom/documents/45446* [Retrieved]: 2021-04-16

European Commission, (2021b). *Recovery plan for Europe.* [Accessed]: https://ec.europa.eu/info/strategy/recovery-plan-europe_en [Retrieved]: 2021-02-15

European Commission, (2021c). *2050 long-term strategy.* [Accessed]: https://ec.europa.eu/clima/policies/strategies/2050_en [Retrieved]: 2021-02-15

European Commission, (2021d). *EU Emission Trading System (EU ETS).* [Accessed]: https://ec.europa.eu/clima/policies/ets_en [Retrieved]: 2021-02-10

Fischedick, M.; Marzinkowski, J.; Winzer, P.; Weigel, M., (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Clean Productions*. Vol. 84, pp. 563–580.

Fossilfritt Sverige, (2021) *Strategi för fossilfri konkurrenskraft - Vätgas*. [Accessed]: https://fossilfrittsverige.se/wp-content/uploads/2021/01/Vatgasstrategi-for-fossilfri-konkurrenskraft-1.pdf [Retrieved]: 2021-02-24

Freeman, C., (1987). *Technology, Policy and Economic Performance. Lessons from Japan*. London: Pinter Publishers.

Friedmann, J., Fan, Z., Tang, K., (2019). Low-carbon heat solutions for heavy industry: sources, options and costs today. Columbia SIPA. *Center on global energy policy*.

Geels, F. W., (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation & Societal Transitions*, Vol. 1(1), pp. 24-40.

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S., (2017). The Socio-Technical Dynamics of Low-Carbon Transitions. *Joule*, 1(3), pp. 463–479.

Geels, F.W., (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, *Research Policy*, 31 (8–9), pp. 1257–1274.

Gielen, D. & Taibi, E. & Miranda, R., (2019). Hydrogen: A renewable energy perspective. [Accessed]:

https://www.researchgate.net/publication/339788120_Hydrogen_A_renewable_energy_perspective [Retrieved]: 2021-02-02

Godin B., (2006). The linear model of innovation: the historical construction of an analytical framework. *Science Technology & Human Values*: 31, pp. 639–67.

H2GreenSteel, (2021). *H2 Green Steel to build large-scale fossil-free steel plant in northern Sweden.* [Accessed]: https://www.h2greensteel.com/newsroom/h2greensteel [Retrieved]: 2021-03-29

Hardman, S., Shiu, E., Steinberger-Wilckens, R., (2015). Changing the fate of Fuel Cell Vehicles: Can lessons be learnt from Tesla Motors? *International Journal of Hydrogen Energy*, Vol. 40, (4), pp. 1625-1638. https://doi.org/10.1016/j.ijhydene.2014.11.149.

Hekkert, M.P. & Negro, S.O., (2009). Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technological forecasting & social change*, Vol. 76 (4), pp. 584–594.

Hekkert, M.P., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological forecasting & social change*, Vol. 74 (4), pp. 413–432.

Holappa, L., (2020). A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry. *Metals*. [Accessed]: https://www.mdpi.com/2075-4701/10/9/1117 [Retrieved]: 2021-02-07

Hybrit, (n.d.). *Summary of findings from HYBRIT Pre-Feasibility Study 2016–2017.* [Accessed]: https://www.hybritdevelopment.se/en/contact/media-bank/hybrit-broschure-engelska-2/ [Retrieved]: 2021-04-02

Hybrit, (2021a). *A fossil-free future.* [Accessed]: https://www.hybritdevelopment.se/en/a-fossil-free-future/ [Retrieved]: 2021-01-25

Hybrit, (2021b). *Pilot scale direct reduction with hydrogen.* [Accessed]: https://www.hybritdevelopment.se/en/a-fossil-free-development/direct-reduction-hydrogen-pilotscale/ [Retrieved]: 2021-03-16

Hybrit, (2021c). *SSAB, LKAB and Vattenfall building unique pilot project in Luleå for large-scale hydrogen storage investing a quarter of a billion Swedish kronor*. Hybritdevelopment, news. April 7, 2021. [Accessed]: https://www.hybritdevelopment.se/en/april-7-2021-hybrit-ssab-lkab-and-vattenfall-building-unique-pilot-project-in-lulea-for-large-scale-hydrogen-storage-investing-a-quarter-of-a-billion-swedish-kronor/ [Retrieved]: 2021-04-05

IEA (2019). *The Future of Hydrogen*. Paris: IEA. [Accessed]: https://www.iea.org/reports/the-future-of-hydrogen [Retrieved]: 2021-01-25

IRENA, (2018). Hydrogen from Renewable Power: Technology Outlook for the Energy Transition. *International Renewable Energy Agency*, September 2018).

Jacobsson, S. & Bergek, A., (2011). Innovation system analyses and sustainability transitions: Contributions and suggestions for research. *Environmental innovation and societal transitions*, Vol. 1 (1), pp. 41–57.

Jacobsson, S., & Bergek, A. (2004). Transforming the energy sector: The evolution of technological systems in renewable energy technology. *Industrial and Corporate Change*, 13(5), pp. 815-849.

Jernkontoret, (2021), Vision 2050. *Hybrit – Toward fossil-free steel production.* [Accessed]: https://www.jernkontoret.se/en/vision-2050/carbon-dioxide-free-steel-production/ [Retrieved]: 2021-03-26

Joltreau, E. & Sommerfeld, K., (2019). Why does emissions trading under the EU Emissions Trading System (ETS) not affect firms' competitiveness? Empirical findings from the literature. *Climate Policy,* 19(4), pp. 453-471.

Jordan, A. & Tosun, J. (2013). Policy implementation, Jordan, A. and Adelle C. (eds.), *Environmental Policy in the EU: Actors, Institutions and Processes*, ed., 3 London: Routledge, pp. 247-266.

Klugman, S., Stripple, H., Lönnqvist, T., Sandberg. E., Krook-Riekkola, A., (2019). *A climate neutral Swedish industry - An inventory of technologies*. IVL. No. B 2367. December 2019.

[Accessed]:https://www.ivl.se/download/18.4447c37f16fa0999d192f8/1579514247120/B2367.pdf [Retrieved]: 2021-03-30

LeadIt, (2021). Leadership group for industry transition. *Green Steel tracker*. [Accessed]: https://www.industrytransition.org/green-steel-tracker/ [Retrieved]: 2021-03-26

Lobbyfacts.eu, (2021). https://lobbyfacts.eu/

LKAB, (2021). *Research collaborations.* [Accessed]: https://www.lkab.com/en/about-lkab/technological-and-process-development/research-collaborations/ [Retrieved]: 2021-04-14

LTU, (2020). *Forskar med Hybrit-tekniken i fokus.* [Accessed]: https://www.ltu.se/research/subjects/Forskar-med-Hybrit-tekniken-i-fokus-1.202143 [Retrieved]: 2021-04-02

Maisonnier, G. & Perrin, J., (2007). Deliverable 2.1 and 2.1a "European Hydrogen Infrastructure Atlas" and "Industrial Excess Hydrogen Analysis". *PART II: Industrial surplus hydrogen and markets and production*. [Accessed]: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=2CE6E8E0372BA3DFB981E8F506C7E6AA?doi=10.1.1.477.3069&rep=rep1&type=pdf [Retrieved]: 2021-02-02

Malerba, F., (2004). *Sectoral Systems of Innovation, Concepts, Issues and Analyses of Six Major Sectors in Europe*. Cambridge: Cambridge University Press.

Malerba, F., (2006). Innovation and the evolution of industries. *Journal of Evolutionary Economics*, 16, pp. 3-23.

Markard, J., (2020). The life cycle of technological innovation systems, *Technological Forecasting and Social Change*, Vol. 153. [Accessed]: https://doi.org/10.1016/j.techfore.2018.07.045. [Retrieved]: 2021-02-26

Markard, J., Truffer, B., (2008). Technological innovation systems and the multi-level perspective: towards an integrated framework. *Research Policy* 37, pp. 596–615.

Markusson, N., Ishii, A., Stephens, J.C., (2011). The Social and Political Complexities of Learning in Carbon Capture and Storage Demonstration Projects', *Global Environmental Change*, 21, No. 2, pp. 293–302.

Marshall, C., & Rossman, G.B., (2016). *Designing qualitative research.* Thousands Oaks, Calif: Saga Publications.

Madsen, A.N., Dannemand, P.A., (2010). Innovative regions and industrial clusters in hydrogen and fuel cell technology, *Energy Policy*, Vol. 38, (10), pp. 5372-5381.

Mohd Arifin, S. R., (2018). Ethical Considerations in Qualitative Study. *International Journal of Care Scholars*,1(2), 30–33. [Accessed]: https://journals.iium.edu.my/ijcs/index.php/ijcs/article/view/82 [Retrieved]: 2021-03-03

Niaz, S., Manzoor, T., Pandith, H.A., (2015). Hydrogen storage: Materials, methods and perspectives, *Renewable and Sustainable Energy Reviews*, Vol. 50, pp. 457-469.

Otto, A., Robinius, M., Grube, T., Schiebahn, S. (2017). 'Power-to-steel: Reducing CO2 through the integration of renewable energy and hydrogen into the German steel industry', *Energies* 10, No. 4, pp. 451.

Rosengren, L., (2018 september 19). Sverige avstår EU-samarbete om vätgas. *Dagens industri*. [Accessed]: https://www.di.se/hallbart-naringsliv/sverige-avstar-eu-samarbete-om-vatgas/ [Retrieved]: 2021-01-26

Rotmans, J., Kemp, R., Van Asselt, M., (2001). More evolution than revolution: transition management in public policy, *Foresight* Vol. 3 (1), pp. 15–31.

Sahaym, U., Norton, M.G., (2008). Advances in the application of nanotechnology in enabling a 'hydrogen economy'. *Journal Mater Science* 43, pp. 5395–5429. https://doi.org/10.1007/s10853-008-2749-0

Santos, D., Sequeira, C., Figueiredo, J., (2013). Hydrogen production by alkaline water electrolysis. *Quimica Nova*, 36(8), pp. 1176-1193. https://doi.org/10.1590/S0100-40422013000800017

SCB, (2018). *The Swedish occupational register with statistics*. [Accessed]: https://www.scb.se/en/finding-statistics/statistics-by-subject-area/labour-market [Retrieved]: 2021-03-29

Schumpeter, J. A., (1943). The process of creative destruction. *Capitalism, Socialism and Democracy*. London: George Allen & Unwin.

Shmelev, S. E., & Shmeleva, I. A., (2012). In Shmelev S. & Shmeleva I. (Eds.), Introduction. *Sustainability Analysis: An Interdisciplinary Approach*. London: Palgrave Macmillan UK., pp., 1-8.

Silverman, D., (2014). *Interpreting qualitative data*. London: SAGE

Smith, A. & Raven, R., (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Research policy*, Vol. 41(6), pp. 1025–1036.

Smith, A. Stirling, A., Berkhout, F., (2005). The governance of sustainable socio-technical transitions, *Research Policy*, Vol. 34 (10), pp. 1491–1510.

SSAB, (2020). *SSAB presentation at 34th meeting of the European Gas Regulatory Forum.* [Accessed]: https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/presentations/02.02_mf34_presentation-hybrit-pei.pdf [Retrieved]: 2021-04-16

SSF, (2019). *Smidigare, smartare snällare - Nya och förbättrade material förändrar och formar*. SSF-rapport nr 33, 2019. ISBN 91-89206-75-74. [Accessed]: https://strategiska.se/app/uploads/ssf-materialrapport-1.pdf [Retrieved]: 2021-04-14

Suurs, R.A.A., Hekkert, M.P. & Smits, R.E.H.M., (2009). Understanding the build-up of a technological innovation system around hydrogen and fuel cell technologies. *International journal of hydrogen energy*, 34(24), pp.9639–9654.

Thyssenkrupp, (2019). *Hydrogen instead of coal. Thyssenkrupp Steel launches pioneering project for climate friendly steel production at its Duisburg site*. [Accessed]: https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/hydrogen-instead-of-coal.html [Retrieved]: 2021-04-02

Ustolin, F., Paltrinieri, N., Berto, F., (2020). Loss of integrity of hydrogen technologies: A critical review, *International Journal of Hydrogen Energy*, Vol.45 (43), pp. 23809-23840.

Van Bree, B., Verbong, G. P. J., & Kramer, G. J. (2010). A multi-level perspective on the introduction of hydrogen and battery-electric vehicles. *Technological Forecasting & Social Change*, 77(4), pp. 529–540.

Van den Hoed, R., Vergragt, P. J., (2004). Institutional change in the automotive industry: or how fuel cell technology is being institutionalised. *Greener Management International*, Vol. 47, pp. 45.

Vattenfall, (2021). *HYBRIT: SSAB, LKAB and Vattenfall to begin industrialization of future fossil-free steelmaking by establishing the world's first production plant for fossil-free sponge iron in Gällivare*. Press release 24/3-2021. [Accessed]: https://group.vattenfall.com/press-and-media/pressreleases/2021/hybrit-ssab-lkab-and-vattenfall-to-begin-industrialization-of-future-fossil-free-steelmaking-by-establishing-the-worlds-first-production-plant-for-fossil-free-sponge-iron-in-gallivare [Retrieved]: 2021-03-16

Verde, S.F. et al., (2019). Free allocation rules in the EU emissions trading system: what does the empirical literature show? *Climate policy*¸19(4), pp. 439-452.
Veziroglu, T.N., (2012). Conversion to Hydrogen Economy, *Energy Procedia*, Vol. 29, pp. 654-656.

Voelstalpine AG, (2020). *H2FUTURE: World's largest "green" hydrogen pilot facility successfully commences operation*. [Accessed]: https://www.voestalpine.com/group/en/media/press-releases/2019-11-11-h2future-worlds-largest-green-hydrogen-pilot-facility-successfully-commences-operation/ [Retrieved]: 2021-04-02

Widera, B., (2019). Renewable hydrogen as an energy storage solution. E3S Web of Conferences, E3S Web of Conferences, Vol.116.

Wieczorek, A.J., Hekkert, M.P., (2012). Systemic instruments for systemic innovation problems: a framework for policy makers and innovation scholar. *Science & Public Policy*, Vol. 39, pp. 74–87.

Wilberforce, T., El-Hassan, Z., Khatib, F.N., Al Makky, A., Baroutaji, A., Carton, G. J., Olabi, A.G., (2017). Developments of electric cars and fuel cell hydrogen electric cars, *International Journal of Hydrogen Energy*, Vol. 42, (40), pp. 25695-25734.

Woolthuis, R. K., Lankhuizen, M., Gilsing, V., (2005). A system failure framework for innovation policy design, *Technovation*, Vol. 25, (6), pp. 609-619.

Yin, R.K., (2014). *Case study research: design and methods* (5 ed). Thousands Oaks, CA: Sage.

Appendix

Appendix 1 – Interview guide – *Hydrogen utilization in Hybrit – Company representatives*

The design of the interview questions was on the one hand based the operationalization of the theoretical concept of ‘Technological Innovation Systems’ regarding Hybrit to gather material to analyze the first research question, including the sub-question, of this thesis. Hence it was divided into two sections consisted of the ‘structural elements’ and the seven ‘functions’. It was furthermore based on national and EU policy instruments of relevance to Hybrit, to gather material for the second research question as well as the sub-question.

Background

- **Inform the interviewee regarding the thesis aim and research questions**
- **Inform regarding the structure of the thesis**
- **Asking for consent**

Structural elements

<u>Actors</u>

- *What other actors, such as companies, NGOs, research institutes etc. are engaged in developing and using hydrogen technologies?*
- *Are you participating in any professional network activities?*
- *Which financial actors are potential partners for you; investors, banks etc.?*

Objective: Map all the relevant actors that are developing and using hydrogen as a source of energy, as well as identifying relevant financial actors in order to grasp potential partnerships.

<u>Institutions</u>

- *Which institutions affects the process of your developing and usage of hydrogen technologies? Both formally in terms of regulations and legislation, but also informal in terms of setting the norms.*

- *Can they contribute to creating growth for your green steel?*

Objective: Identify institutions involved in the development of the hydrogen technology for the company, as well as mapping policies and regulations that affect the development of hydrogen technologies.

Infrastructures

- *How do you perceive the infrastructural conditions in using hydrogen energy? Given the geographical region that you are producing your steel with the hydrogen energy in for example, do you see any infrastructural potentials and bottlenecks?*

Objective: Map the infrastructural conditions, including potential bottlenecks of the usage of hydrogen technologies in the projects, enabling analysis for regional aspects as well.

System functions

How do you innovate? What innovations have you applied to increase your sale? How do you document and share the learning from an innovation in the hydrogen field with other actors? What kind of formats are these learnings shared?

Objective: Map system functions of F1-*entrepreneurial activities*, F2 - *knowledge development* and F3 - *knowledge diffusion*.

Are you participating in research and development projects with your technology? Are you planning on hosting events regarding your hydrogen technology?

Objective: Map system functions of F2 – *knowledge development and* F3 – *knowledge diffusion*.

Has there been an increasing demand in terms of the green steel? How is Hybrit doing in relation to its competitors? Are there any niche markets regarding development and usage of green steel? Are you funded by public and or private investments? Has there been heavy *investments into Hybrit? Does there exist any national and EU- public targets and incentives for the use of green hydrogen? Are there any subsidies in place?*

Objective: Mapping the system functions of F4 – *Guidance of the Search,* F5 – *Market formation* and F6 – *Resource mobilization.*

Do you have any examples of successfully achieved targets of lobbying? Do you experience resistance of your development of green hydrogen by other actors, such as in the industry? Do you receive support?

Objective: Map the system functions of F7 – *Support from advocacy coalitions.*

Which possibilities and bottlenecks do you perceive from Swedish and European policy instruments? What policy actions are needed to foster the development of hydrogen and green steel?

Objective: Identify and assess Swedish and European policies, strategies and regulations in regards to hydrogen and green steel developments.

Appendix 2 – Interview guide – *Hydrogen utilization in Hybrit – Researchers*

The design of the interview questions was on the one hand based the operationalization of the theoretical concept of 'Technological Innovation Systems' regarding Hybrit to gather material to analyze the first research question, including the sub-question, of this thesis. Hence it was divided into two sections consisted of the 'structural elements' and the seven 'functions'. It was furthermore based on national and EU policy instruments of relevance to Hybrit, to gather material for the second research question as well as the sub-question.

Background

- **Inform the interviewee regarding the thesis aim and research questions**
- **Inform regarding the structure of the thesis**
- **Asking for consent**

Structural elements

Actors

- *What other actors, such as companies, NGOs, research institutes etc. are engaged in developing and using hydrogen technologies?*
- *Does Hybrit participating in any professional network activities?*
- *Which financial actors are potential partners for Hybrit; investors, banks etc.?*

Objective: Map all the relevant actors that are developing and using hydrogen as a source of energy, as well as identifying relevant financial actors in order to grasp potential partnerships.

Institutions

- *Which institutions affects the process of Hybrit's developing and usage of hydrogen technologies? Both formally in terms of regulations and legislation, but also informal in terms of setting the norms.*
- *Can they contribute to creating growth for Hybrit's green steel?*

Objective: Identify institutions involved in the development of the hydrogen technology for the company, as well as mapping policies and regulations that affect the development of hydrogen technologies.

<u>*Infrastructures*</u>

- *How do you perceive the infrastructural conditions in using hydrogen energy? Given the geographical region that Hybrit are producing their steel with the hydrogen energy in for example, do you see any infrastructural potentials and bottlenecks?*

Objective: Map the infrastructural conditions of the usage of hydrogen technologies in the projects, enabling analysis for regional aspects as well. Furthermore, the question aims to identify other technological parts that are crucial in the process of using hydrogen energy.

System functions

How does Hybrit innovate? What innovations have Hybrit applied to increase their sale? Is research being conducted within the field? Are there an increase of Hybrit, hydrogen and green steel research? Any knowledge-sharing activities?

Objective: Map system functions of F1-*entrepreneurial activities*, F2 - *knowledge development* and F3 - *knowledge diffusion*.

Are you participating in Hybrit-related research and developments?

Objective: Map system functions of F2 – *knowledge development and* F3 – *knowledge diffusion*.

Has there been an increasing demand in terms of the green steel? How is Hybrit doing in relation to its competitors? Are there any niche markets regarding development and usage of green steel? Is Hybrit public financed? Has there been heavy investments into Hybrit? Does there exist any national and EU- public targets and incentives for the use of green hydrogen? Are there any subsidies in place?

Objective: Mapping the system functions of F4 – *Guidance of the Search*, F5 – *Market formation* and F6 – *Resource mobilization.*

Do you have any examples of successfully achieved targets of Hybrit-lobbying?

Objective: Map the system functions of F7 – *Support from advocacy coalitions.*

Which possibilities and bottlenecks do you perceive from Swedish and European policy instruments? What policy actions are needed to foster the development of hydrogen and green steel?

Objective: Identify and assess Swedish and European policies, strategies and regulations in regards to hydrogen and green steel developments.