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Exploring sustainability transitions in the iron and steel industry:
A case study from Sweden

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1. Introduction

The iron and steel industry accounts for one third of global industrial CO2 emissions (IEA, 2015a), putting transformative pressures on the industry to shift towards more sustainable modes of production. Steel is widely used in every country and almost all industries, with a growing trend around the globe. There is a common agreement that the industry needs to improve energy efficiency, recycle more and switch to low-carbon production processes (IEA, 2015a; Rynikiewicz, 2008; Sridhar and Li, 2016; WSA, 2016). However, this transition requires a lengthy and complex process at which radical innovations are required to reduce emissions and, thus, facilitate the sustainability transitions (Wesseling et al., 2016).

The research on sustainability transitions (Markard et al., 2012) has for the past few decades studied how socio-technical systems transform into more sustainable modes of production and consumption. Several research streams, such as multi-level perspective (e.g., Geels, 2006), strategic niche management (e.g., Nill and Kemp, 2009), transitions management (e.g., Rotmans and Loorbach, 2009) and technological innovation systems (e.g., Bergek et al., 2008) have been developed and have enriched our understanding how these transitions could be guided, managed and governed. Although the field of sustainability transitions is growing fast (Chappin and Ligtvoet, 2014; Geels, 2013; Markard et al., 2012), the applicability of the concepts in empirical settings is still a challenge. For instance, a socio-technical system of a technology is influenced not only by other technologies and several industrial sectors but also by the geographical and political context structures (Bergek et al., 2015; Binz et al., 2014; Hansen and Coenen, 2015; Hekkert et al., 2007). This presents a challenge not only on how to measure these influences but also to define the empirical boundaries of the focal cases studied. Thus, it is valuable to bring context-specific contributions in well-defined context structures, i.e., technology, sector, geography and policy. However, the iron and steel industry has received little attention by few studies in the field (e.g., Rynikiewicz, 2008; Wesseling et al., 2016). The contextual focus of the literature has been limited and mostly dominated by the studies on a few industrial sectors, i.e., energy, transportation, water, sanitation and food (Markard et al., 2012).

In this study, we focus on the iron and steel industry in Sweden – a rarely studied context in the field of sustainability transitions. The country is the host of SSAB AB, known to be a highly promising steel company to lead the sustainability transitions of the industry worldwide (Fryer et al., 2016), as well as the
LKAB, which is the EU’s largest iron ore producer with 78% market share (LKAB, 2016). The SSAB and LKAB, together with the Swedish policy makers and Vattenfall – as electricity supplier –, committed themselves making Sweden to be the country place to reach zero-carbon steel production (PC, 2016). However, despite the ambitious goals, a few decades might be needed. For example, much is expected from the radical innovations, such as the hydrogen based reduction technology (HYBRIT, 2016), which are still at the experimental stage.

The iron and steel industry is often perceived to be slow and resistant towards large scale transitions. It has an oligopolistic production structure with high entry barriers at which technological innovations are risky and expensive (Rynikiewicz, 2008; Wesseling et al., 2016). This makes any possible transition a complex and lengthy process. For instance, open-hearth furnace had been the dominant way to produce steel for almost 50 years until the revolutionary basic oxygen furnace was commercially available in the 1950s. Basic oxygen furnace, developed by Austrians, caused not only a large scale transition towards a more productive and profitable modes of production but also a leadership shift from the United States of America to the Japan (Lee and Ki, 2015). Today, the iron and steel industry is on the verge of another technological transition. This time, the goal is not only about productivity and profitability but also environmental sustainability, often emanating from the climate change mitigation policies to reduce C02 emissions (IEA, 2015a; PC, 2016; WSA, 2016). That is why the sustainability transitions in the iron and steel industry is worth exploring.

In this study, we raise the following research question: **What are the possible pathways for sustainability transitions in the iron and steel industry in Sweden?** The case of Sweden is highly relevant for the field of sustainability transitions because there is a collective guidance and governance towards carbon free steel production (PR, 2017). As a method, we choose an explorative case study approach (Yin, 2003). We combine primary qualitative data, such as semi structured interviews, with secondary data, such as such as reports, papers and press materials. This data is used to discuss the possible transition pathways for the industry. The rest of this paper is structured as follows. Section 2 gives an overview of the theoretical concepts as well as the state of the art of literature. Section 3 presents the methodological details, especially about the process of data collection and analysis. Section 4 explains the findings and discuss the key contributions of this paper. Lastly, section 5 derives conclusions and presents the implications for theory, industry and policy.

2. Conceptual perspective

Our analysis of the iron and steel industry in Sweden has its roots in the recent approaches of sustainability transition studies such as technological innovation systems (TIS) (Carlsson and Stankiewicz, 1991) and multi-level perspective (MLP) (Geels, 2002). Grounded in the seminal works of Dahmen (1989), Dosi (1982), and Nelson and Winter (1982), the TIS and MLP approaches jointly provide a better understanding of radical innovation processes and socio technical transformations (Markard and Truffer, 2008). Although the TIS and MLP approaches have different perspectives of transitions, they share a number of comparable concepts. In the sustainability transitions literature, there are several recent attempts to better integrate of
these two approaches (e.g., Markard and Truffer, 2008; Meelen and Farla, 2013; Walrave and Raven, 2016). Figure 1 presents the interactions between some core concepts from TIS and MLP approaches (such as niches, regimes, landscape and contextual structures). A focal TIS is considered to interact with one or more socio-technical regimes (Markard and Truffer, 2008) and contextual structures such as other TISs, relevant sectors, geographical contextual structures and political context (Bergek et al., 2015).

![Figure 1. Interactions of the conceptual elements in technological innovation system and multi-level perspective](image)

A sociotechnical regime is a semi-coherent set of rules embedded in a complex of technological artefacts, infrastructures, regulations and social groups (Geels, 2002). In this token, the notion of sociotechnical regime extends the concept of technological regime (Nelson and Winter, 1982) by including the alignment activities from the sociotechnical groups. Geels and Schot (2007) points out that a sociotechnical regime can change in long-term, triggered by destabilizing pressures from the landscape (an exogenous environment such as macro-economics, deep cultural patterns and macro-political developments) or by upcoming technological niches (micro-level formations where radical novelties emerge).

Contextual structures encompass four dimensions: technology, sector, geography and policy. These contextual structures go beyond the boundaries of a focal TIS and, thus, elaborate on the influence of factors which are not necessarily embedded inside the boundaries. In a recent study, Bergek et al. (2015) highlights the importance of these four dimensions. First, a focal TIS is influenced by other technological developments beyond the technology in focus. Second, there is a mutual interaction between a focal TIS and several sectors. Third, regional development and geographical dimension affect the focal TIS. Fourth, a wide political context is important and influential on the development of a TIS.

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1 Adaptation of Fig. 4 in Markard and Truffer (2008). We replaced the “complementary innovation system” with “contextual structures” and refined the graphical representation.
Sustainability transitions are long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption (Markard et al., 2012). The process depends on the structural elements such as actors, institutions, interactions, infrastructure (Section 2.1). In the case of well-developed systemic functions (Section 2.2), innovations are generated and widely diffused. Thus, depending on the niches and regimes, different kinds of transition pathways (Section 2.3) can emerge and facilitate sustainability transitions.

2.1. Structural elements

The structural elements of a focal TIS consist of a set of actors, institutions, interactions and a specific infrastructure. Wieczorek (2014), as well as Wieczorek and Hekkert (2012), delineates these structural elements into several sub-categories, offering a systematic typology (see Table 1). Actors encompass civil society, companies, knowledge institutes, non-governmental organizations as well as the other parties such as legal, financial and consulting agencies. Institutions include both formal and informal aspects (see Hodgson, 1988; North, 1990). For instance, hard institutions are formal, written and often consciously created institutions while soft institutions refer to informal and implicit rules of the game which are often evolved spontaneously (Negro et al., 2012). Infrastructures encompasses physical, knowledge and financial dimensions. The physical infrastructure can be deduced to artefacts, instruments, machines, roads, buildings, telecommunication networks, bridges, harbours etc. The knowledge infrastructure encompasses knowledge, expertise, know-how and as well as the strategic information. Financial infrastructure can be in the form of subsidies, financial programs or grants. Interactions are the relationships or links between the actors, both at individual and network levels.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-categories</th>
</tr>
</thead>
</table>
| Components: Actors| - Civil society  
                   - Companies: start-ups, SMEs, large firms, multinational companies  
                   - Knowledge institutes: universities, technology institutes, research centres, schools  
                   - Government  
                   - NGOs  
                   - Other parties: legal organisations, financial organisations/banks, intermediaries, knowledge brokers, consultants |
| Institutions      | - Hard: rules, laws, regulations, instructions  
                   - Soft: customs, common habits, routines, established practices, traditions, ways of conduct, norms, expectations |
| Infrastructure     | - Physical: artefacts, instruments, machines, roads, buildings, networks, bridges, harbours  
                   - Knowledge: knowledge, expertise, know-how, strategic information  
                   - Financial: subsidies, fin programs, grants etc. |
| Interactions      | - At level of networks  
                   - At level of individual contacts |
2.2. Systemic functions

Systemic functions are the key processes which need to run well for the system to perform smoothly. If the systemic functions are well-developed for a focal innovation, it is assumed that the focal innovations have the potential to be widely diffused. The “functional perspective” gained its momentum following two influential papers (Bergerk et al., 2008; Hekkert et al., 2007) that proposed a set of functions to assess the performance of an innovation system. Since then, several researchers have used the functional perspective, especially for analysing the a technology’s innovation dynamics (e.g., Hellsmark et al., 2016; Stephan et al., 2017).

Systemic functions are composed of knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation, market formation, legitimation, resource mobilization, and the development of positive externalities (Bergerk et al., 2008; Hekkert et al., 2007). For a technological innovation system to avoid failures, its functions must be sustained by its structural elements such as actors, institutions, interactions and a specific infrastructure (Negro et al., 2008). Table 2 presents a summary of these functions as well as their explanations compiled by Wieczorek et al. (2013).

Table 2. Systemic functions of a technological innovation system (Wieczorek et al., 2013)

<table>
<thead>
<tr>
<th>Category</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimentation by entrepreneurs</td>
<td>Entrepreneurs are essential for a well-functioning innovation system. Their role is to turn the potential of new knowledge, networks, and markets into concrete actions to generate — and take advantage of — new business opportunities.</td>
</tr>
<tr>
<td>Knowledge development</td>
<td>Mechanisms of learning are at the heart of any innovation process, where knowledge is a fundamental resource. Therefore, knowledge development is a crucial part of innovation systems.</td>
</tr>
<tr>
<td>Knowledge exchange</td>
<td>To learn relevant knowledge needs to be exchanged between actors in the system.</td>
</tr>
<tr>
<td>Guidance of the search</td>
<td>This system function refers to those processes that lead to a clear development goal for the new technology based on technological expectations, articulated user demand and societal discourse. This process enables selection, which guides the distribution of resources.</td>
</tr>
<tr>
<td>Market formation</td>
<td>This process refers to the creation of markets for the new technology. In early phases of developments these can be small niche markets but later a larger market is needed to facilitate cost reduction and incentives for entrepreneurs to move in.</td>
</tr>
<tr>
<td>Resource mobilization</td>
<td>The financial, human and physical resources are necessary basic inputs for all activities in the innovation system. Without these resources, other processes are hampered.</td>
</tr>
<tr>
<td>Creation of legitimacy</td>
<td>Innovation is by definition uncertain. A certain level of legitimacy is required for actors to commit to the new technology with investment, adoption decisions, etc.</td>
</tr>
</tbody>
</table>

2.3. Transition pathways

Transition pathways are different than a “business as usual” situation. Depending on the timing and nature of multi-level interactions, one of the four different kinds of transitions (i.e., transformation,
reconfiguration, technological substitution, and de-alignment and re-alignment) might occur (Geels and Schot, 2007). Based on the recent works of Geels et al. (2016) and Walrave and Raven (2016), Table 3 presents a typology of transition pathways and its relation to technological innovation systems.

Table 3. A typology of transition pathways and its relation to technological innovation systems (TIS)

<table>
<thead>
<tr>
<th>Timing</th>
<th>Pathway</th>
<th>Institutions</th>
<th>Dynamics</th>
</tr>
</thead>
</table>
| Landscape pressures occur when a TIS has not yet developed substantially | Transformation | Limited change | - Regime actors try to keep the existing regime through innovative efforts  
- Incremental improvement in existing technologies |
| | | Broader change | - Regime actors try to substantially re-orientate  
- Reorientation in existing technologies/business models  
- Incorporation of symbiotic niche-innovations |
| De-alignment and re-alignment | Broader change | | - Regime actors search for alternative regimes  
- Institutions are disrupted by shocks  
- Decline of old technologies  
- Space for several competing innovations  
- Incumbents may collapse |
| Landscape pressures occur when a TIS has developed substantially | Technological substitution | Limited change | - Regime actors try to keep the existing regime through innovative efforts  
- New entrants may overthrow the incumbents |
| | | Broader change | - New entrants may replace the incumbents  
- New institutions drive the niche innovations |
| Reconfiguration | From limited to broader change | | - Regime actors search for alternative regimes  
- New combinations of new and existing technologies  
- New alliances between incumbents and new entrants |

A *transformation pathway* often occurs when landscape pressures are developed while a technological innovation system is not mature and regime resistance is large (Walrave and Raven, 2016). For this pathway, regime-actors respond to landscape pressures either by increasing their innovative efforts on the dominant socio-technical design (Walrave and Raven, 2016) or by reorientation to radically new technologies, new beliefs and new business models (Geels et al., 2016). Geels et al. (2016) argues that the former respond of the incumbent actors occurs when new institutions are layered on top of existing arrangements without affecting their core logic while the latter respond occurs in times of a more significant change institution. A *de-alignment and re-alignment pathway* often occurs when landscape pressures are developed, while a technological innovation system is not mature and regime resistance is relatively small (Walrave and Raven, 2016). For this pathway, decline of old technologies usually open space for several competing innovations and new entrants while the incumbents are under danger of collapse (Geels et al., 2016). A *technological*
A substitution pathway often occurs when landscape pressures are developed while a technological innovation system is mature and regime resistance is large (Walrave and Raven, 2016). As Geels et al. (2016) argues, this pathway might occur under either limited or broader institutional change, often creating opportunity for new entrants to overthrow the incumbents. A reconfiguration pathway can occur when landscape pressures are developed while a technological innovation system is mature and regime resistance is relatively small (Walrave and Raven, 2016). This pathway often leads to new combinations of new and existing technologies as well as new alliances between incumbents and new entrants (Geels et al., 2016).

3. Methodology

Prior studies on sustainability transitions have used different methods and data sources to answer their research questions. On the one hand, some studies have conducted case studies and relied mostly on interviews, observations, public reports and statistics (e.g., Hellsmark et al., 2016). On the other hand, some others have used event history analysis (e.g., Reichardt et al., 2016), social network analysis (Binz et al., 2014), system dynamics model (e.g., Walrave and Raven, 2016), bibliometric analysis (e.g., Chappin and Ligtvoet, 2014) and patent analysis (e.g., Stephan et al., 2017), combining different kinds of qualitative and quantitative data sources. In order to answer our research question of “What are the possible pathways for sustainability transitions in the iron and steel industry in Sweden?”, we use an explorative case study approach (Yin, 2003). As data sources, we combine the primary qualitative data, such as semi-structured interviews, with the secondary data, such as reports, papers and press materials (see Table 4).

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
<th>Reference / information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reports and papers</td>
<td>Industrial company</td>
<td>(LKAB, 2016; SSAB, 2016; Vattenfall, 2016a)</td>
</tr>
<tr>
<td></td>
<td>Governmental</td>
<td>(Regeringskansliet, 2013; STIC, 2016)</td>
</tr>
<tr>
<td></td>
<td>Associations including NGOs</td>
<td>(Fryer et al., 2016; IEA, 2015a, 2015b; Jernkontoret, 2017a, 2017b, 2017c)</td>
</tr>
<tr>
<td></td>
<td>Knowledge institutes</td>
<td>(Andersson et al., 2017; Brolin et al., 2017; CCC, 2012; Johansson, 2014; Lee and Ki, 2015; Morfeldt et al., 2015a, 2015b; Quader et al., 2016; Ryden, 1998; Rynikiewicz, 2008; Sridhar and Li, 2016; Wesseling et al., 2016)</td>
</tr>
<tr>
<td>Press material</td>
<td>Conference/ release</td>
<td>(PC, 2016; PR, 2017)</td>
</tr>
<tr>
<td></td>
<td>News</td>
<td>(Reuters, 2017; Thorpe, 2016; Vattenfall, 2016b)</td>
</tr>
<tr>
<td>Semi structured interviews</td>
<td>Industrial company</td>
<td>A consultant, Enetjärn Natur (32min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A consultant, Material Economics AB (12min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A principal R&amp;D Expert, LKAB (27min)</td>
</tr>
<tr>
<td></td>
<td>Governmental</td>
<td>A politician from Örobro (11min)</td>
</tr>
<tr>
<td></td>
<td>Associations including NGOs</td>
<td>The energy and environment director of Jernkontoret (the Swedish Steel Producers' Association) (2h20min)</td>
</tr>
<tr>
<td></td>
<td>Knowledge institutes</td>
<td>2 Researchers, Luleå tekniska universitet (41min and 18min)</td>
</tr>
</tbody>
</table>

Table 4. Data sources
Reports and papers include documents from industrial companies, governmental agencies, associations including NGOs and knowledge institutes (such as universities). These reports and papers covers topics from specific to general such as (specifically) on iron and steel industry in Sweden and (generally) mining and metal industry around the globe. Press materials encompass press conferences (as a report or as a recording), press releases, news as well as broadcasted interviews and talks. Semi-structured interviews were conducted with representatives from industry, government, associations and knowledge institutes. These interviews took place in two parts at different times in different locations. The first part was conducted in Lulea during an industrial conference “Bergforskdagarna 2016” – which served as a forum of collaboration and knowledge-sharing for the actors involved in Swedish mining and metal industry. The second part was conducted in Stockholm with face-to-face meetings with the representatives of diverse actors. The content of interview questions varied between two parts as well. The first part focused (generally) on the mining and metal industry and the questions were related to social networks, main actors and individual relationships. The second part focused (specifically) on the iron and steel industry and the questions were related to the technology, institutions and systemic functions. Overall, the durations of the interviews varied between 10min to 2h20min.

4. Sustainability Transitions in the Swedish Iron and Steel Industry

The iron and steel industry is one of the oldest industries of the modern world. Thus, its contextual structures in terms of technology, sector, geography and policy (Bergerk et al., 2015) is highly influenced by the centuries of sociotechnical change. In Sweden, the industry’s history goes back to the 12th century when steelmaking was immature and wrought iron was the most common form of malleable iron. This era of wrought iron began with the production of so called Osmond iron (which was made by melting the pig iron in a hearth), continued with bar iron (a more workable form of forging iron) and overall had lasted for over five centuries (see Table 5). In the 14th century, annual production of Osmond iron reached 2000 tones, half of which was exported (Jernkontoret, 2017a). During the 16th century, the iron industry witnessed a transition from Osmond iron to bar iron – driven by both the supply and demand sides. This process was eased with the technical knowledge of foreign forgers who were recruited to work in Sweden. From 1640s to the 1740s, Sweden’s exports of bar iron were more than tripled and reached to 40000 tonnes per year (Jernkontoret, 2017a). The strong growth of bar iron exports during the 18th century had increased the competition for charcoal and pig iron in Sweden. At the same time, the competition from Russian bar iron had increased. During 1746-47, two major steps were taken. First, Jernkontoret (the Swedish Steel Producers’ Association) was established. Second, a limitation on forge production was introduced in Riksdag (the Swedish Parliament), regulating the market for next 90 years.
Table 5. The milestones of “wrought iron” era in Sweden

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400s</td>
<td>Annual production of 2000 tonnes of “Osmond iron”</td>
</tr>
<tr>
<td>1500s</td>
<td>Transition towards “bar iron” production</td>
</tr>
<tr>
<td>1604</td>
<td>Export prohibition of “Osmond iron”</td>
</tr>
<tr>
<td>1640s</td>
<td>Annual exports of 11000 tonnes of “bar iron”</td>
</tr>
<tr>
<td>1690s</td>
<td>Annual exports of 27000 tonnes of “bar iron”</td>
</tr>
<tr>
<td>1740s</td>
<td>Annual exports of 40000 tonnes of “bar iron”</td>
</tr>
<tr>
<td>1746-47</td>
<td>Forging limitation created in Riksdag (the Swedish Parliament)</td>
</tr>
<tr>
<td>1747</td>
<td>Establishment of Jernkontoret (the Swedish Steel Producers’ Association)</td>
</tr>
<tr>
<td>1830-40s</td>
<td>Forging limitation abolished in Riksdag (the Swedish Parliament)</td>
</tr>
<tr>
<td>1845</td>
<td>Ekman furnace developed and rolling mills set up</td>
</tr>
<tr>
<td>1860s</td>
<td>Annual production of 40000 tonnes of “bar iron”</td>
</tr>
<tr>
<td>1870-80s</td>
<td>Transitions from smaller to larger mills</td>
</tr>
</tbody>
</table>

Until the middle of 19th century, the bar irons in Sweden were produced through a charcoal-fired finery in a finery forge. However, this method was not any more competitive in compare to cheaper British iron production. In 1845, a mill owner, Gustav Ekman visited Britain and observed the puddling processes in Cumbria (then Lancashire). On his return to Sweden, he adapted the Lancashire furnace to Swedish conditions. The adaption of the Lancashire process, a puddling process, gradually caused production units to grow in size in Sweden. However, to make a profit, the Lancashire forges required a larger production volume than charcoal-fired finery. With the final abolishment of forging limitation in Riksdag, the new method of puddling rapidly replaced the charcoal-fired finery in Sweden. The change took place most rapidly in the hometown of Gustav Ekman, Värmland (Ryden, 1998). Overall, this transition also affected the size and number of mills. Albeit an increase of production and new furnaces in Sweden, the smaller mills were shut down while larger miles flourished.

The so-called “steel age” started to take off during 1850s, took larger market share (than iron) on 1900s and has kept its importance until today. This transition from wrought iron to steel took decades, driven by factors related to the technological breakthroughs and industrial dynamics. Several technological breakthroughs have enabled the industry to produce cheaper and good-quality steel. First, Bessemer method (after 1856) made economic production of steel possible. Second, Siemens-Martin open hearth process (after 1865) enabled producers melt and refine large amounts of scrap iron and steel. Third, electric arc furnace (after 1900s) basic oxygen furnaces (after 1950s) increased efficiency and labour productivity. These technological transitions have not happened in isolation. They were accelerated by the advances in other sectors and other technologies (Dahmén, 1989; Mokyr, 1998). For instance, during 1900-1974 in Sweden, electricity enabled the emergence of a development block for mining and metal producing industry (including iron and steel), machinery and railways (Enflo and Kander, 2008).

Today, crude steel production in Sweden is around 4.6 million tonnes (0.02% of world production), two third of which comes from the iron ore based steel production (see Table 6). In 2016, steel was exported
from Sweden to 140 countries around the globe and accounted about 3.4 per cent of Sweden’s total exports (Jernkontoret, 2017c).

<table>
<thead>
<tr>
<th>Production type</th>
<th>Primary material</th>
<th>Furnace</th>
<th>No. of plants</th>
<th>National production Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron ore based</td>
<td>Pig iron</td>
<td>Basic Oxygen</td>
<td>2</td>
<td>2/3</td>
</tr>
<tr>
<td>Scrap based</td>
<td>Steel scrap</td>
<td>Electric arc</td>
<td>10</td>
<td>1/3</td>
</tr>
</tbody>
</table>

Iron ore based steel production requires a different process compared to the scrap based steel production. Globally, the most common process for iron ore-based steel production is the route of blast furnace and basic oxygen furnace, but there is also the less common route of direct reduction and electric arc furnace route (Johansson, 2014). This is also the case in Sweden (Jernkontoret, 2017c). Overall, iron ore based steel production results in high CO2 emissions (Morfeldt et al., 2015a). The route of blast furnace is often fed with iron ore (in form of pellets or sinter), limestone and coke (which acts as a reducing agent). Often, pulverised coal, natural gas, or oil is injected to blast furnace in order to reduce the need for coke and improve the energy efficiency (Johansson, 2014). The route of direct reduction is also fed with iron ore, but different from blast furnace, the reducing agent is either coal or a gas. In scrap based steel production, there is no need for iron ore. Steel is produced by steel scraps which are melted in electric arc furnaces. Although the scrap based production is theoretically close to zero CO2 emissions, scrap availability is limited to meet the future demand (Morfeldt et al., 2015a).

There are several incremental and radical technologies with a potential to reduce the CO2 emissions in iron and steel making, as widely discussed in the literature (e.g., Morfeldt et al., 2015a; Quader et al., 2016; Sridhar and Li, 2016; Wesseling et al., 2016). Most of these technologies have been under investigation for decades, receiving policy support through CO2 programs in the USA (e.g. AISI – technology roadmap programme), South Korea (e.g., POSCO CO2 breakthrough program), Japan (COURSE 50) and the EU (ULCOS – Ultra low carbon dioxide steelmaking) – which Sweden also took active part (Quader et al., 2016).

Recently, building upon the years of experimentation with different methods and technologies, Sweden has signalled that the country aims to be the first to reach zero CO2 emissions in iron and steel industry. On the 4th of April in 2016 in a press conference, the main Swedish steel producer SSAB, the state owned energy company Vattenfall and the Swedish iron ore extractor LKAB announced the start of a long term vision of collaboration (e.g., through joint research) to fully develop a hydrogen based direct reduction process to replace coal or natural gas (PC, 2016). Less than a year after, on the 27th of February 2017, the initiative received new support from the Swedish Energy Agency, a funding of SEK 102 million (approximately 10 million €) over the next four years, in addition to previous SEK 7.7 million (approximately 700 thousands €) which was granted for the feasibility study (PR, 2017). This long term vision on a single technology (hydrogen based direct reduction) was also acknowledged in the interviews:
“The main emissions, 90 per cent of the emissions in the Swedish steel industry, are from the blast furnaces of SSAB at the two sites […] What SSAB has now decided is that they focus on the hydrogen based reduction within HYBRIT project. Together with LKAB and Vattenfall, they started this project.”

“Besides [hydrogen based reduction], there are not really other possibilities except carbon capture and storage […] By 2045-50, [we expect] the production will be mostly ore based. So, you need a technology to implement at the large scale. What we think now is [that] the best possibility is the hydrogen based reduction technology. Because the other possibility [carbon capture and storage] is an end of pipe solution and it’s no really handling the problem. [With carbon capture and storage], you still have the carbon dioxide.”

“The investments [needed for transition to hydrogen based reduction] is extremely high. Someone has to pay […] Also, we need a lot of electricity and we have the issue of infrastructure on how to store and supply hydrogen”

Overall, the Swedish government, SSAB, LKAB and Vattenfall have the joint goal of driving the sustainability transitions from current iron and steel production methods (iron ore and scrap based) to the carbon free iron and steel production. The technological differences between these current methods and carbon free production (with hydrogen based direct reduction) is presented in Figure 2. With the carbon free production by using hydrogen instead of coal as a reducing agent, the emissions are deduced to water instead of carbon dioxide.

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**Figure 2. The current methods (in 2017) and the long term goal (for 2045) in Swedish iron and steel industry**

### 4.1. Structural elements

In Sweden, iron and steel are generally produced at thirteen plants (see Figure 3). Ten of these are scrap-based steel production plants, two of them are iron ore based (also called integrated iron and steel production), and only one is ore based direct reduction plant (Jernkontoret, 2017b) (see Table 2). The

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2 Own elaboration.
The geographical concentration of iron and steel industry has been traditionally critical, especially for communication and transportation purposes (Jernkontoret, 2017a).

Figure 3. Iron and steel production plants in Sweden

Table 7. Production types of the plants in Sweden

<table>
<thead>
<tr>
<th>Location</th>
<th>Company</th>
<th>Production type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luleå</td>
<td>SSAB Europe</td>
<td>Iron ore based</td>
</tr>
<tr>
<td>Hofors</td>
<td>Ovaka Sweden AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Sandviken</td>
<td>AB Sandvik Materials Technology</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Södertors</td>
<td>Erasteel Kloster AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Smedjebäcken</td>
<td>Ovako Bar AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Avesta</td>
<td>Outokumpu Stainless AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Hagfors</td>
<td>Uddeholms AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Hallstahammar</td>
<td>AB Sandvik Heating Technology</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Torshälla</td>
<td>Carpenter Powder Products AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Björneborg</td>
<td>Scana Steel Björneborg AB</td>
<td>Scrap based</td>
</tr>
<tr>
<td>Oxelösund</td>
<td>SSAB Special Steels</td>
<td>Iron ore</td>
</tr>
<tr>
<td>Halmstad</td>
<td>Höganäs AB</td>
<td>Scrap based steel</td>
</tr>
<tr>
<td>Höganäs</td>
<td>Höganäs AB</td>
<td>Sponge iron</td>
</tr>
</tbody>
</table>

In addition to production plants, the Swedish iron and steel industry involves the interactions with other actors: civil society (e.g., Sami people, the indigenous Finno-Ugric people in northern Sweden), equipment producers (e.g., ABB, Sandvik and Atlas Copco), universities (e.g., Luleå University of Technology, LTU) and regional and national policymakers. However, several interviewees pointed out that there is a lack of small and medium sized enterprises (SMEs) in the industry:

“Iron and steel industry is very different to something like “solar” – which is perhaps a new market and a lot of new actors. Iron and steel industry is composed of large companies. It is not many actors and players there.”

“We (Sweden) have very advanced mining companies like LKAB and Boliden. During the years, companies like ABB and Atlas Copco have developed, supplying to the mining companies. Together, we have developed machines...
and equipment that they are now selling and using at the international level. I think this combination is very strong."

We [Swedish mining and metal producing sector] have a quite good diversity with manufacturers, suppliers of equipment, the mining companies itself, universities, research institutes etc. What you miss a little bit is what maybe you call SMEs, smaller companies. The ones in the network now are really global companies like ABB and Atlas Copco, really international companies.”.

The interactions and relationships in the industry is well established, roots of which goes back to decades of collaboration and cooperation. For instance, Jernkontoret (the Swedish Steel Producers’ Association) has been serving as a platform to safeguard industry’s interests and strengthen the networks since 1747. Today, Jernkontoret, with representatives from the industry, focuses on cooperation for research, education, standardisation, energy, environment, product ecology, services, metallurgy and communications related topics. As one of the interviews also emphasizes, while there is a high competition in the international market, there is a lack of competition at the national level. The difference of competition between national and international levels influence the ties in the network:

“For a long time, it has been large-scale cooperation between the companies to develop new processes technologies. The reason that makes it possible is that there is not really competition between the companies in Sweden. Because they work on different products and markets. For the cooperation to develop new processes technologies, we have networks and groups to discuss new technologies and develop new projects”.

“We [LKAB] are acting on national, European and International levels. We are involved in activities together with Australian and Canadian research institutes […] It is important for us [LKAB] to really look and see what is going on with our competitors in the business. They are not in Sweden or in the EU. They are, for example, in Australia, South America or Canada so on. We have to follow the development of technology in those parts of the world […] We [LKAB] have a position within the company that has a role of lobbying to Swedish Government. We also had one person based in Brussels, working at the European Level […] We [LKAB] are more and less the “iron ore business” in Europe. We are the largest iron ore company in Europe. In that respect, we represent the whole iron ore business in Europe.”

4.2. Systemic functions

In the Swedish iron and steel industry, entrepreneurial activity and experimentation of new technologies are led by large incumbent companies (e.g., LKAB and SSAB) and research institutes. This might come as a surprise as (it is sometimes assumed that) the entrepreneurial activities are mostly driven by small and medium sized companies in most industries. However, from a technological innovation system perspective, this is an illustrative example of a well-known type of “experimentation by entrepreneurs” at which incumbent companies diversify their business strategies to take advantage of new developments (Hekkert et al., 2007, p. 421). This is also captured in one of the interviews:
“In steel industry, we are talking about large companies. It is not really the same [with other industries]. It may be the supplier who have an idea to come in. But the entrepreneurial activity [in the form of a start-up or an individual], I do not really see it in this kind of industries.”

Overall, knowledge development (e.g., on specific technologies) are led by several actors (such as companies, associations and institutions), through established networks (e.g., Jernkontoret) at which new ideas, visions and practices are exchanged. In the case of hydrogen based induction technology, the support from SSAB, LKAB, Vattenfall and the policymakers is relatively high. This is in line with Sweden’s commitment to completely phase out greenhouse gas emissions by 2045. However, hydrogen based induction technology is still at its experimental stage. Although the pre-feasibility studies have been successful, the technology needs to be tested at demonstration plants from 2025 to 2035 in Sweden (PC, 2016) before it becomes commercially available. Also, the transition is expected to be expensive:

“It is important to know that the companies drive the technology [hydrogen based reduction]. They are really ambitious. They are putting a lot of resources in it. The societal discussion and the political support helps as well. They [the companies] cannot do it [transition] without financial help [from the government]. This [transition to hydrogen based reduction] is extremely expensive.”

In summary, the case of hydrogen based reduction technology demonstrates a combination of strengths and weaknesses in the systemic functions. The knowledge exchange and guidance for research are significantly high. The activities for knowledge development, resource mobilization and legitimacy function moderately well. However, the market formation is still at its very early stage (see Table 8 for an overview). Interestingly, the diversity of different levels of functionality is also similar to what is observed in another industry, i.e., bio-refinery, in Sweden (see Hellsmark et al., 2016).
Table 8. The assessment of the functions of technological innovation systems in iron and steel industry

<table>
<thead>
<tr>
<th>Category</th>
<th>Observation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimentation by entrepreneurs</td>
<td>Moderate</td>
<td>Experimentation is led by large incumbent companies and research institutes (not by new entrants)</td>
</tr>
<tr>
<td>Knowledge development</td>
<td>Moderate</td>
<td>There are several actors (such as companies, associations and institutions) leading the knowledge development.</td>
</tr>
<tr>
<td>Knowledge exchange</td>
<td>High</td>
<td>Established networks creates sufficient exchange of knowledge</td>
</tr>
<tr>
<td>Guidance of the search</td>
<td>High</td>
<td>The actors and institutes clearly set the goals (e.g., zero carbon by 2045) and policymakers support new technologies (e.g., hydrogen based reduction technology)</td>
</tr>
<tr>
<td>Market formation</td>
<td>Low</td>
<td>The market for new technologies (such as hydrogen based reduction technology) are not yet started to develop</td>
</tr>
<tr>
<td>Resource mobilization</td>
<td>Moderate</td>
<td>The governmental agencies supports the new technologies through funds</td>
</tr>
<tr>
<td>Creation of legitimacy</td>
<td>Moderate</td>
<td>There is not much resistance against new technologies. But, the activities of providing legitimacy (for new technologies) target the long term</td>
</tr>
</tbody>
</table>

4.3. Transition pathways

In the Swedish iron and steel industry, there has been recent landscape pressures on regime actors (such as SSAB) to move towards more sustainable modes of production. These pressures mostly related to the fact that SSAB is one of the largest CO2 emitters in Sweden:

“SSAB is a small company globally. But, they want to be at the forefront and their products are very specialized. They have these high strength steel which are also doing something for decreasing emissions when use it as a product. But still, they are the largest source of emissions in Sweden and of course it creates a pressure.”

“The possibility for SSAB to reduce its emissions today is quiet low. You cannot do much about it. The blast furnaces of SSAB is the among the most efficient worldwide, but still we have the emissions. Sometimes, it is difficult [for others] to understand because all they see these big emissions “

Although there are several incremental and radical technologies with a potential to reduce the emissions in iron and steel making (see e.g., Morfeldt et al., 2015a; Quader et al., 2016; Sridhar and Li, 2016; Wesseling et al., 2016), the Swedish actors and institutions strongly believe that hydrogen based reduction technology is the best option to invest on. The reasoning behind this belief is threefold. First, hydrogen based reduction technology has the potential to overthrow the blast furnaces – which are the main sources of emissions. Second, the scrap-based solutions do not have the potential to supply the steel on their own (because there is a limited amount of scrap available). Third, natural gas based solutions comes along with some shortcomings, e.g., their limited capacity to reduce emissions in the steelmaking and the political complexity of accessing the natural gas. These three reasons were also mentioned in the interviews:
“We need to able to use iron ore to produce steel [in the future]. Because steel products have long life time, so we have a lot of steel in the society. But, the scrap is not enough to be able to supply the steel we [will] need.”

“The rest of our [iron and steel industry’s] emissions is connected to the use of fuels [e.g., heating purposes and melting]. For example, we have a stepwise transition from oil to liquid natural gas. If we want to get rid of such emissions [from the use of fuels], we have to have the biogas. But it depends on the possibility to get biogas. That is a political issue and it is complicated […] Everybody wants the biogas and there is competition”

“In Sweden, except one pipeline on the West Coast, there have never been any natural gas. Because there has been a political resistance to natural gas. This resistance is based on the assumption that you should not built something which puts you into fossil infrastructure”

Overall, the potential transitions towards hydrogen based reduction in the industry is highly relevant to the transition pathways topology (Geels and Schot, 2007; Geels et al., 2016) and its links to innovation system (Walrave and Raven, 2016). First, the technological innovation system for the hydrogen based reduction is not yet developed. Although some of the systemic functions (such as the knowledge exchange and guidance for research) perform well, the market is not formed at all. Second, incumbent actors (e.g., SSAB and LKAB) reorient themselves towards a new radical technology, hydrogen based reduction which, if successful, will lead to a technical substitution of blast furnaces in long-term. Third, new alliances (e.g., with Vattenfall) are formed to potentially reconfigure system components and their relations (e.g., connecting hydrogen based reduction with electric arc furnace). Thus, using the reformulated terminology of Geels et al. (2016), the case demonstrates characteristics from both transformation (with reorientation towards a new technology) and reconfiguration.

5. Concluding remarks

In this study, we addressed the research question of: What are the possible pathways for sustainability transitions in the iron and steel industry in Sweden? To do so, we used a case study approach (Yin, 2003), combining primary qualitative data, such as semi-structured interviews, with the secondary data, such as reports, papers and press materials. As a theoretical approach, this study is grounded in both technological innovation systems (TIS) approach (Carlsson and Stankiewicz, 1991) and multi-level perspective (MLP) (Geels, 2002), with a special focus to contextual structures, structural elements, systemic functions and transition pathways (Bergek et al., 2015; Geels and Schot, 2007; Geels et al., 2016; Wieczorek, 2014; Wieczorek and Hekkert, 2012; Wieczorek et al., 2013).

In the iron and steel industry in Sweden, the actors (such as the companies, governmental agencies and knowledge institutions) strongly collaborate to drive the transitions towards hydrogen based reduction technology. Hydrogen based reduction technology is perceived as the ultimate goal in the industry since there is no other technology available to able to reduce the CO2 emissions at the same level. In line with the governmental goal of carbon free production by 2045, this transition is expected to fully happen over the next three decades - which would be perceived as lengthy elsewhere. However, for an industry over six
hundred years old, few decades are not a long time rather it is Lagom - a traditional Swedish word to express the meaning of “neither too much nor too little” (Lexikon, 2017).

The case of the iron and steel industry in Sweden is highly interesting for the ongoing research in sustainability transitions studies, especially for literature on technological innovation systems (Bergek et al., 2015; Hekkert et al., 2007; Walrave and Raven, 2016) and transitions pathways (Geels and Schot, 2007; Geels et al., 2016). On the one hand, the case of hydrogen based reduction technology demonstrates a combination of strengths and weaknesses of the functions in the innovation system. For instance, the knowledge exchange and guidance for research are significantly high, while the market formation is still at its very early stage. On the other hand, incumbent actors try to reorient themselves towards a new radical technology (i.e., hydrogen based reduction technology) which may lead to both a technical substitution and a reconfiguration of the system components. Thus, this case (initially) shows some characteristics from two distinct transition pathways: transformation and reconfiguration. Although the shifts between the pathways are recently discussed in the literature (Geels et al., 2016), an overlap between them is a relatively new phenomenon which needs further investigation.

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