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Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study

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ABSTRACT

The Swedish steel industry stands before a potential transition to drastically lower its CO_2 emissions using direct hydrogen reduction instead of continuing with coke-based blast furnaces. Previous studies have identified hydrogen direct reduction as a promising option. We build upon earlier efforts by performing a technological innovation system study to systematically examine the barriers to a transition to hydrogen direct reduction and by providing deepened quantitative empirics to support the analysis. We also add extended paper and patent analysis methodology which is particularly useful for identifying actors and their interactions in a technological system. We conclude that while the innovation system is currently focused on such a transition, notable barriers remain, particularly in coordination of the surrounding technical infrastructure and the issue of maintaining legitimacy for such a transition in the likely event that policies to address cost pressures will be required to support this development.

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1. Introduction

The steel industry is responsible for approximately 7% of global CO_2 emissions (Philibert, 2017) and is thus a critical component of addressing the challenge of climate change. On the 15th of June, 2017, Sweden passed a climate law, referred to as 'the climate law' in this paper, requiring national carbon neutrality by 2045 (MoE, 2018). In 2016, Sweden's steel industry emitted 6.06 Mt CO_2-eq, or 11% of a national total of 53 Mt (SCB, 2018a), with 4.8 Mt coming from the remaining blast furnaces at the SSAB (earlier Svenskt Stål AB) sites at Oxelösund and Luleå (Naturvårdsverket, 2018).

The Swedish steel industry has long been among the most carbon emission efficient in the world (Sandberg et al., 2001) and thus the higher than average share of national CO_2 emissions represents a comparatively large industry. CO_2 emissions per ton of steel have dropped by approximately 10% in Sweden and globally since 2000 (IEA, 2015), but there is a fundamental limitation to further reductions from the blast furnace process arising from the fact that coke (made from imported fossil coal) does not only fuel the process but also acts as the reduction agent for reducing iron ore to iron and hereby causes so called "process emissions". Literature describes numerous potential routes to further lowering the carbon intensity of primary steel production (e.g. Ribbenhed et al., 2008), but only three offer the theoretical possibility of nearly eliminating CO_2 (Nilsson et al., 2017): direct reduction with hydrogen (described in e.g. SSAB et al., 2018) which we abbreviate as H-DR to differentiate from natural gas direct reduction, Carbon capture and storage (CCS) of the furnace off-gases which has been studied in detail on many aspects, and the somewhat more theoretical electrowinning of iron from an aqueous oxide solution (Yuan et al., 2009; Licht and Wang, 2010). Previous studies on the steel sector in Sweden have identified and highlighted direct reduction as one possible promising transition pathway (Åhman et al., 2012; Karakaya et al., 2018).

The techno-economic aspects of hydrogen direct reduction have been studied (Eketorp, 1989; Birat, 2013; SSAB et al., 2018; Vogl et al., 2018). CCS has been investigated and experiments with the Ultra-Low CO2 Steel (ULCOS) program at Swedish iron ore producer LKAB's test reactor indicate that furnace modifications with CCS could result in a 50% reduction of CO_2 emissions (Quader et al., 2015) at full system costs estimated from 56€/ton and up (Leeson et al., 2017). The time frame and technological readiness of CCS

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are particularly daunting in the specific case of Oxelösund due to the required industrial redesign and very early state of reservoir investigations for potential storage sites (Johansson and Söderström, 2011; Mazzetti et al., 2014; Åhman et al., 2018a together give a good overview of the challenges).

In summary, direct reduction appears to be the only option at a sufficient technology readiness level (TRL) if Sweden is to reach its 2045 target and retain its primary steel production capability. We therefore choose to study H-DR in depth.

At present, there is a unique opportunity in Sweden as the heart of the energy supply system at the Oxelösund site, the coke oven responsible for the bulk of national steel CO_2 emissions, needs to be replaced after running in continuous operation since the late 1950s. The coke oven is the heart of the energy supply system at an integrated blast furnace steel mill as it not only transforms imported coal to coke but also provides the rest of the integrated steel mill with energy from the off-gases. The decision on if and with what to replace the coke oven and the blast furnace will determine the CO_2 emissions of the steel sector in Sweden for several decades.

This study departs from the assertion that Swedish climate targets are all but impossible without either H-DR or losing the industry and aims to narrow the general topic of possible transition pathways that exists in literature into a more focused question: "*What, if any, systemic barriers exist to implementing direct reduction in the steel industry in Sweden?*". More specifically, the aim is to evaluate the conditions and potential barriers for the possibility of choosing H-DR for the iron ore reduction step in Sweden, and to suggest areas where policy or system building activities may play a role in ensuring that it is a viable choice.

The aim of this paper is to complement the existing techno-economic studies of H-DR with an innovation systems approach, and to complement the one extant TIS example of the subject (Karakaya et al., 2018) with enhanced empirical assessment for the indicators used to assess functionality. In addition to general extension of analysis in the TIS indicators, we use insights from patenting and scientific publication to add considerable depth to defining the system and identifying actors and their interactions. In so doing, we show that patent and paper analysis can play an important role in delineating the system as opposed to merely providing quantitative indicators.

2. Method

The object of study is the iron ore/steel *innovation system* in Sweden and its capacity to adopt a new core technology for iron ore reduction. Iron ore reduction is a crucial step in primary steel production with connections to all downstream processes and direct reduction with hydrogen will represent a new and imperfectly understood metallurgy. An assessment with such a general scope demands a systemic approach to the industry and its value chain. Most generally, assessing the determinants and constraints of such a technological choice must move beyond prices and rationality of single firms (Jacobsson and Johnson, 2000) to account for networks of actors and an institutional environment for the development and diffusion of new technologies (Carlsson and Stankiewicz, 1991). We thus adopt the technological innovation system (TIS) approach as a framework.

2.1. Aims and scope

The introduction of H-DR represents a substitution of one part of the value chain but will have potential knock-on impacts in a large variety of downstream and related systems, which we identify from assessing the technology itself. This paper thus incorporates the Swedish electricity system and the emerging electrolysis technical system as well as the steel production innovation system.

Although the study is based on the Swedish steel TIS, various factors cannot be separated from the global "landscape" (Geels and Schot, 2007) i.e. macro factors long outside the capacity of system actors to affect. Overcapacity, climate goals, and the exported steel product mix all have a role, and the emerging technical clusters in direct reduction and electrolysis are not based in Sweden. The scope of the study should thus not be construed as strictly Swedish.

2.2. Technological innovation system methodology

To assess how the TIS functions with respect to adoption of H-DR, we adopt a functional approach modelled on the work of Bergek et al. (2008, 2015) and Hekkert et al. (2011). In this approach, the systemic processes related to diffusion and adoption of technologies are conceptualized as "functions", related sets of activities that contribute to the path-dependent evolution of the system. Each function has a number of indicators proposed in various literature sources, which are collected and summarized in Table 1, adapted from Kushnir (2012). Alternative framings of these functions exist (Hekkert et al., 2007, 2011; Suurs, 2009) but mostly represent small alterations to how things are categorized or labelled and do not represent an alternative or orthogonal framework (see Table 2).

The initial steps of a TIS analysis follow those of generic technology systems studies, e.g. defining the technology and identifying its constituents. Our process of analysis is adapted from Bergek et al. (2008) and follows the following steps, with the 5th step suggested by Hekkert et al. (2011).

1. Defining the technology and system boundaries	Section 3
2. Identifying the components of the system (Actors, artefacts, institutions) and stage of development	Section 4
3. Evaluating functions based on evidence from indicators	Section 5
4. Identifying blocking and inducement mechanisms	Section 5
5. Discuss potential policy mechanisms to address barriers	Section 5,6,7

After defining the technological system and identifying its components we systematically assess the proposed indicators from Table 1 and discuss their implications for the adoption of H-DR. In particular, we note that the mode of innovation that would apply to a hypothetical H-DR adoption represents a 'technology push', i.e. an attempt to adopt a specific new technology (Suurs, 2009) in a mature industry, and thus the knowledge development, resource mobilization, legitimacy and direction of search functions receive extended attention in our analysis.

With regard to knowledge development, there are only a small number of R&D projects and hydrogen reduction technology is not widespread enough yet to produce enough data for learning curves. Additionally, the entities involved in knowledge development outside the main firms in the system are unknown *ex-ante*. We thus include a significant effort to an extended analysis of scientific papers and patents in order to strengthen our insight into the system. This analysis aims to satisfy the following objectives and extend the possibilities for evaluating the TIS: To identify the usual indicators i.e. how many patents, what part of the technical system is patented and who is doing the patenting. Second, we aim to extract the collaboration graph, e.g. which entities collaborate over the study period. Finally, we wish to identify extant and emerging clusters in the related technologies of direct reduction and electrolysis.

Table 1
Potential indicators for TIS functions. Originally derived from Bergek et al. (2008).

Function	Information potentially suitable for constructing indicators
Knowledge development	• patent and paper analysis (citations, volume, orientation, trajectories) • number, size and orientation of R&D and academic projects • learning curves
Influence on direction of search	• visions, expectations and beliefs in growth potential • actors' perceptions of the relevance of different types and sources of knowledge. • actors' assessments of the present and future technological opportunities • regulations and policy • articulation of demand from leading customers • technical bottlenecks • crises in current business.
Legitimation	• the level of the legitimacy of the TIS • alignment between the TIS, current legislation and the value base in industry and society • how legitimacy influences demand, legislation and firm behavior • what (or who) influences legitimacy, and how
Resource mobilization	• changing volume of capital, including seed and venture capital • changing volume and quality of human resources (e.g. number of university degrees) • changes in complementary assets
Entrepreneurial experimentation	• number of new entrants, including diversifying established firms • number of different types of applications • the breadth of technologies used and the character of the complementary technologies employed
Developing external economies	• emergence of pooled labor markets • emergence of specialized intermediate goods and service providers • information flows and knowledge spill-overs
Market formation	• many possible indicators; customer groups, application types, sales, etc.

Table 2
Top publishers of scientific documents in the steel domain in Sweden. Count based on inclusion in a paper rather than first authorship.

Top Firms	Publications	Top Academic Institutions	Publications
Sandviken AB	328	KTH	1476
Höganäs	177	Chalmers University of Technology	971
Swerea KIMAB	169	Luleå University of Technology	643
Outokumpu Stainless AB	87	Uppsala University	437
Uddeholms AB	74	Linköping University	364
ESAB AB	62	Lund University	243
Swerea MEFOS	35	Swedish Institute for Metals Research	179
SSAB Tunnplåt AB	35	Dalarna University	108

3. Technical description of the system and hypothetical changes

While there are many steel producers at various places in the value chain in Sweden, the actual technical change to H-DR encompasses a smaller set of facilities, the primary steel production facilities at Oxelösund and Luleå and the mining and pelletizing at LKAB (Luossavaara-Kiirunavaara Aktiebolag). SSAB also owns a site in Raahe, Finland which is part of the HYBRIT consortium, but which is excluded here because of the completely different physical and governance infrastructure there. A detailed history of the Swedish industry in a TIS format can be found in Karakaya et al. (2018).

Fig. 1 shows a simplified diagram of the currently existing facilities at Oxelösund, and the prospective change. The blast furnace and basic oxygen vessel is slated to be replaced with an electric arc furnace (EAF) capable of running on scrap steel (secondary steel making) regardless of other developments (SSAB, 2018). The major change for H-DR would be the replacement of the coke oven with direct reduction infrastructure to supply sponge iron (DRI) to the electric arc furnace.

The major physical changes are the substitution of the coke oven with direct reduction infrastructure, including electrolytic hydrogen production at the site where iron ore is reduced. Adding one ore more electric arc furnaces requires a substantial grid connection which is already being planned for the Oxelösund site. Adding electrolysis capacity also requires major grid connections. The replacement of the coke oven with hydrogen also raises the question of replacing the use of coke-oven gases today used for casting/rolling with another energy. Biomethane or electricity are main fossil free contenders in the long term and in the short term, the site could rely on imported liquefied natural gas (LNG).

The change implied for the local electricity system is a large one. The estimated increase is ~3200 kWh electricity/ton capacity difference of which 2600 kWh are required for hydrogen production (SSAB et al., 2018; Vogl et al., 2018). At 1.5 Mt steel per year, this implies 4.8 TWh/y in additional electricity demand for this single facility. Total figures for all Swedish sites are estimated at closer to 17 TWh/y (SSAB et al., 2018). This can be compared to a total national consumption of 140 TWh in 2016, a year in which 12 TWh were net-exported from Sweden (Energimyndigheten, 2017). In gross terms, the network already possesses the generation capacity for such a change, but sufficiency is not the issue, rather local capacity, which is in turn decided by transmission infrastructure. There may be additional constraints, particularly with regard to reactive and balancing efforts (Larsen et al., 2016; SSAB et al., 2018), if the system is tied with the wider network. Most importantly, new transmission lines will be required, necessitating the immediate selection of a site and commencement of work and planning. The Transmission System Operator (TSO) and possibly also the Distribution System Operator (DSO) need to be involved.

The time frame for these changes is given by the replacement schedule for the key facilities and the projected timeline of the HYBRIT project and is shown in Fig. 2. The time frame for key events

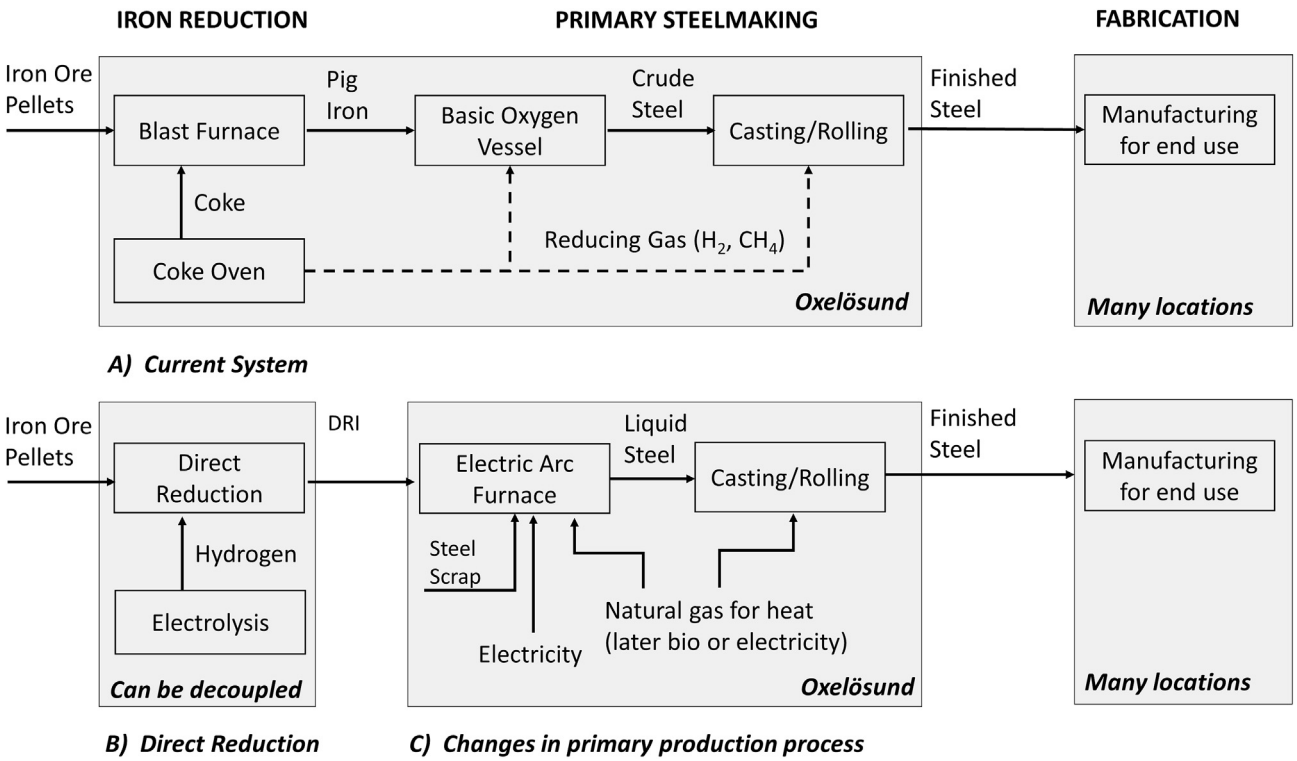

Fig. 1. A) Current technical system, B) Direct reduction infrastructure, and C) planned changes to the current system.

in the transition encompasses the present until approximately 2040, slated as the projected full operation of a direct hydrogen reduction facility (see Fig. 2).

Clearly visible from Fig. 2 is that the incremental additions to supply the electricity demanded by the prospective transition, as well as transmission infrastructure must be added well in advance

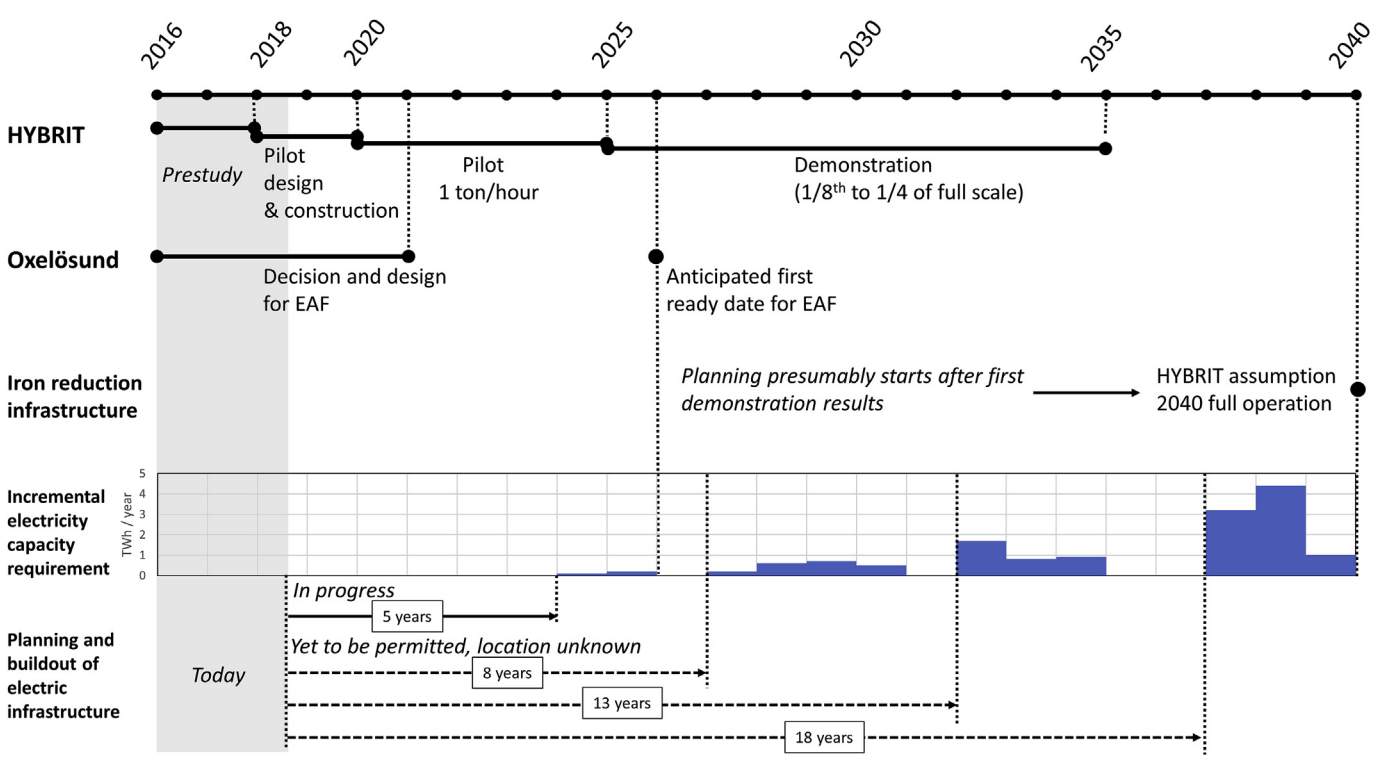

Fig. 2. Timeline for decisions in related facilities and projects. Incremental electricity capacity requirement adapted from HYBRIT prestudy and reflects both the conversion to EAF and the prospective start of full-scale hydrogen reduction in 2040.

of the final date. The decision for the final addition will probably need to be made not long after the demonstration starts up given the lead times. Although, as noted, the gross capacity by and large exists now, the steel industry is not the only competitor for the electricity. Other green industrialization initiatives, modern and electricity dependent industries such as data centers, and the expansion of normal electricity use will place demands that could be as large as the one described here (Larsen et al., 2016), and the grid must achieve this while potentially losing some nuclear production capacity. Timely expansion of renewable capacity is a precondition for success.

Another notable system change is that H-DR would ease the direct coupling between the iron ore reduction stage and the furnace, allowing more flexibility in the location of industrial facilities (Vogl et al., 2018). This flexibility will however be constrained by the availability/feasibility of grid connections. This means that a single reduction facility could produce iron for all of Sweden's EAFs and be exported as well, which could possibly enable CO_2 emission reductions beyond Swedish borders. There is an additional energy requirement if reduction/pelletization and steel production are not co-located due to additional processes, e.g. passivation of DRI, that are necessary if the reduced briquettes (Hot Briquetted Iron - HBI) need to be transported, but this addition is very minor. The HYBRIT project has investigated the impact of different locations for the reduction, with initial results indicating only minor differences (SSAB et al., 2018). Once again, grid connections will be decisive in final placement.

Finally, fossil free steel production is still a comparatively new subject area, and a transition to H-DR might represent a radical change in that the well understood technical relationship between the basic oxygen furnace (BOF) and the final steel composition and properties. This is an area of knowledge that simply requires learning by doing, and a substantial effort is still required to develop a process that does not disrupt the tight coupling with the end users in terms of material properties product specifications.

4. Structural description of the Swedish steel TIS

We describe the TIS structure in terms of actors, networks and institutions. We identify actors in the network using formal associations and through including entities identified through analysis of patents and papers. From the various associations, we identify a number of core firms in addition to the primary industrial actors in the core steel system and the electricity system. The HYBRIT project is a joint venture of SSAB, LKAB and Vattenfall. All steel producers in Sweden share group membership in Jernkontoret. Academic actors are visible from scientific paper and patent assignees.

4.1. Actors and networks

The entities identified as relevant to the transition can be diagrammed as follows (Fig. 3), with detailed lists provided in supplementary information. A similar structural view of the system can be found in Karakaya et al. (2018).

We highlight HYBIT and Jernkontoret, the two pre-eminent associations in the system. Our analysis (Figs. 5–6) reveals additional connections between some of the actors from the collaboration graph of the patents and papers, indicating shared scientific enterprise - the significance of which is discussed in the section analysing the knowledge development function. The most significant collaboration cluster is intra- and inter-university collaboration on scientific papers. Among industrial entities there exist many

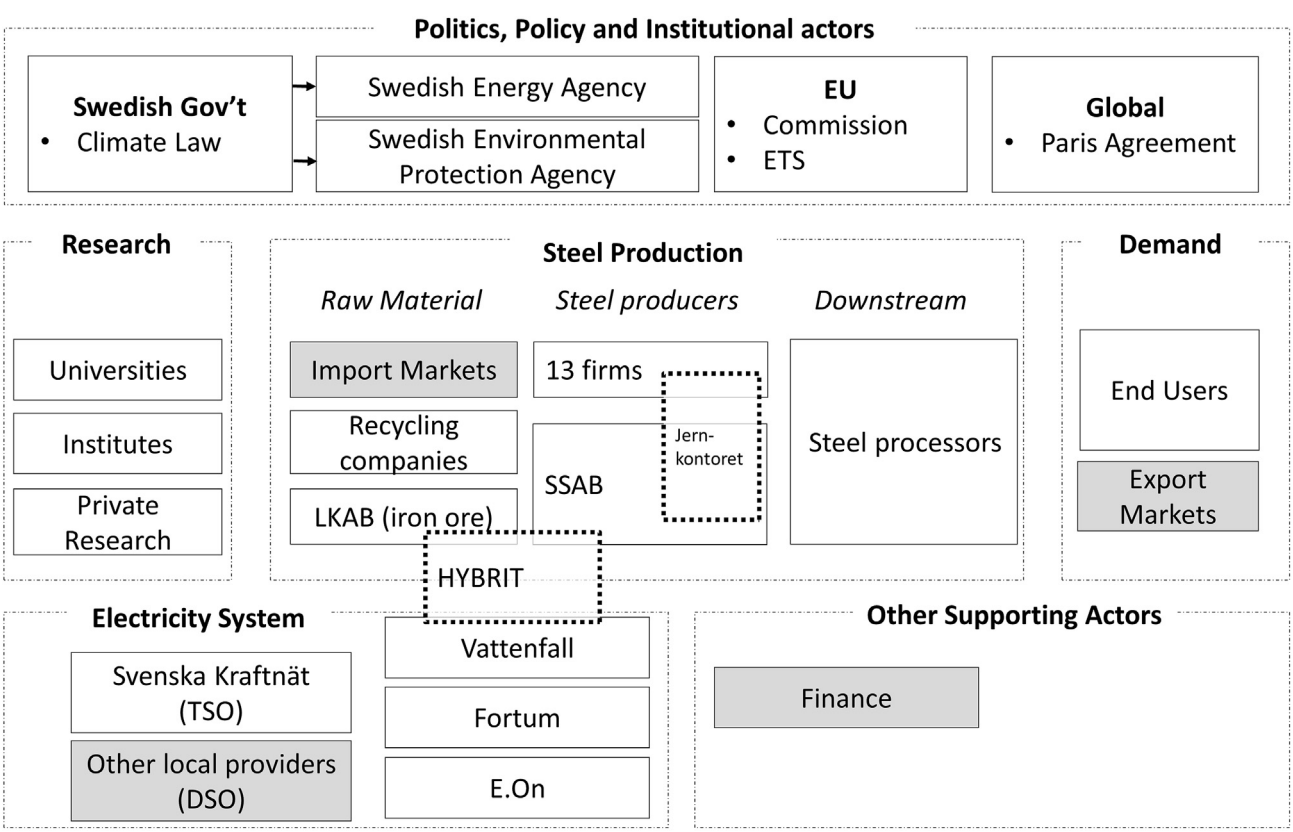

Fig. 3. Actors within the TIS. Layout is according to Hekkert et al. (2011), based previously on Kuhlmann et al. (2001). Greyed out boxes are inferred, and not directly identified from associations or the assessment of scientific publications and patents.

isolated groups of collaborating entities. The most significant instance of industrial collaboration on publishing output is revealed between Sandvik AB and Höganäs AB, which also have some connections via patenting inventors, along with some other non-primary producers. Almost all other major entities are unconnected. It is however known that many end users of high grade steel interact directly with primary steel producers for product design and quality control (e.g. (Jernkontoret, 2017; EuroFER, 2018), an observation which can be strengthened via our patent analysis.

The global industry suffers from an overcapacity, but Swedish industrial actors have a comparatively concentrated focus on high-value alloys, as can be seen in the export mix of 48% high strength steel versus an 8% EU average (Jernkontoret, 2017; EuroFER, 2018). This focus has existed for a long time (Sandberg et al., 2001). In addition, the Swedish steel industry maintains higher gross margins than the global average, indicating that they are less affected by the global situation.

4.2. Institutions in the Swedish steel TIS

Institutions comprise both the codified and informal, e.g. the basic expectations and rules of the game (Bergek et al., 2015). The most relevant codified aspects of these institutions directly affecting the TIS are the Swedish Climate law, the Paris Agreement, and the mandatory European Union (EU) Emission Trading Scheme (ETS), under which SSAB has a CO_2 permit allocation for its activities slated to decline to 30% of the industry benchmark by 2020 (Healy et al., 2017; EU, 2018a). There is no clear replacement for the carbon leakage protection currently afforded by the ETS. H-DR will likely cost more and thus risks losing production to outside the EU, so other trade institutions post-ETS are highly relevant. The EU does not permit internal trade barriers and the World Trade Organisation (WTO) restricts the use of trade barriers outside the EU, currently including carbon tariffs, although this element may need to be revisited in the future to address the industrial sector for global climate ambitions (Åhman et al., 2017). The climate law and the EU ETS, as described earlier, essentially requires either H-DR, CCS, or the cessation of blast furnace activities in Sweden, and thus represents a much harder target than Sweden's commitments under the Paris Agreement.

Sweden is characterized by a high trust in state institutions and a high degree of public support for environmental policy (Harring and Jagers, 2018; Harring et al., 2018) There is significant public willingness to both support and punish firms in order to achieve environmental goals.

5. Functional description and evaluation

In this section, we systematically work through the functions and indicators given in Table 1.

5.1. Knowledge development

Understanding how and where knowledge is created and disseminated in the steel TIS is a critical aspect of this study and therefore receives extended treatment. Of particular relevance are the questions of what parts of the value chains are covered by accessible scientific output, and the degree of connectedness and collaboration between the innovation system entities.

We look first at codified knowledge in the form of scientific papers and patents. Scientific papers are drawn from the SCOPUS abstract database. Patent data was obtained by downloading the bulk US Patent and Trademark Office (USPTO) patent set, supplemented by using World Intellectual Property Organization (WIPO) data for global patents. The selection and refining methodology for each set is documented in the following section. The final selected sets are available in.tsv format in the supplementary material.

To perform the collaboration analysis, we extract the inventors and assignees (authors and institutions for papers). We then build a graph where the nodes are entities, and for each document, we create an edge (a connection) on the graph between every combination of entities that produced the document. The result is a graph showing which authors and institutions have worked together over time, producing Figs. 5 and 6.

5.1.1. Scientific papers

To select the paper data set, we begin by taking the widest possible view and retrieved all journal papers with 'steel' or 'direct reduction' in the title, abstract or keywords and at least one Swedish institutional affiliation, as well as all papers published by SSAB, Vattenfall or LKAB (the HYBRIT partners). We then reduce the set by excluding papers on subjects not linked to steel properties or production. The final set contains 7085 documents.

We recalculate the affiliations so that each unique link is only counted once. E.g., using Scopus data tables, a paper with one Swedish and two German authors will only produce one Sweden-Germany link. The following figure shows publication statistics for Sweden.

Looking at Fig. 4a–b, we can see a steady increase in Swedish publication regarding steel over the last thirty years. A majority and increasing fraction of all publications include more than one academic institution. Approximately one quarter of all publications include an academic-firm collaboration. Finally, firm-firm collaboration occurs in approximately one in seven scientific papers published in 2017.

From Fig. 4c, there is also an exponentially increasing pool of authors that have a steel related publication in the last five years. The shaded regions show what is causing the change. The dark region shows 'experienced' authors returning to the field, and the light represents new authors, which account for most of the increase in active authors. Areas where the dark shaded area is below 0 represent a net retirement of experienced authors. The number of repeat authors is however slowly increasing over time. The average number of publications per active author has risen from 1.45 in 1980 to 2.17 today.

The universities unsurprisingly dominate scientific paper publication and have extensive cooperation between them. All of the top 5 universities have recent collaborations in the steel domain with all of the other top universities and at least one of the top industrial partners. Sandviken, Swerea and Höganäs AB are by far the dominant industrial collaborators, while the most common foreign collaborator could be Outokumpu AB (A Swedish subsidiary of Outokumpu Finland), depending on what is defined as 'foreign'. This interconnection of actors can be seen in the institutional and national collaboration maps, calculated by drawing edges between institutions (or nations) appearing together on a paper. The result is as follows in Fig. 5.

We can also count the collaborations between the HYBRIT group (LKAB, SSAB, Vattenfall). One paper between SSAB and Vattenfall exists on optimizing a plant to account for external systems, and five papers have been cowritten between SSAB and LKAB, all on blast furnace processes. There are thus some minor channels of scientific communication and collaboration between the companies involved in the HYBRIT project.

By focusing on the much smaller body of knowledge incorporating both hydrogen reduction and steel, we can see that there are a few papers regarding complex effects relevant to final steel properties, e.g. composition, and grain sizes and boundaries. The question of how direct hydrogen reduced iron can be worked to the existing demanding specifications of the advanced steel sector is

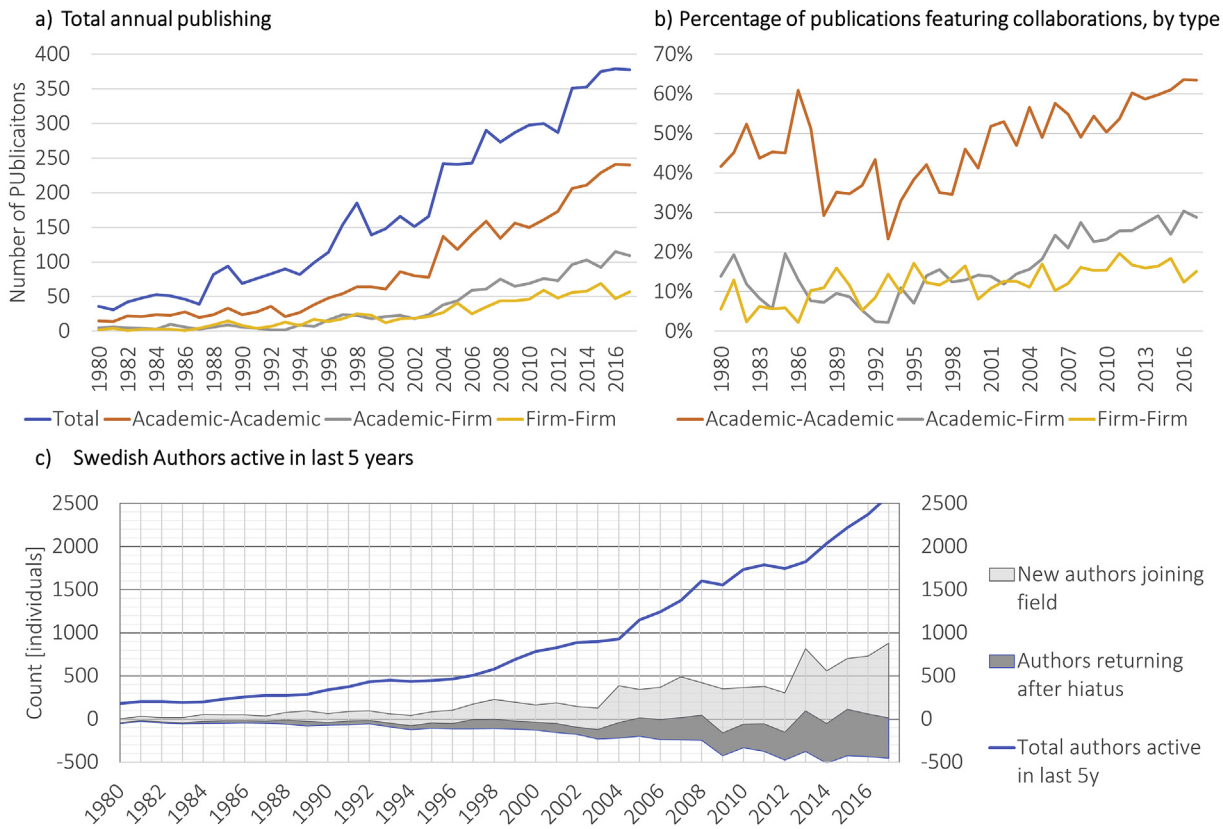

Fig. 4. Scientific paper statistics. a) Annual publication including at least one Swedish affiliation, and number thereof featuring collaborations b) Restated as a percentage c) Total scientists with a publication in the last 5 years (line), and annual changes (shaded). Returning Authors are authors publishing after a hiatus of >5 years. The baseline starts below zero because of 'retiring' authors, e.g. those that no longer have a publication in the last 5 years.

thus an important area for R&D efforts. It is also possible to note very little output on direct reduction.

5.1.2. Patenting

To select the patent sets for examination, we use the US patent and trade office (USPTO) bulk download set and supplement with the World intellectual property organisation (WIPO) database to include international patents. We first select all patents within the C21B and C21C WIPO classifications (both Manufacture of Iron and Steel), comprising some 6000 documents. We also select a national subrange where the assignee is Swedish.

We run a similar social analysis to the scientific publications where we assign a link between all participants in a patent. The results are visible in Fig. 6. Because assignees are usually corporations, and inventors are always individuals, this does not paint the same picture as the corresponding scientific paper analysis. Rather, it shows when inventors have patented for more than one company and thus indicates a flow of knowledge rather than direct collaboration. The Swedish data set is almost completely unconnected, e.g. mostly populated by a limited pool of individuals patenting for a single company over their career. The global set features some clusters, but all are national in character.

Examples a) and b) in Fig. 6 show the two largest connected sets in the Swedish data set. Both feature personnel links between end users (e.g. SKF and Sandvik/Seco Tools) and primary producers (Ovako Steel AB and Höganäs AB, respectively). This is some additional documentation for the knowledge link between producers of advanced steels and end users. Both clusters contain some individuals who are not Swedish and are representative of what an 'international' collaboration looks like in the data set, i.e. some foreign individuals patenting with Swedish corporations. There is no instance of a Swedish corporation sharing a link with a non-Swedish corporation.

From this analysis, we can conclude that the global patenting scene is typically based on very limited collaboration within national industries. In Sweden, patenting is typically not done in collaboration, individuals (and their patenting skill) tend not to move between companies, and there is no international collaboration other than a few otherwise unconnected foreign nationals patenting for Swedish corporations. The converse is also true, with a few instances of Swedish nationals patenting for foreign companies.

For a final selection, there is only one global cluster that features 'direct reduction' in a text search, and that is from the MIDREX company, who provide turnkey NG-DR operations comprising 76% of the world's direct reduction capacity. The other common process is HYL/Energiron from Tenova, who uses syngas, but this is not directly visible in the patenting. There is no patenting regarding direct reduction yet from Swedish entities.

5.1.3. Tacit knowledge

The HYBRIT project is unique in Sweden for providing direct experience with hydrogen reduction, and is intended to develop knowledge and experience with many key systemic barriers identified in the conclusions of the prestudy (SSAB et al., 2018) as well as to develop the necessary inter-actor cooperations. With regard to barriers, most importantly no particular technological breakthroughs were found to be necessary for processes taking iron ore to liquid steel, as 'off the shelf' technologies are available. Other issues were ranked in a two dimensional grid of complexity versus

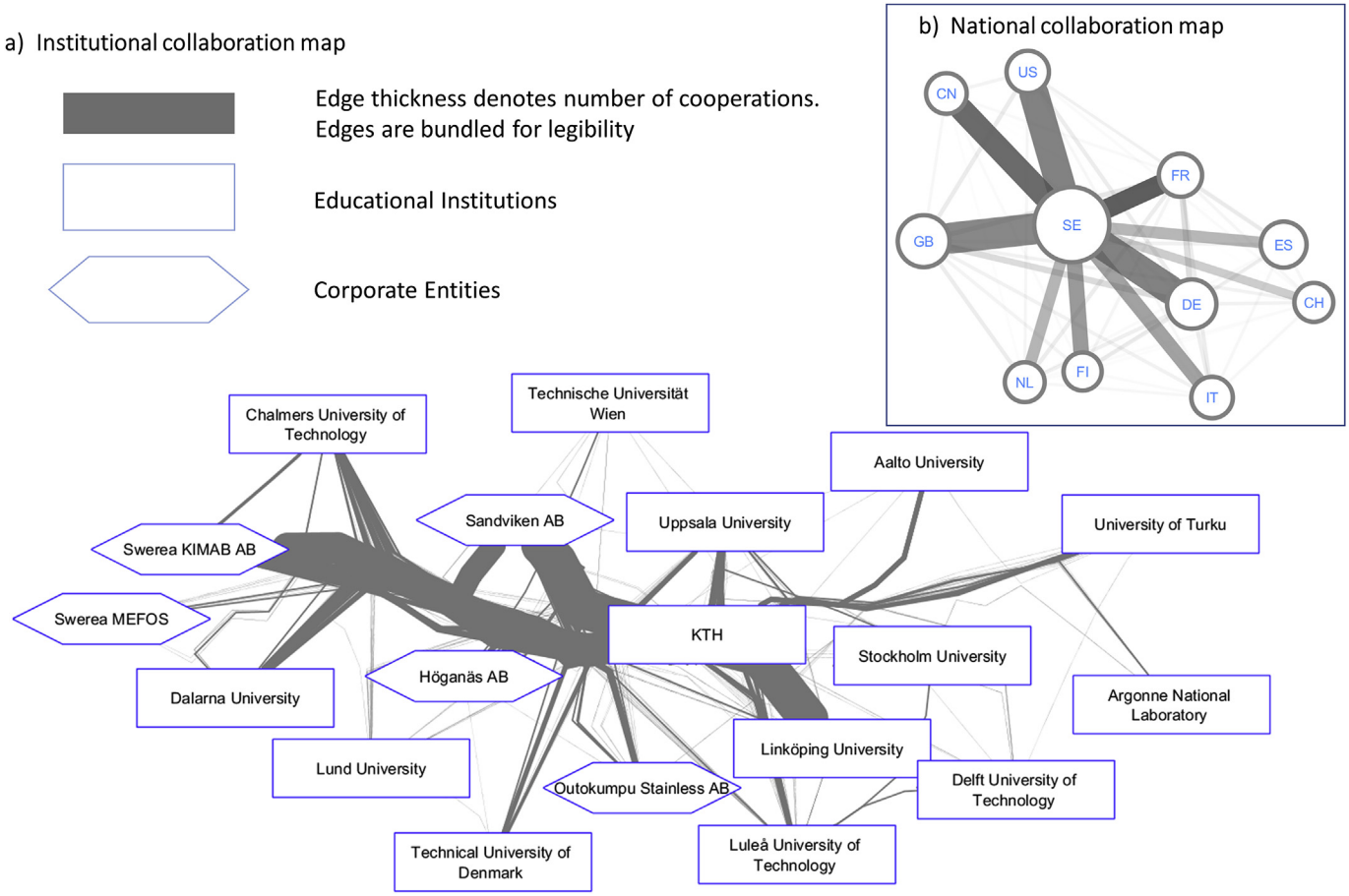

Fig. 5. a) Institutional and b) International collaboration maps for scientific papers related to steel and with one Swedish entity in the authorship set. Network arranged by spring force layout and line strength indicating number of collaborations. Most common collaborating countries for international collaboration. Lines between countries not including Sweden indicate a three or more nation collaboration. In both diagrams, lines are weighted by total amount and shaded in b) by total amount in the last five years.

impact. The few issues furthest from the origin are as follows [translated from Swedish]:

- Determination of the process parameters to make H-DR work as a single unit and as part of an integrated process chain.
- Reorganization of the value chain and its consequences for the company
- Determining the feasibility of hydrogen production on that scale
- Policy 'may be required' to ensure a viable business

In short, the major barriers remaining are not part of the codifiable knowledge domain, instead they are centered on experience with the practicalities of the new system and how to integrate the new flow into existing business and technical processes. Only experience will resolve them.

5.1.4. Summary

We can observe active knowledge development in scientific papers and patenting. The mode of operation is very different however. There is an integrated scientific community, but very siloed patenting efforts with the exception of a few small clusters. The focus of most scientific effort is on material and alloy properties with patents focused on downstream (and mining) processes, all with comparatively little international cooperation. There is also very little on furnace technology or post furnace metallurgy, verifying the industry consensus that this is one of the primary locations of tacit knowledge – or 'secret sauce'.

While it is not likely that SSAB would be publishing about its business plans, thus far, there is little scientific effort in Sweden directly addressing a H-DR transition or the primary barriers identified in HYBRIT. The complementary technologies – electrolysis and DRI – have very little scientific work done on them in Sweden and virtually no patenting. We can therefore conclude that the innovations in hydrogen electrolysis or the reduction process itself are unlikely to be domestically developed. The innovation required of the TIS will therefore reside in the integration of these new complementary technologies. Indeed, the firms in the TIS perceive the change as 'systemic' (SSAB et al., 2018) rather than 'rocket science' and anticipate that more research will be required at every process stage and at the systemic level. As noted, the HYBRIT RP1 research program is explicitly aimed at these systemic factors, but only started in 2017 and thus the major impacts on scientific output would be expected in the future.

5.2. Direction of search

The determinants of where innovation efforts are aimed in the particular case of a H-DR transition are constrained by the limited menu of technical options for meeting the current policy vision and international commitments. Although various technical options have been researched by the industry for a long time – e.g. natural gas DR (Twidwell, 1980; Eketorp, 1989; Birat et al., 1999; Sandberg et al., 2001), and CCS – these efforts were not aligned with all social goals (e.g. the political difficulty of natural gas pipelines) or the

Fig. 6. Examples of patenting clusters. a) SKF-Ovako Steel AB. b) Sandvik-Höganäs. Lines denote a co-patenting relationship between entities.

explicit vision of the steel industry until 2013 when the industry published its vision for the future, which involves staying in Sweden, maintaining or improving the share of advanced steel products, and drastic reductions in carbon output.

At present, the Sweden 2045 climate law and the Vision 2050 (Jernkontoret, 2017) from the industry are more or less aligned on the necessity of a low (zero) carbon transition for the steel industry. Subsequently the perceived technical possibilities have been constrained to either H-DR or simply outsourcing the iron reduction step in the steel industry, and there is evidence from interviews (Karakaya et al., 2018), Jernkontoret (the industry association) literature and from transcripts of investor calls from the major actors that the industry has coalesced around this vision for the future.

Another factor guiding the direction of search is inclusion in the EU ETS. The Emission Allowances have both recently regained price after the effects of the financial crises in 2008/2009 and have historically been a source of windfall profits for SSAB (and the Swedish industry). The free allocation of allowances will be changed after 2020, however the steel sector is currently on the preliminary leakage list (EU, 2018b) and thus eligible to continue receiving full allocation up to the benchmark of carbon allowances. The price of allowances could represent a significant incentive for the switch to H-DR at current prices of approximately 20€/ton CO_2. The free allocation will, at least for a couple more years, continue to provide a protection from carbon leakage, but also lower the incentive for switching away from the blast furnace and thus losing eligibility to the blast furnace benchmark. Regardless of the incentive provided by the EU ETS, evidence suggest that they still only form a marginal incentive to innovate for industries (Woerdman et al., 2009; Laing et al., 2013) rather than a *raison d'être* supporting any transition to lower emission intensity technology. Instead, from the industry association literature, the vision of 'zero fossil use' was inspired by both the climate law and the Paris agreement and reflection about how industry could fit into such a world.

5.3. Legitimation

Legitimacy for a low carbon society is very high in Sweden, as is public acceptance of climate related policies. As a further example, the climate law was passed with 87% in favour in parliament. As mentioned while discussing the direction of search, the TIS actors and social goals are now aligned on the necessity of a transition, and the legitimacy of pursuing H-DR as the primary technical option. This initial institutional alignment is often a barrier in both general TIS studies, and in the more specific case of technology push type transitions (Suurs, 2009).

The steel industry is however both comparatively minor in terms of direct employment in Sweden, 0.4% of the labour force (SCB, 2018b), and has long been known as the largest industrial emitter in the country. There is thus no guarantee that legitimacy for a transition to H-DR will remain if it turns out that substantial public financial support is necessary beyond the planned aid with pilot and demonstration projects. The initial cost estimates from the HYBRIT prestudy indicate higher production costs in a low margin industry, and thus there is a high probability that some sort of public attention to cost pressure will be required to make the transition viable, at least viewed through a risk perspective. This scenario risks the legitimacy of adopting the technology and will require attention to motivating why public support is necessary.

5.4. Resource mobilization

In terms of funding R&D and development, the initial stages of HYBRIT (pilot and research programme) were partially funded by the government (through the Energy Agency). Acquiring research funding and industry buy-in has so far been rather smooth, which stands in contrast to transition processes in other resource-intensive industries (e.g. Dewald and Achternbosch, 2016; Hansen and Coenen, 2017).

The steel industry is characterized by a high level of investment in capital assets. In Sweden, capital investments are both large (300 M€/y) and continuous. The major investments are in machinery and long-term capital replacement. Finance has been raised internally through profits and private debt issuance, indicating a general ability to plan, finance, and execute large and capital intensive projects. The potential adoption of H-DR is more capital intense (SSAB et al., 2018) but on the same order of magnitude as simply replacing the blast furnace would be, and thus is a serious, but not insurmountable burden. While the long planning cycles would normally be a formidable barrier, the preceding facility is now at the end of its life.

What would be different from the normal capital cycle in the industry is the increased dependence on novel complementary systems – renewable generation, transmission lines, electrolysis, and hydrogen infrastructure. The generation and possibly the transmission and electrolysis will presumably be handled by Vattenfall and Svenska Kraftnät, which are perfectly capable of financing and executing such projects on their own. Vattenfall is planning 1.3 G€ of new wind capacity and 300 M€ of new grid projects for the 2018–19 fiscal year. All in all, roughly 17 TWh/y of new capacity would be required for a total conversion of the steel industry, 10.5 TWh/y for the reduction step alone, roughly following the timeline given in Fig. 2 for when the capacity has to come online. The electricity produced from Swedish wind generation has risen an average of 1 TWh per year over the last decade (Energimyndigheten, 2017). Given the 12 TWh/y trade surplus and pace of investment, such development to support H-DR would not initially seem to be problematic. However, both the prospective retirement of nuclear capacity and the prospective green conversion of other industries will compete for green electricity. Additionally, the 3 and 4 TWh increases in Fig. 2 right before the full scale reduction capacity comes online would be larger than the largest historical increase in Swedish wind generation (2014) and thus would represent a historic capacity addition.

Transmission grids are likely the critical, if often overlooked part of the complementary infrastructure. In the ideal situation, the reduction facility will be situated very near to a large generation facility such as an offshore windfarm with the electrolyzer co-located. Otherwise, more significant alterations to the electricity grid may be required. From the HYBRIT feasibility report, which assumes that the new facility is to be operational in 2040, most of the incremental electricity demand comes online in two major bumps, 3 TWh/year from 2028 to 2032 and 9 TWh/year from 2038 to 2040. The capacity to handle this demand needs to be in place by these dates. The issue in complementary assets may thus be more a question of time rather than raw capital. Interestingly, in two recent futures studies by the main grid operators, this possibility is not yet included in formal scenarios (Larsen et al., 2016; Statnett et al., 2017). There may thus arise coordination issues in ensuring that the necessary grid infrastructure is designed, permitted and deployed in time. At present, neither the clear selection of a site or the necessary coordination for permitting and planning is visible.

5.5. Entrepreneurial experimentation, market formation, and developing external economies

These three functions are typically investigated in the context of a growing technology attempting to move from niche applications to mainstream adoption. The scenario presented here has some notable differences: the market for steel already exists in a mature and competitive form, and the prospective transition would be to replace almost the entire primary material technology underlying it. Swedish industry is quite explicit about its desire to maintain its market position, and the general demand for high-strength steels has been increasing year over year (Jernkontoret, 2017; EuroFER, 2018).

Similarly, there are few free utilities to be highlighted other than the slow march forwards in the complementary technical fields of direct reduction, renewable energy and hydrogen technology. All of these fields feature increasing employment, research and firm capital, which would indicate growing and maturing industries (SCB, 2018b).

Despite these general observations, a few points can probably be made. The first is that knowledge has been gained globally through observing the unsuccessful attempt at direct reduction by ArcelorMittal in Trinidad. Other ongoing efforts in Austria (H2Future, Voestalpine) and Germany (SALCOS project, Salzgitter) will provide additional knowledge and legitimacy to H-DR by showing what works and what aspects of the system need new solutions. There is a small but growing experience in the EU and global industries regarding the integration of large-scale industrial electrolysis with energy grids. Sweden is a leader in both renewable energy production and has domestic and growing capacity in integrating complementary technologies like smart grids.

The second point is that there is a clear need, and one that is recognized by the HYBRIT consortium, to spend more effort in investigating and learning about the possible business model changes that would be implied by the transition. Aside from the already mentioned issue of making sure that the resulting steel products would be acceptable to downstream consumers, there are other possibilities such as eventually expanding the ore reduction capacity to the point where it could supply other steel operations in Europe with 'emission free' iron pellets (HBI). There are additional possibilities that may arise such as demand side management for the grid, and the possible licensing and export of any technologies

developed to address technical issues.

Finally, while the market for steel is indeed mature, there is yet to be seen whether a market for 'fossil free steel' that captures some sort of premium can be created. Steel has very low product visibility for most final consumers, but is typically a low proportion of the cost of a good containing it. It is not inconceivable that someone may pay a hundred euros extra for a car made with fossil free steel, but the value of such an option has not received much investigation (Rootzén and Johnsson, 2016). Niche markets, created if necessary by policies such as public procurement (e.g. Åhman et al., 2018b) may be required to create and discover the potential to capture value in this area.

6. Discussion and synthesis

6.1. The TIS

The Swedish steel TIS operates as an integrated national industry. Between the industry associations and the relations between entities identified from the analysis of knowledge production, we can see a connected scientific community actively working alongside industrial actors, although the total scientific output dedicated to H-DR technology is a comparatively small fraction. Patenting is a much less connected domain but displays evidence that producers of specialty steel have some small degree of personnel connection with end users.

6.2. Technology

Analysis of the knowledge domain shows that the reduction equipment itself has no endogenous innovation system but has progressed to an 'off the shelf' component available from at least two global suppliers – Midrex and Tenova. For complementary technologies such as electrolysis, older technologies such as alkaline have existed at one order of magnitude lower scale (>100 MW) and the newer PEM electrolysis has operational examples at one order of magnitude lower scale, e.g. a 6 MW electrolyser is operational in Austria (Siemens, 2018). World production capacity for PEM electrolysers was only approximately 100 MW in 2017 (Satyapal, 2018), so such H-DR would require multiples of the current annual production if PEM were to be the choice. Sweden has the capacity to plan, build and integrate the required electricity grid modifications with domestic and state-controlled enterprises. The major technical building blocks of a H-DR system thus exist and their arrangement points towards a specific outline of what a H-DR transition would look like: to order the required complementary assets from the global market and integrate them using domestic competence in the electricity and steel industries.

With a strong industry and development in the supporting technologies as a base, as of now everything that can presently be done on the technical side to make H-DR possible is being done, with the centerpiece being the HYBRIT project. There is still however significant caution on the part of SSAB with regards to the possibility, and the entire industry recognizes that there is technical risk involved with such a transition (Karakaya et al., 2018; SSAB et al., 2018; Vogl et al., 2018). Despite the 'off the shelf' nature of the components and ongoing work on a pilot facility, it should be emphasized that R&D is not complete, particularly in systems integration and ensuring that the final products of the process do not jeopardize the customer requirements/markets of the industry. Policy makers should therefore be aware that even a positive result from the pilot project is only the beginning and that more R&D support will be required at every stage.

6.3. Economics

Given a new 'off the shelf' technology, the discussion naturally should turn to the economic and systemic implications of a hypothetical 'technology push'. The economic profile of the technology is uncertain but estimated to increase production costs by 20–30% with a wide margin of error (SSAB et al., 2018; Vogl et al., 2018). The cost increase is roughly split between capital and energy costs. These figures can be substantiated by Midrex's assessment and experience with installations that natural gas DR is roughly cost competitive with traditional processes (Midrex, 2013). This suggests that the typical derisking and support policies to control input costs, and marketing/value add policies could be useful and may in fact be necessary.

The condition of energy price sensitivity is interesting for a collaboration between an energy producer and a consumer, particularly where the prospective producer (Vattenfall) is state owned. Given the known variability of H-DR production cost with the electricity price, efforts to ensure competitive electricity prices and grid access will greatly affect its perceived riskiness. The economics of the HYBRIT project as understood at present would be improved markedly by attaining electricity prices of 30€/MWh or lower. At present, only hydropower has levelized costs below this figure (IRENA, 2018), with onshore wind estimated at closer to 50€/MWh. If the observed learning rates persist however, wind will reach affordability in the mid-2020s and potentially approach the 30€ figure by the mid-2030s. Offshore wind is more expensive, but is also coming down in cost. Relying on simple technical advance to produce the necessary energy costs is thus risky, but if carbon prices move upwards then the costs relative to competitors will improve commensurately.

Cost of capital was the other half of the price increase, with an internal estimate in HYBRIT of a 9% discounting rate as a corporate hurdle. At the time of writing, the Swedish government can currently borrow for 30 years at approximately 1.5%. Given that the transition would be risky and at least partially in support of national and societal goals, it seems reasonable to suggest that there might be room for some financing arrangement such as "Green Bonds" (Reichelt, 2010), where the state could underwrite debt for the project and thus de-risk the capital expenditure.

Steel is an industry suffering from global overcapacity, indicating low pricing flexibility, but this may be ameliorated to some degree in the advanced steel markets (EuroFER, 2018). Nevertheless, there is not much opportunity with the current market structure to pass on increased costs, a fact that is well understood in the industry. While some protective policy options such as tariffs are currently infeasible due to EU and WTO rules, there remain other potential cost levers on the cost side of the equation, namely reductions in labor or corporate taxation. Any future modification of WTO rules to allow carbon tariffs would greatly help this policy gap. Other potential policies for market and value building require more cooperation from other actors and are covered in the next section.

7. System building

The economics show that attaining competitive cost will require policy effort, at least initially. This observation is unsurprisingly a general finding in literature on TIS adoption of a radical new technology (e.g. Suurs, 2009), with the following aspects typically being identified as potential barriers in such circumstances in addition to the standard observation that new technologies generally appear expensive (Bergek et al., 2015):

- Weak involvement on the market side

- Limited group of [usually government] enactors and insufficient system building (alignment of many actors and institutions)
- Focus on one technical option leaves little room for failure and magnifies risks

Asides from energy and capital focused economic policies, there is a potential need and role for system building activities to capture some sort of green premium for the product as it is still likely that H-DR will raise overall input costs for steel production, and thus any method of increasing the output value will be helpful. Literature is full of helpful policy advice for this issue, but the possibilities will need to be studied individually. Green-certificate type schemes are one possible avenue for future research to investigate. Although there appears to be no demand articulation from steel consumers for such an initiative (Rootzén and Johnsson, 2016; Karakaya et al., 2018) there is always the possibility to stimulate demand for low emission steel through public procurement directives and branding.

In addition to the cost, there are many coordination efforts necessary if H-DR is to be seen as feasible. Work to guarantee that the electricity will be available and transmitted to the site must credibly start well in advance given the lead time on components such as transmission and distribution infrastructure. The final push in the last few years before an H-DR facility begins operation would represent the largest two-year increase in renewable capacity in Swedish history. With a 2040 start date, there are only 18 years before the first of this capacity needs to be online and yet it does not appear in the strategic scenarios of the major grid operators. There are also other items on the policy menu such as working on access to generation sites, finance collaboration, or even price guarantees.

Advocates of a new technology typically have extreme difficulty overcoming a lack of legitimacy and organizational alignment (Bergek et al., 2008). That is not the case here, but the required activities will require unusually broad coordination between many governmental and corporate actors, with the aforementioned risk that the legitimacy currently enjoyed will be tested when subsidy of some form is required. Special attention may be needed to broaden the coalition of governmental enactors.

8. Conclusions and potential roles for policy

The Swedish steel industry has a unique opportunity to become the first nearly fossil free steel industry in the world. This opportunity is afforded through the natural obsolescence of a critical facility and thus there is a finite window of opportunity. Because of the capital investments and the difficulty of modifying the process after locking it in, the choice will have a lasting effect on Sweden's climate profile. The effect will be of sufficient magnitude that it will be a pivotal determinant of whether or not maintaining the steel industry and honoring the targets in the national climate law are mutually exclusive. The importance of success extends beyond Sweden to at least the climate ambitions of the EU.

We applied the TIS framework to evaluate how the system is performing with regards to a transition to hydrogen direct reduction and find that the framework is suitable for structuring discussion around such a comprehensive transition. To existing efforts, we add empirical data about various functionalities of the system that allow deeper assessment. We also demonstrate how deeper paper and patent analysis can contribute to system delineation and discussion of TIS functions. We can conclude that the innovation system is accumulating knowledge and the basic resources necessary to enable an H-DR transition, and the overall technical feasibility is known and under active improvement. H-DR is however a very small fraction of overall scientific output, although this will increase as results from HYBRIT become available. R&D is still necessary, perhaps with a shifted focus, particularly in areas such as ensuring that the outputs of an H-DR process can be used and keep the strict quality control necessary to satisfy end users of advanced steel. Support for efforts along these lines will be necessary as soon as the pilot process is producing sufficient material to experiment.

While the technology itself has comparatively knowable risks, by examining the economics, logistics and innovation aspects of pushing it we identify several potential barriers that are within the domain of Swedish policy makers to affect. The economics of the project suggest policy needs both on the input (cost of capital, cost of energy), and the output side (potential markets). The systemic logistics imply a strong need for a coordinating vision, collaboration on complementary assets, and a steady hand. In the end, the decision of which investments to make will be taken by an entity without full control over the necessary complementary assets such as power grids. Derisking and strong attention to cost pressures will be required to make a decision to change processes viable. Yet there is a risk that cost pressure may have an important impact on legitimacy without careful attention. We can suggest that a deep look at transmission infrastructure planning, and assessment of the possibility for creating 'green steel' markets are likely to be important future areas of study for this transition.

Broadening the scope for a final conclusion, there are alternatives to H-DR: giving up on the climate law, losing part of the industry, or waiting and hoping for some other technical option. Policy makers should note that losing the iron reduction capacity may help Swedish CO_2 emissions, but will likely increase global emissions as the Swedish facilities are already more efficient than both the global and the EU averages. It is therefore in the global climate interest to make sure the industry can be kept. Without H-DR though, Sweden's climate goals will be extremely difficult to attain. Ultimately, H-DR will require the government to fully commit to both the 2045 zero carbon vision and to the future of the steel industry in Sweden and to act decisively and consistently over the entire transition phase.

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Abbreviations

BF	Blast Furnace
BOV	Basic Oxygen Vessel
CCS	Carbon Capture and Storage
DR	Direct Reduction
DRI	Direct Reduced Iron
DSO	Distribution System Operator
EAF	Electric Arc Furnace
ETS	Emissions Trading System (EU carbon trading directive and platform)
EU	European Union
HBI	Hot Briquetted Iron
HYBRIT	HYdrogen BReakthrough Ironmaking Technology. Comprises a research project and a company (HYBRIT AB)
H-DR	Hydrogen Direct Reduction
LKAB	Luossavaara-Kiirunavaara Aktiebolag
LNG	Liquefied Natural Gas
NG-DR	Natural Gas Direct Reduction (or just DR)
PEM	Polymer Electrolyte Membrane (an electrolysis technology)
SSAB	Svenskt Stål AB
TIS	Technological Innovation System

TRL	Technology Readiness Level
TSO	Transmission System Operator
ULCOS	Ultra-Low CO2 Steel (a consortium effort)
USPTO	United States Patent and Trademark Organisation
WIPO	World Intellectual Property Organisation
WTO	World Trade Organisation

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118185.

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