Bigger is sometimes better: demonstrating hydrogen steelmaking at scale
Stockholm Environment Institute
Linnégatan 87D 115 23 Stockholm, Sweden
Tel: +46 8 30 80 44 www.sei.org

Author contact: Olle Olsson
olle.olsson@sei.org
Editor: Tom Gill
Layout: Richard Clay
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Abbreviations used

BF     Blast furnace
BOF    Basic oxygen furnace
CCS    Carbon capture and storage
CCU    Carbon capture and utilization
DRI    Direct reduced iron
EAF    Electric arc furnace
GHG    Greenhouse gas
H-DR   Hydrogen direct reduction
PDP    Pilot and demonstration plant
TRL    Technology readiness level
Executive summary

The steel sector currently makes up about 7% of global CO₂ emissions, with the vast majority of emissions resulting from the use of coke in blast furnaces for reduction of iron ore. One of the more promising applications for decarbonizing steel production is to instead use hydrogen direct reduction (H-DR) of iron ore. HYBRIT is a Swedish initiative, launched as a joint venture between the companies LKAB (mining), SSAB (steel production) and Vattenfall, aims to commercialize a steel supply chain based on the H-DR process. If this ambition is realized, it could become an important piece in the puzzle for achieving global deep decarbonization. Transitioning to HYBRIT is a two-decade venture that is still in its early stages. With full implementation to be complete by 2040, at the time of writing the project is just entering its pilot phase. This will be followed by a demonstration phase toward the latter half of the 2020s and a move towards full commercialization thereafter.

This working paper focuses on the demonstration phase in HYBRIT. Recent years have seen growing interest within the innovation systems research community in the role that demonstration plants can play in bridging the so-called “valley of death”, in which a technology or a technological system progresses from lab-scale to commercial implementation. As it happens, there are plenty of examples of how unsuccessful design and setup of a demonstration plant can turn out to be detrimental for the overall innovation process. Therefore, it is vital to understand matters of design, organization and mobilization of policy support in preparation for any demonstration phase.

In this working paper, we apply insights from research on innovation systems and industrial economics to identify and analyze key risks around demonstration plants, especially pertaining to decisions around scale, i.e., how large should a demonstration plant be? While our analysis is focused on the HYBRIT project, we also place the issue of demonstration plants in the broader context of decarbonization of heavy industry.

To the best of our knowledge, there have been no decisions made on the precise design and setup of the HYBRIT demonstration plant. We therefore choose to discuss two hypothetical demonstration plant alternatives: one “small”, which is more of a large pilot plant (i.e. 200 000 metric tons per annum, with 80 megawatts of electrolysis capacity) and one “large”, which is of a size (800 000 t/annum, with 320 MW electrolysis capacity) closer to a commercial scale. Note that we do not consider that both of these would be built; rather, it is a case of deciding on either the small or large option.

Our analysis finds that, in the choice between the two alternatives, there is much that points in favour of building a large demonstration plant. This is mainly because the key role of the demonstration phase is to address issues such as the optimization and coordination of the supply chain, business models, public policy, regulatory issues and stakeholder relations. And to address these issues successfully, it is highly important to initiate substantial collaboration with authorities and society at large, on issues like financing and permitting. Our view is that such collaboration would be best achieved by building a large demonstration plant. It would also be advantageous in terms of signaling and marketing, because it would build on the currently strong momentum of HYBRIT as a flagship project moving towards a future in which steel production is free of fossil fuels.

Having said this, setting up a large demonstration plant will also entail significant challenges, with risks related to regulatory processes being particularly important. Permitting issues, linked both to actual industrial sites and to the expansion of power transmission capacity needed for hydrogen production, could become a bottleneck. In recent years there has been growing discussion in Sweden about the long time horizons involved in permitting processes and how these could create obstacles for industrial decarbonization in Sweden. This is an issue that is more likely to come into play if the choice is to aim for a large demonstration plant, and an issue that needs to be addressed promptly.
In the broader context, it is worth noting that while full implementation of the HYBRIT concept is a very large project, its extent is not unique in the broader context of decarbonization of heavy industry. Metals processing, cement production and petrochemicals are all highly capital-intensive sectors whose products play key societal functions, while also currently having a massive footprint in terms of greenhouse gas emissions. If these sectors are to transition to technological configurations that are compatible with global climate change mitigation ambitions, a host of innovations will have to be proven not just to be technologically viable but to function in a broader business and policy context as well. Demonstration plants will be a central vehicle to this end.

While some of the literature on the design of demonstration plants cautions against too-rapid scale-up and argues for more gradual and iterative processes, the nature of industrial transition could call for a different approach. The reason for this is that although exact designs in terms of scale and supply-chain setups will vary between industries and geographies, one common theme is urgency: 2050 may seem to be a long way into the future, but with the technological inertia and long investment cycles of heavy industry, conceptual studies and trials are becoming less relevant. Policymakers and business leaders alike need to shift focus in terms of overall strategy to ensure that transition of heavy industry moves from conceptual discussions to on-the-ground deployment.

1. Introduction

1.1 Steel industry decarbonization from concept to reality

The 2015 Paris climate agreement aims to put the world on a pathway that restricts global warming to well below 2°C above pre-industrial levels. Translated into emission trajectories, this means that net global greenhouse gas emissions have to decrease to zero in the latter half of this century (United Nations 2015). In terms of realizing the Paris ambitions, the recent decade has seen very positive developments in the form of rapid cost reductions and increases in deployment volumes for several central technologies, including solar photovoltaics, wind turbines and Li-ion batteries for battery electric vehicles (IRENA 2019; Nykvist et al. 2019). However, while this has improved the prospects for decarbonization in the electricity generation and road transport sectors, substantial challenges remain, notably in aviation, shipping, and heavy industry like cement, petrochemicals and steel (IEA 2019a).

The steel industry alone is the source of about 7% of global CO\textsubscript{2} emissions, with more than two-thirds of these emissions originating from primary steel production based on blast furnaces, wherein coke (produced from coking coal) is used to remove oxygen from iron ore to produce pure iron, with CO\textsubscript{2} as the main by-product (IEA 2017). Emission reductions in industry have hitherto primarily been achieved by incremental improvements of incumbent technologies, but efficiencies of the best-performing blast furnace process are now edging close to theoretical limitations. If the steel industry is to align with global ambitions towards net-zero GHG emissions across the economy, substantial process innovations will be necessary.

The past five years have seen a significant increase in the number of initiatives aimed at achieving substantial GHG emission reductions from the production of primary steel. Previously, most such initiatives have been largely reliant on different forms of carbon capture and storage (CCS), but this has now been complemented with quite a few other approaches, most of which have been initiated by Europe-based steel companies (Lechtenböhmer et al. 2018). In addition to approaches based on CCS/CCU (the latter – carbon capture and utilization – entails utilization of captured CO\textsubscript{2} for e.g., production of fuels or chemicals) there are several ongoing projects that in one way or another draw upon the use of hydrogen (H\textsubscript{2}) for reduction of iron ore into iron. The

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1 Primary steel is produced from iron ore, secondary steel is produced from recycled scrap.
main advantage of this is that instead of CO₂, the process by-product is water (H₂O), thereby enabling drastic GHG emission cuts from the iron ore reduction process (Vogl et al. 2018).

1.2 HYBRIT and the H-DR pathway to fossil-free steel production

Hydrogen direct reduction (H-DR) of iron ore is a process that has been known about for a long time. However, interest in commercial implementation has emerged only in recent years in the wake of growing ambitions to decarbonize the global economy and in anticipation of low long-term electricity prices. However, in order to reach low life-cycle emissions by this pathway, the H₂ needs to be produced with a very low carbon footprint. This can be achieved either by steam reforming of natural gas combined with CCS, or by use of electrolysis powered by low-carbon electricity (Vogl et al. 2018).

HYBRIT – a joint venture between LKAB, SSAB and Vattenfall – is a concept based on H-DR² that was first announced in 2016, with the concept comprehensively presented in a pre-feasibility study released publicly in early 2018. The HYBRIT concept entails implementation in Sweden of a steel production supply chain that would use an H-DR process in combination with an electric arc furnace (EAF). The concept also includes the transition to renewable energy in pre-processing of iron ore (known as “pelletizing”) and the use of non-fossil carbon as an alloying element in the final processing of iron to steel (HYBRIT 2018b). Figure 1 shows a comparison between the blast furnace route and the HYBRIT route.

An important component in terms of enabling low life-cycle emissions from the HYBRIT concept is that the Swedish electricity mix is almost completely fossil-free, currently composed of approximately 40% hydropower, 40% nuclear and 12% wind with the remainder made up of primarily biomass-fueled combined heat and power (Swedish Energy Agency 2020)³. This means that, if fully implemented, HYBRIT would entail a 98% reduction of CO₂ emissions per metric ton of steel compared to the blast furnace production route. Converting all of Sweden’s blast furnace-based steel production to a HYBRIT concept would translate to a 10% reduction in total Swedish GHG emissions. At the same time, though, the production of hydrogen would require vast amounts of electrical energy and increase Swedish electricity demand by around 10% of current Swedish electricity consumption (HYBRIT 2018b). Production costs have been estimated to be in the order of 20–30% higher with HYBRIT compared to today’s blast furnace-basic oxygen furnace process technology (HYBRIT 2018a).

HYBRIT has been presented as an undertaking spanning more than two decades, with full completion around 2040, at which point all of SSAB’s steel mills in Sweden and Finland would be converted to HYBRIT. In terms of technological maturity, some of the technologies and individual building blocks of the project are already available commercially, some have been scaled up to work at semi-industrial scales, and some have thus far only been proven at a lab scale (HYBRIT 2018b).

But just as a chain is no stronger than its weakest link, project readiness may come to be limited by its least mature process or technological component. Furthermore, even if all individual components were available off-the-shelf, process integration alone can itself be a significant challenge (cf. Merrow 2011). In addition, there are challenges of a more systemic nature, e.g., how to integrate an increased electricity demand in the order of 10% of current annual electricity consumption in Sweden. In other words, even though the technological challenges in themselves may not be unsurmountable, realizing the project’s ambitions will still be a long and, in all likelihood, complicated process.

² Other European H-DR concepts in development include SALCOS, GrinHY, SuSteel and H2FUTURE (Lechtenböhmer et al. 2018).

³ The coming decade will likely see an increase in the share of wind power and a decrease in the share of nuclear power, though the overall carbon footprint is unlikely to change much. Sweden has committed to having a 100% renewable electricity system by 2040 (Swedish Energy Agency 2019a).
1.3 The crucial role of the demonstration phase
According to the original roadmap presented by HYBRIT (2018a), the plan is to have the first commercial facility in place in 2035. This is to be preceded by trials in a pilot plant (2018–2024) followed by a demonstration phase (2025-2035). In this working paper we focus on the role that the demonstration phase can play on the path to full commercialization. In particular, we discuss pros and cons related to different setups and sizes of the demonstration facility. Given that the HYBRIT pilot phase is only in its early stages at the time of writing (early 2020), one might argue that it is premature to discuss the demonstration phase. However, as we discuss in more detail in section 2, pilot and demonstration phases may very well overlap and with the grand scale and scope of the HYBRIT project, it is important to initiate discussions on the demonstration phase early on. In addition, in September 2019 the HYBRIT owner companies stated their ambitions to accelerate the project time plan and have the demonstration plant in operation by 2026 (Hall et al. 2019). Consequently, demonstration plant planning within HYBRIT is increasingly becoming a near-term endeavor.
1.4 Report aim, research questions and outline

Recent years have seen increased focus on, and interest in, deep decarbonization of heavy industry. Several studies have shown that technologically, there are in fact substantial opportunities to achieve strong emission reductions in these so-called “hard-to-abate” sectors and that the costs involved could from a societal perspective be relatively modest (Bataille et al. 2018; ETC 2018). However, these discussions tend to be held at a fairly abstract and conceptual level. Our objective with this working paper is to take these discussions to a more concrete level and map risks as well as enabling factors that will be especially important for realizing deep decarbonization projects in the steel industry. While we focus on the HYBRIT project, many of the issues that we discuss will be relevant for other industries and in other geographical contexts as well.

Our analytical framework takes its starting point in the innovation systems literature, and in particular research that addresses the challenges involved in taking the final crucial steps towards full commercialization; what is often referred to as the “valley of death”. In heavy industry innovation processes, the demonstration phase tends also to be associated with **up-scaling**, i.e., a substantial increase in the scale and capacity of processes. We argue that scale is an important but somewhat neglected concept in the analysis of heavy industry innovation processes. In particular, the underlying rationale for why a demonstration project is designed to have a particular capacity is an issue that merits more attention. Choices connected to size and capacity are likely to influence both a) the value of a demonstration plant project and b) the risks associated with setting up and carrying out the demonstration phase itself.

We ask the following research questions:

- What are the key purposes of demonstration plants in general, and in the HYBRIT project in particular?
- How do choices pertaining to scale influence the risk/reward profile of a HYBRIT demonstration plant?
- How do overall project priorities affect the choice of demonstration plant scale?

In terms of empirical material, we draw on a broad range of sources, including published information by different actors involved in the HYBRIT project as well as a series of discussions with HYBRIT representatives at project conferences, workshops and meetings.

This working paper is organized as follows. Section 2 gives an overview of the existing research literature on pilot and demonstration plants (PDPs) and the lessons learned from previous studies on their implementation in different sectors. Section 3 presents the HYBRIT project in some detail and gives an updated (early 2020) view of developments in some strategic areas that we deem particularly important for HYBRIT. Section 4 discusses how the question of scale influences the setup of the HYBRIT project and presents two hypothetical setups – “small” and “large” – for the demonstration plant. Section 5 concludes with an overview of different risks and rewards related to the demonstration phase and discusses how these may play out under a “small” or a “large” case.
2. Demonstration plants and scale

2.1 Demonstration plants as bridges across the “valley of death”

The central challenge when it comes to any form of innovation process is how to take a solution that has been proven in a laboratory setting and implement it in a real-world setting. While successful tests at a lab-scale may be an indication that a technology could become a successful innovation, they are by no means a guarantee. In fact, most technologies that have passed lab tests do not become commercialized whereas others take many decades from lab to industrial application (Hellsmark, Frishammar, et al. 2016; Moore 2014). As the phrase “valley of death” suggests, this formative phase of technology development processes is characterized by a long list of complicated challenges and uncertainties pertaining to the development of the technology itself but also to financing, marketing and – especially relevant for cleantech – public policy (Jacobsson and Bergek 2004; Mossberg et al. 2018; Nemet et al. 2016).

A common approach to crossing the valley of death is gradual deployment of a technology in reduced scales and in settings that are shielded from market competition (Nemet et al. 2016). When implemented in process industries or the energy sector, these reduced-scale innovation infrastructures take the form of so-called pilot and demonstration plants, or PDPs (Frishammar et al. 2015a; Tolio et al. 2019). While PDPs have been the topic of much research in recent years, there is a lack of consensus around their terminology. Depending on context, the PDP category can include everything from large lab-scale facilities to semi-industrial plants producing at the same orders of magnitude as commercial installations. So, in terms of technology readiness level (TRL), the term PDP can be applied to installations all the way from TRL 5 to TRL 8 (e.g., Global CCS Institute 2009; Tolio et al. 2019).

A further point of confusion is that whereas some authors refrain from distinguishing between “pilot plants” and “demonstration plants” and only refer to different forms of “PDPs” (Frishammar et al. 2015b; Hellmark, Frishammar, et al. 2016; Mossberg et al. 2018), others speak only in terms of different forms of “pilot plants” (Tolio et al. 2019). Finally, others still reserve the term “pilot plant” for PDPs at the lower end of the TRL 5–8 interval, whereas “demonstration plants” are closer to commercialization (Global CCS Institute 2009).

In this study we will follow the latter approach of distinguishing between pilot and demonstration plants, for two main reasons. To begin with, our aim is primarily to analyze PDPs with a high TRL, for which the term “demonstration plants” is fairly well-established (Bossink 2015; Nemet et al. 2016). Secondly, the distinction between “pilot plant” (lower TRL) and “demonstration plant” (higher TRL) has been adopted by the HYBRIT consortium in its long-term plan and public communication. Following the same terminology should make the remainder of the report more accessible for the reader. Note also that this terminology largely follows the structure presented by the Global CCS Institute (see Table 1 below).

It is important to acknowledge that although envisioned as separate entities, pilot and demonstration phases may very well overlap and interact in various ways. For example, a pilot plant need not necessarily be abandoned as the project moves into demonstration phase. Instead, the pilot facility could be kept in operation to try out new solutions and optimize processes in parallel with both the demonstration phase and commercial operations. Figure 2 illustrates this process.

Finally, even if the distinction between pilot plant and demonstration plant is clear, there is still plenty of space for variation within the “demonstration plant” category. In the context of large process industries, it matters greatly if the demonstration plant is more of a “large pilot plant” or if it is more of a “small commercial plant”, because the latter might be an order of magnitude
Table 1. Nine technological readiness levels and corresponding pilot and demonstration plants.

<table>
<thead>
<tr>
<th>TRL</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>TRL-9</td>
<td>Full-scale commercial deployment</td>
</tr>
<tr>
<td>TRL-8</td>
<td>Sub-scale commercial demonstration plant</td>
</tr>
<tr>
<td>TRL-7</td>
<td>Pilot plant</td>
</tr>
<tr>
<td>TRL-6</td>
<td>Component prototype Demonstration</td>
</tr>
<tr>
<td>TRL-5</td>
<td>Component Prototype Development</td>
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<tr>
<td>TRL-4</td>
<td>Laboratory Component Testing</td>
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<tr>
<td>TRL-3</td>
<td>Analytical, “Proof of Concept”</td>
</tr>
<tr>
<td>TRL-2</td>
<td>Application Formulated</td>
</tr>
<tr>
<td>TRL-1</td>
<td>Basic Principles Observed</td>
</tr>
</tbody>
</table>

Source: (Global CCS Institute 2009)

2.2 Risks related to demonstration plants

Risk-reward balances
Demonstration plants sit at an awkward position in the innovation process. On the one hand, they play a crucial role in offering opportunities to test processes at a scale closer to that of a full-scale commercial setting. If successfully implemented, a demonstration plant should remove much of the risk associated with full-scale implementation of a commercial facility. However, whereas pilot plants realize some high initial rewards at very low risk and can be budgeted for as research and development costs, larger demonstration plants might have to operate at, or close to, commercial conditions. This means that demonstration plants themselves come with substantial risks due their size and the costs involved.
Ideally, then, a demonstration plant should be set up in a way that maximizes learning and reduces the risks of moving towards full-scale commercialization, but at the same time makes the demonstration phase itself as low-risk and low-cost as possible (Nemet et al. 2016). This balance can be illustrated in a modified version of a risk-reward curve (see Figure 3), where the “risk” is the risk of setting up the demonstration plant itself and the “reward” is the increased certainty about commercial viability accrued from learning in the demonstration phase, which then helps reduce risks in the steps to full commercialization.

Along this line of reasoning, the optimal design of a demonstration plant would be one that maximizes the amount of learning necessary for successful commercialization at the lowest possible risk and cost. Note, though, that this conceptual optimal point that maximizes the amount of learning per investment cost and demo project risk still will not provide all the lessons of actually building a full commercial-size facility. It is highly likely that there will be issues linked to the process, the supply chain or the business model that remain unresolved until the full commercial facility is up and running.

Figure 3. Design of demonstration plants can be seen as a question of finding a balance between risk (associated with the demonstration plant) and reward (learning and risk-reduction in the next steps towards commercialization). The size of demonstration facilities also tends to be correlated with technological readiness levels.

Mitigating demonstration plant risks
Clearly, the different forms of risk related to demonstration projects are associated with the technology being demonstrated. However, factors that relate to finance, policy and markets are often of equal or higher relevance than purely technological factors. Furthermore, these non-technological factors can interact in ways that further complicate the overall picture.

To begin with, owning and running demonstration facilities often comes with what is sometimes called first-mover disadvantages, where competing firms can observe and draw lessons from the demonstration project in question but without bearing any of the cost or risk (Nemet et al. 2016). This can be considered a positive externality to society at large but is obviously problematic for the firm that is investing in the demonstration plant. If the investment does not result in tangible competitive advantage, the firm might refrain from the investment altogether. This is commonly noted as a rationale for why public funding should be used for demonstration plants.
In general, financing demonstration facilities is difficult and fraught with potential obstacles. This is partly due to the sheer amounts required, because demonstration facilities – especially in the energy and heavy industrial sectors – can require investments of US$1 billion or more (Nemet et al. 2016). These kinds of investments are not uncommon in process industries and the energy sector, but even with mature technologies, these types of “megaprojects” tend to be associated with budget overruns and delays (Flyvbjerg 2014; Merrow 2011). In addition, the high-risk profile of immature technologies to be demonstrated in demonstration plants means that the challenge of finding a suitable funding setup increases further. For a pure research project, public funding would make the most sense, whereas a commercial project with mature technologies would be funded through standard project finance processes. But for demonstration plants, the means of financing tends to lie somewhere in between. Finding an appropriate mechanism for funding that balances the public-private financial burden in a way that still ensures private sector buy-in and “skin in the game” is difficult, but imperative (Åhman et al. 2018).

Policy risks overlap with financial risks, and are of two main types: a) dependence on public sources of funding to help cover capital costs, and b) business models that rely on public policies in the form of, e.g., renewable energy subsidies or a high price on carbon (Hellsmark, Frishammar, et al. 2016). This problem has been especially notable for projects focused on carbon capture and storage (CCS) (Nykvist 2013; Russell et al. 2012) and biofuel production (Hellsmark, Mossberg, et al. 2016; Mossberg et al. 2018). Both are technologies that rely heavily on policy measures (or in the case of biofuels, possibly a very high price of oil) for operational costs to be competitive and make the technologies and/or their products marketable.

In order to set up demonstration projects to minimize these risks, the literature points to a few key factors. From a policy perspective, it is important to work with a mix of measures that can meet the different demands along the road from the laboratory to commercialization. The mix should include both supply-push policies (such as R&D funding), and demand-side policies that improve the market competitiveness of clean technologies compared to less environmentally benign alternatives (Hellsmark and Söderholm 2016; Nemet et al. 2016). In terms of finance, there is a gap in the risk-profile of different investors: while there are venture capital investors willing to fund high-risk projects, they tend not to be willing to commit the kinds of sums that are necessary for revolutionary transitions in capital-intensive industries. At the opposite end of the spectrum there are investors – like pension funds – that have “deep pockets” and a long-term view in terms of investments but are looking for low-risk investments. Here, the public sector needs to step in to fill the gap and ensure availability of “risk-seeking but patient capital”.

2.3 Is bigger always better?

Economies and diseconomies of scale

Figure 2 also illustrates how the gradient from pilot plant to commercial plant runs in parallel with an increase in scale, i.e., a commercial facility is assumed to be larger in terms of production capacity than facilities at the lower down on the TRL scale (Wilson 2012). The underlying reason is that commercial industrial facilities tend to be characterized by economies of scale, i.e., a larger unit can be operated at lower average costs than a smaller unit (Buzacott 1982; Tribe and Alpine 1986). What scale of demonstration plant to opt for is a crucial decision, yet the underlying heuristics of such decisions have not been analyzed to a very large extent (Nemet et al. 2016). One reason for this is that the logic that underpins economies of scale can vary widely between technologies as a result of different and sometimes interacting factors (Buzacott 1982). Some factors are related to fundamental physical phenomena such as the cube-square rule in expanding equipment size, or the fact that industries dealing with high temperature processes are typically more energy efficient at larger scale. Other factors act on the organizational level.

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5 The capacity of many forms of industrial equipment increases with volume, whereas the amount of materials needed only expands with the surface area that encloses the vessel (Buzacott 1982).
For example, in most industrial activities, fixed costs such as overhead expenses tend to increase at a slower pace than a facility's capacity (Dahlgren 2013). Regardless of the underlying factors, though, there is a need for commercially operational facilities to be built at scales that reduce costs to a scale where the facility in question can compete on the market, commonly referred to as the minimum efficient scale (McGuigan et al. 2013; Nemet et al. 2016).

However, there are also diseconomies of scale, where average costs rise as production increases. As with economies of scale, diseconomies can be caused by both physical factors – e.g., by pushing structures beyond the point at which materials can support their own weight – or organizational factors related to problems of coordination in large organizations or projects (cf. Flyvbjerg 2014; Merrow 2011). The point at which the diseconomies start to dominate and overall average costs begin to increase with scale is called the maximum efficient scale (McGuigan et al. 2013). An illustration of the relationship between scale and average costs can be seen in Figure 4.

Figure 4. Relationship between scale and average costs.

![Figure 4. Relationship between scale and average costs.](Adapted from McGuigan et al. 2013).

However, it is important to emphasize that characteristics of specific technologies can have a substantial impact on the nature of scale economies. Some technologies, such as blast furnaces or large thermal power stations using steam turbines, rely heavily on economies of unit scale where costs decrease as the individual unit grows larger. Other technologies, such as solar photovoltaics, are more dependent on economies of numbers, where costs decrease as small individual units are mass-produced in large production facilities. There are also technologies that lie somewhere in-between. For example, wind turbines are an example of a technology whose economies of scale rely partly on individual turbines becoming larger and partly on mass-deployment of many individual units (Wilson 2012).

### 2.4 How do economies of scale play into the HYBRIT concept?

New industrial concepts – new scale logic?

It is important to note that as of yet the H-DR/EAF value chain is untested in a commercial setting. This means that it is not clear what the minimum and maximum efficient scales are. The shift from a blast furnace-basic oxygen furnace process to H-DR/EAF could entail a shift in the underlying logic of production economics. While the blast furnace is a classic example of a piece of equipment that relies on economies of unit scale based on the cube-square rule (Egenhofer et al. 2013),
several of the key processes comprising the HYBRIT value chain are somewhat different (see also Vogl et al. 2018). These processes include:

- Electrolyzers, used to produce hydrogen by using electricity to split water, are modular in the sense that above a certain level, capacity expansion tends to be achieved not by building a larger unit, but rather by adding more units to be operated in parallel (Schmidt et al. 2017). However, the threshold at which capacity additions are made by parallelization rather than increased unit size will likely vary between applications.

- Direct reduction (DR) shafts are commercially available with MIDREX and Energiron being the dominant suppliers. Both companies offer DR shafts in a range of sizes from “micro-modules” with a production capacity around 200,000 tons of DRI per year to custom modules with a capacity above 2 million tons per year. Most modules deployed in recent years have been in the range 1-2.5 Million tons per year (Energiron 2014; MIDREX 2019). It is important to note that while commercial DR shafts use natural gas, both MIDREX and Energiron emphasize that their respective systems can be adapted to use H_2 without major design modifications.

- Electric arc furnaces (EAFs) were the central technology behind the “rise of the mini-mills” in the last decades of the 20th Century (Chavez 1981). Mini-mills were relatively small steel mills that used scrap as raw material, and turned out to be economically very competitive with integrated blast furnace-basic oxygen furnace mills. A key reason for the success of mini-mills was that EAFs have a substantially lower minimum efficient scale than an integrated steel mill and can be deployed more rapidly and with lower capital outlay (D’Costa 1999).

Exactly how this shift in scale logic plays out in reality in terms of minimum efficient scale of the HYBRIT process is as of yet uncertain, but changes might occur in economies of scale both due to a more modular set of technologies and the potential for substantially higher operational flexibility built in to the H-DR/EAF process (Vogl et al. 2018). In addition, there could be a potential to change product market characteristics, i.e., to establish “HYBRIT steel” or “green steel” as a differentiated product distinct from steel in general. If “green steel” could warrant a price premium, this enables a new logic in the marketing of the steel as well and could in turn affect the cut-off point for what constitutes the minimum efficient scale.

Diseconomies of scale?

While there remain questions about economies of scale at the plant level, it is also important to acknowledge that issues of scale come into play at broader levels as well, i.e. in interactions with society at large. The required expansion both in electricity generation (most likely to be in the form of wind power) and transmission and distribution could entail diseconomies of scale. An expansion of wind power production in northern Sweden at the levels required to supply full deployment of HYBRIT could run into obstacles in the form of permitting delays and land-use conflicts (cf. Larsen et al. 2016). In addition, the demand for electricity that would follow from the need to produce adequate hydrogen for full deployment of HYBRIT would require additional transmission capacity. This would entail reaching a threshold where diseconomies of scale would rapidly increase. Again, the reason for this is that to increase transmission capacity entails risks linked to permitting, and controversy and competition over land use.

It is important here to emphasize that risks related to permitting and land use conflicts are not just time delays and increased costs, but are also reputational. Currently, HYBRIT is held in very high regard across the political spectrum in Sweden and is presented as a flagship project to global audiences (Karakaya et al. 2018; Magnergård Bjers 2019). If the project becomes entangled in long-running permitting processes over land use caused by the expansion of electricity generation, transmission and distribution, this may tarnish the project’s reputation and make it more difficult to brand and market HYBRIT steel as a green or sustainable product. Proactive, transparent and continuous engagement with stakeholders will be a crucial factor to prevent this.
3. HYBRIT overview, context and outlook

3.1 The HYBRIT time plan from pre-feasibility to demonstration

Figure 5 presents an overview of the original HYBRIT project time plan as it was laid out in 2018, with the pre-feasibility study (2016–17), pilot phase (2018–24) and demonstration phase (2025–35) in sequence.

As background, at this point it is worth reviewing the current status of the different phases, based on information available in early 2020.

In the summer of 2018 the HYBRIT pilot phase was initiated, as a SEK 528 million grant for the pilot phase was secured from the Swedish Energy Agency, with the remainder of the total pilot phase cost of SEK 1.4 billion to come from the HYBRIT owners LKAB, SSAB and Vattenfall (Swedish Energy Agency 2018). Shortly after this, construction of a pilot H-DR facility began in Luleå (LKAB 2018). In the following months, Tenova HYL/Energiron was contracted to supply DR technology for the pilot plant (Tenova 2018) and later NEL Hydrogen was chosen to deliver an electrolyzer solution with a capacity of 4.5 MW (NEL Hydrogen 2019). In addition to the H-DR plant, the pilot phase includes two additional components (HYBRIT 2019):

- Investigation and evaluation into using non-fossil energy (bio-oils and/or plasma technology) for heat in processing iron ore pellets. For this purpose, construction of a test facility in Malmberget began in April 2019 (LKAB 2019).
- Construction of a test facility for hydrogen storage in Luleå, to be carried out in 2021. This facility will evaluate the use of lined rock cavern (LRC) technology for hydrogen storage (see Johansson et al. (2018) for a review on LRC) and has more recently received complementary funding from the Swedish Energy Agency (2019b).

The original HYBRIT roadmap plans the demonstration phase for 2025–35, with demonstration plant operations to begin in 2028 (Mostyn 2019), thus indicating that 2025–28 will be dedicated to preparations and construction. However, a more recent announcement by Hall et al. (2019) implies an ambition to initiate operations for the demonstration phase in 2025 rather than 2028.
3.2 Outlook – current developments in the steel decarbonization landscape

Growing interest in H-DR steel: threat or opportunity?
Since HYBRIT was first presented in 2016 there has been a substantial increase in the rate of innovation in hydrogen-based iron reduction, with several European projects now operating in parallel with HYBRIT (Lechtenböhmer et al. 2018). This represents a risk for HYBRIT, especially in the light of how, for example, SSAB has emphasized the strategic importance of being the first company to commercialize fossil-free steel (Lindqvist 2019). At the same time, there are positive aspects to these developments. With the H-DR supply chain concept still being quite immature, there are gains to be made. More H-DR initiatives could make investors, suppliers and customers alike more comfortable with the idea of steel supply chains based on hydrogen produced from electrolysis. In other words it can reduce the overall perception of risk in the eyes of key stakeholders (cf. Egli et al. 2019).

A related issue that could become important is the expansion of the so-called “hydrogen economy” more broadly. The HYBRIT project could very well benefit from an expected growth of investment over the coming decade in hydrogen technology and infrastructure in the Nordic countries as well as globally (IEA 2019b). These benefits could come both in the form of growing societal acceptance of hydrogen as an energy carrier, but also from reduced costs. In particular, the modular technology characteristics of electrolyzers indicate that mass-production could push their cost downwards, as has happened with both solar PV and Li-ion batteries (Glenk and Reichelstein 2019).

Industrial electrification – aligned with infrastructure planning?
The HYBRIT project is the most prominent example in Sweden of an overarching trend towards electrification of society in general and heavy industry in particular. As noted in section 1.2, full implementation of HYBRIT is envisioned to demand electricity volumes in the order of 10% of today’s total Swedish consumption, with most of this demand needed for the electrolysis-based production of hydrogen. An inventory of how the decarbonization ambitions of Swedish industry would affect demand for electricity (SWECO 2019) identified a need for an additional 37 TWh of electricity between 2018 and 2045. However, it is worth noting that this scenario assumes a large amount of bioenergy in transport and industry. Scenarios that also include, for example, full electrification of personal vehicles and a large share of the heavy road vehicle fleet – an increasingly likely development (Nykvist and Olsson 2019) – would imply an even larger growth in electricity demand in coming decades.

In addition to the annual increases in Sweden’s overall demand for electricity, another, perhaps more important issue is transmission and distribution. This has come to the forefront of discussions of decarbonization in Sweden, especially in light of recent announcements that several urban areas already have problems with insufficient grid capacity (Stamn 2019; Stiernstedt 2019). Given that grid expansion is notoriously slow, largely due to time-consuming regulatory processes (Tenggren et al. 2016), this will become a critical parameter in HYBRIT. It is worth noting that discussions on Swedish electricity infrastructure have been focused on integration of more renewable energy into electricity supply, but – depending on how the plant is configured – commercial implementation of HYBRIT could entail an unprecedented level of point source demand in the order of 10 TWh per annum or more. This is a factor three to five times larger than any current single point load in Sweden (Widerberg 2014).

Large power transmission and distribution projects also tend to be characterized by controversies resulting from interactions with other forms of land use. This is an issue which is already a reality in the project that aims to supply power for the planned electric arc furnace at SSABs’ site in Oxelösund (TT 2019). And the electricity demand for the electrolysis phase of a full-scale HYBRIT
setup will be much larger than that needed for the electric arc furnace in Oxelösund. Hence, it is likely that electricity supply will be a critical component in the move both to demonstration and eventual commercialization of the full HYBRIT supply chain.

Another issue of potential relevance to HYBRIT are the tensions in northern Sweden between large industrial and infrastructure projects and the reindeer herding communities of the Indigenous Sami population. Reindeer herding requires large areas of land and even though individual projects – be they mines, wind farms, power transmission cables or railroads – may not appear in themselves to be significant users of land, the cumulative effects on reindeer herding from many parallel projects of this sort can be substantial (Larsen et al. 2016). Sweden has repeatedly been criticized by international bodies for not living up to its obligations when it comes to Indigenous rights, and there is significant regulatory uncertainty over how these issues will be addressed (Olsson et al. 2019).

Technology characteristics and exposure to policy
As noted in section 2, policy uncertainty has been highlighted as a key factor in unsatisfactory outcomes in large-scale demonstration projects. The reason why policy uncertainty is so central is that clean innovations often rely on policy measures to make them competitive against high-emitting alternatives in the market. However, it is important to be aware of differences in technology characteristics. Åhman et al. (2018) show that under the EU’s NER-300 programme, which funded large demonstration projects for climate change mitigation, projects focused on CCS and biofuel production were unsuccessful, while wind and solar projects fared better. It appears that CCS and biofuel production demonstration facilities need to be set up on a large scale to be relevant, while “granular” technologies like wind and solar are less reliant on economies of unit scale, enabling rapid technological learning and associated cost reductions (Samadi 2018; Wilson et al. 2020).

Wind turbines and solar PV are examples of technologies that in many ways (especially so for solar PV) are completely different from conventional fuel-based systems for electricity generation. Hence, technological development for these takes place along different pathways than those for traditional power stations. While public policy support – e.g., in the form of Germany’s Energiewende – has obviously played a key role in enabling technological development, market introduction and industrial scale-up of solar and wind (Nemet 2019), these technologies are in many places becoming cost-competitive even without support for operating expenses in the form of tax exemptions or direct subsidies. In contrast, CCS and biofuels are technologies that at their heart are very similar to the incumbent high-emitting systems. It is difficult to imagine how biofuels or CCS could compete with fossil transportation fuels or a non-CCS fossil fuel power station or industrial facility without policy support in the form of subsidies or a high price on carbon. In other words, biofuels and CCS are technologies that will depend heavily on a stable policy framework over the foreseeable future to ensure market demand, whereas technologies like wind power and solar PV seem more compatible with policy measures that can gradually be phased out as technologies and markets mature.

In light of the above it is worth noting that the HYBRIT process is in several ways quite different from the incumbent blast furnace-basic oxygen furnace process in the steel industry. First, whereas the latter process is very mature and approaching its theoretical limits in terms of efficiency, at least parts of the HYBRIT process draw on relatively immature technologies that should hold potential for cost reductions. As noted in section 2.4, this seems especially likely for the hydrogen production phase, because electrolyzers from a broad technology perspective are quite similar to solar PV and Li-ion batteries. They are modular and have economies of scale that are realized by adding more (largely identical) units rather than by only building bigger units (Schmidt et al. 2017). This opens up prospects for mass-production, manufacturing automation and substantial cost reductions (Glenk and Reichelstein 2019). In fact, with very low electricity prices and low capital costs for electrolyzers, the H-DR process has the potential to be cost-competitive with the blast furnace-basic oxygen furnace process even in the absence of a price on carbon (Hall...
et al. 2020; Vogl et al. 2018). In other words, while the policy landscape is noted as an important challenge in the pre-feasibility study (HYBRIT 2018b), the H-DR process may in the long run turn out to be less vulnerable to policy fluctuations and CO$_2$ price developments than CCS.

The role of product markets

An important aspect of demonstration plants that has been given relatively little attention in the literature is marketing of what is produced in the demonstration plants. This could be due to the substantial focus on technologies used for electricity generation or fuels production. These can be characterized as commodity markets with fungible goods – i.e., one unit on the market is equal to any other unit – in effect leading to a situation where unit price and production cost become the central factors for market competitiveness (Radetzki 2010). Although steel is sometimes referred to as a commodity market (Englyst et al. 2008), this is only partially true. In reality, the steel market is composed of several different sub-markets where some do have commodity characteristics whereas others are more niche-like, where brands and marketing play an important role (Schorsch 1994).

In relation to biorefinery demonstration facilities, Mossberg et al. (2018) note that one problem is that “…there are few (if any) naturally occurring niche markets for the products emanating from advanced biorefineries in Sweden; this implies that an important role for policymakers is to create and maintain such niche markets through some kind of support scheme” (p.87). The situation in the steel market is somewhat different. Niche markets in steel have developed over the last two decades as a result of a global over-capacity in the 1990s, which forced steel companies either to consolidate or seek out niche markets (Ahlberg et al. 1999). The price of different types of steel reflects different value-added and end-products – such as a car – often contain a mix of steels with a wide range of costs (Rootzén and Johnsson 2016). In the case of HYBRIT, SSAB produces a wide range of steels from commodity steels to niche products characterized by a strong focus on customer relationships (Alriksson and Henningsson 2015; Skarp and Gadde 2008). It is also worth emphasizing that Ruuki steel, now a part of SSAB, has been showcased as a company that managed to reinvent itself by building a successful brand around what was previously considered a commodity product (McQuiston, 2004).

To the extent that marketing is discussed in the literature on demonstration projects, focus tends to be on exploring possible markets for new products emerging from, for example, a biorefinery (Mossberg et al. 2018). But from SSAB’s perspective, the challenge of HYBRIT seems to be more about retaining its existing product portfolio while replacing the very core of the production process. In this context, and related to the discussion on the role of niche markets, an important question to ask is whether the fossil-free qualities of HYBRIT steel could enhance SSAB’s offer. Of course, a key factor here is what the price premium for “green steel” would be and how costs of the HYBRIT steel production route compare with the incumbent blast furnace route.

Financing: what capital is available?

In terms of financing, the HYBRIT demonstration plant could be a familiar illustration of how large-scale demonstration plants are a poor fit for existing funding mechanisms. The technological setup is not proven in commercial operations and the capital required will likely be in the order of US$ 1 billion or more (see section 4 and Nykvist et al. (2020)), which from most perspectives is a very large investment. From the point of view of financial actors, investments in decarbonization technologies has to follow the same risk-reward calculations as other investments, unless new mechanisms of risk-sharing are developed. This imposes important limits on the expectation of which types of sustainability projects will gain access to finance (Nykvist and Maltais, submitted manuscript).

So a critical question is this: what characterizes HYBRIT as an investment? A demonstration plant of the same size as a commercial scale plant has to operate under long term certainty – possibly
a period of several decades. It is unlikely that it would be possible to find a (private) commercial investor whose risk profile would accommodate taking on the full extent of this investment. Consequently, some form of public capital will have to play a role. While the HYBRIT pilot plant was financed partly from *Industriklivet*, a programme run by the Swedish Energy Agency aimed at supporting decarbonization innovation in heavy industry, annual funds available within the programme are limited to SEK 600 million (around EUR 60 million). This is likely at least ten times smaller than what will be needed for the demonstration phase.

The question of funding thus may have to go beyond Sweden and become an EU matter. Funds could, for example, be sought via the European Investment Bank or the EU Innovation Fund, the successor to NER-300 (European Commission 2019a). Notably, the European Commission explicitly mentioned a breakthrough in zero-emission steel production as a component in the European Green Deal that it presented in December of 2019 (European Commission 2019b). However, given the growing number of hydrogen-based initiatives in the European steel sector, it is likely that HYBRIT will face competition with other European consortia that aim to demonstrate breakthrough technologies for decarbonizing steel sector decarbonization (Lechtenböhm et al. 2018).

Finally, building on strong brands and relationships with existing and prospective customers (see previous section) interested in fossil-free steel could also help to reduce risks in the demonstration phase. Prospective battery customers helped fund the Northvolt battery factory currently under construction in northern Sweden (Kane 2019) and, similarly, there could be potential for the HYBRIT demonstration plant to be co-funded by steel customers. One approach could be to set up offtake agreements, through which customers would contract volumes of the product before a production facility is set up, so reducing some of the uncertainty around market demand (Yescombe 2013). Another option could be to set up a new joint venture that includes other supply chain partners, in addition to the three owner companies. One advantage of this could be to enable the demonstration phase to serve the role of testing new business models for marketing of fossil-free steel, building on existing SSAB experiences around marketing of premium steel products.
4. Risk analysis of a HYBRIT demonstration plant from a scale perspective

4.1 Two hypothetical demonstration plants: “small” and “large”

Both the HYBRIT consortium and the literature on innovation systems agree that a demonstration plant should be “sub-scale” and, in terms of capacity, lie somewhere in between a pilot plant and a commercial plant. However, this is still a quite broad range, as the H-DR pilot facility in the HYBRIT case has an iron ore reduction capacity that is a mere 1% of that of a commercial blast furnace.

In the concluding discussion, we focus on how the scale of a HYBRIT demonstration plant affects both its value in terms of learning and on the characteristics of risks associated with the setup of the demonstration plant.

We envision two hypothetical H-DR demonstration plants that are distinctly different in terms of capacity. They are both significantly larger than the HYBRIT pilot plant yet significantly smaller than a typical commercial primary steel mill in terms of iron reduction capacity. The first one, which we call “small”, is a demonstration plant that is more akin to large pilot plant, whereas the second one, “large”, is closer to the size of a commercial facility.

The specifications for the two options draw on the assumption that the H-DR unit to be used for the HYBRIT demonstration phase will be based on existing DR shafts offered by MIDREX (2019) or Energiron (2019). “Small” is based on the smallest commercial DR system we could identify (an Energiron micro-module) and “large” was selected to be substantially larger than “small” but still with substantially smaller iron reduction capacity than corresponding blast furnaces on SSAB sites.

Table 2 gives an overview of the two hypothetical alternatives. Included for comparison are also specifications for the pilot plant and an envisioned future commercial facility. The setup of the latter is based on HYBRIT (2018b), except for the cost estimates, which are based on Nykvist et al. (2020). Note that the cost figures for the two hypothetical demonstration facilities should be seen as “guesstimates”. Electrolysis capacities for the two demonstration plant alternatives and the commercial unit are based on estimations from MIDREX of 400 MW needed for a 1 million tons/annum H-DR shaft.

Table 2. An overview of different hypothetical setups for the HYBRIT demonstration phase. The HYBRIT pilot plant – currently in construction – is included for comparison, as is an approximate setup for a fully commercial unit. (SEK 1 = USD 0.1 in May 2020)

<table>
<thead>
<tr>
<th></th>
<th>Pilot</th>
<th>Demo option 1: “Small”</th>
<th>Demo option 2: “Large”</th>
<th>Fully commercial unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRI capacity</td>
<td>15 000 t/y</td>
<td>200 000 t/y</td>
<td>800 000 t/y</td>
<td>2 500 000 t/y</td>
</tr>
<tr>
<td>Electrolysis capacity</td>
<td>4.5 MW</td>
<td>~80 MW</td>
<td>~320 MW</td>
<td>~1000 MW</td>
</tr>
<tr>
<td>Investment need</td>
<td>SEK 1.4 billion</td>
<td>SEK 5-10 billion</td>
<td>SEK 10–15 billion</td>
<td>SEK 20 billion</td>
</tr>
</tbody>
</table>
4.2 Framework for risk mapping

We evaluate the value of a “small” and “large” demonstration plant by qualitatively discussing the extent to which each alternative mitigates key risks and reduces key uncertainties that should be resolved before full commercialization. In parallel, we also discuss the risk profile of the deployment of each alternative.

The risk mapping uses nine different risk categories, divided into three different themes: a) technical, b) political/societal and c) business/financial. The selection of the risk categories is based on a set of challenges identified and analyzed in the HYBRIT pre-feasibility study (HYBRIT, 2018a, pp. 51–53). However, we augmented this set of risks with some additional aspects that we found to be particularly important based on our review of the literature streams on innovation systems and mitigating risk in megaprojects (Denicol et al. 2020; Merrow 2011). Table 3 gives an overview of the set of risks used in the mapping.

Table 3. Overview of risks used in the risk mapping.

<table>
<thead>
<tr>
<th>Risk category</th>
<th>Risk specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological (T)</td>
<td>T1. H-DR technology</td>
</tr>
<tr>
<td></td>
<td>T2. Hydrogen production and storage</td>
</tr>
<tr>
<td></td>
<td>T3. Value chain process integration</td>
</tr>
<tr>
<td>Societal / institutional / political (S)</td>
<td>S1. Electricity supply</td>
</tr>
<tr>
<td></td>
<td>S2. Regional coordination and permitting processes</td>
</tr>
<tr>
<td></td>
<td>S3. Climate policy</td>
</tr>
<tr>
<td>Business case and financial (B)</td>
<td>B1. Internal coordination and cross-value chain optimization</td>
</tr>
<tr>
<td></td>
<td>B2. Marketing of green steel</td>
</tr>
<tr>
<td></td>
<td>B3. Financial risk and cost of capital</td>
</tr>
</tbody>
</table>

4.3 Risk mapping: how does scale influence opportunities to mitigate risk?

Technological risks

T1. Hydrogen direct reduction

Hydrogen direct reduction is the technology that forms the heart of the HYBRIT process. Gaining a comprehensive understanding of this technology will be a crucial component of the pilot phase that will begin in summer 2020. However, verification of and confidence in the fundamentals of the H-DR process at the pilot level is a necessary precondition for any move to the demonstration phase. Therefore, issues related to verification of H₂ reduction technology should not be an important factor in the decision to build a large or small demonstration plant.

T2. Hydrogen production and storage

The fact that the hydrogen used for direct reduction is produced via electrolysis using low-carbon electricity is – in combination with a fossil-free fuel used for iron ore processing – what enables the HYBRIT process to have very low CO₂ emissions compared to blast furnace-based steel production (ETC 2018; Vogl et al. 2018). In terms of risk profile, electrolyzers can be procured off-the-shelf and can be scaled in a modular way by adding more electrolyzers. This indicates a low level of technological risk and room for flexibility in design. On the whole, therefore, issues pertaining to the production of H₂ should not be a very important factor when it comes to the decision of whether to build a large or small demonstration plant.
The storage facility is different in that it will be a bespoke on-site construction, and increasing its size will obviously be more difficult than increasing the number of electrolyzers. However, the actual size of the storage is, as far as our analysis reveals, not a crucial factor for the scale of the demonstration plant. However, it is clearly important in terms of permitting and for the integration of HYBRIT into the Swedish electricity system, issues that we discuss further in section 4.3.

T3. Value chain process integration
This challenge is partly similar in nature to T1 in that the core technical feasibility of combining hydrogen direct reduction with downstream steel manufacturing must be validated in the pilot phase. Key uncertainties need to be eliminated before the move to the demonstration phase, regardless of the scale of the latter. However, if the challenge is more related to the integration of technologies across the value chain, this poses a different challenge. How to optimize and best integrate technologies across the whole process is an issue that is probably only possible to resolve at a large-scale demonstration plant closer in size to a commercial plant. Hence, this challenge is important to deciding on the size of demonstration plant, but the whole question is also inextricably linked to navigating business risk as well as the long-term strategic choices and positioning among LKAB, SSAB and Vattenfall.

Societal, institutional and political risks

S1. Electricity supply
The centrality of electrolysis-based H\(_2\) production for the overall HYBRIT concept makes availability of adequate electricity supply essential for the completion of the HYBRIT project. It is also a factor that may become crucial to the decision on the size of the demonstration plant. For the “large” demonstration plant, the total annual electricity demand will be in the same order as the largest individual industrial power consumers in Sweden today (Widerberg 2014). However, the question here is not so much about the availability of electricity volumes on an annual basis as it is a question of integration with the power grid. There have been exhaustive discussions in Sweden in recent years about the consequences of growing shares of variable power generation on the grid, resulting from a rapid increase in wind power generation (especially in the northern parts of the country) and concurrent closure of two nuclear reactors. However, this need not be a risk for the HYBRIT project, because one of the key roles envisioned to be played by the hydrogen storage component is to draw on electricity price variability and match hydrogen production with time periods of, for example, excess wind power generation (HYBRIT 2018b).

A potentially more challenging issue is to secure sufficient power transmission capacity at a specific site, because this could set limits in terms of maximum load and hence maximum electrolysis capacity. In addition, the grid connection might require redundancy. Today’s regulation and concession processes are not tailored for this unprecedented type of large-scale connection to the grid. We argue that this is a factor that can be very important for determining the size of the demonstration plant. It may be only with a “large” demonstration plant that the full set of barriers and challenges related to national grid infrastructure is exposed. At the same time, this means that the potentially difficult question needs to be addressed in the near-term so as to ensure that the issue is resolved in line with the accelerated time plan presented by Hall et al. (2019).

If a “small” demonstration plant can be built in a way so that its power demand for hydrogen production is manageable within current boundaries of power infrastructure, or if the infrastructure can be easily adapted, this could be a backup option (See S2). On the other hand, opting for the “small” option could also mean that a significant challenge in moving to the commercial scale is not demonstrated and tested and hence the value of the demonstration phase would be reduced. If the integration of power grid infrastructure with the national grid is
the only major challenge remaining, then it might still be better to address this problem early and initiate work on permitting and coordination with local and national authorities rather than postponing it. If, on the other hand, significant new power grid connections are needed regardless of the size of the demonstration plant, it is not a key determining factor in choosing the size of the demonstration plant.

S2. Permitting and stakeholder relations
Closely related to S1, availability of power transmission capacity is increasingly a topic for discussion in the Swedish debate on societal electrification. There is a discrepancy between a) the pace foreseen in many electrification ambitions and b) the pace at which new transmission capacity can be built (Pöyry 2018). The extensive time frames are largely a result of lengthy permitting processes. Permitting, as it relates to decarbonization of heavy industry more broadly, is a key factor both for investments at industrial sites, including the hydrogen storage in HYBRIT, but permitting and stakeholder acceptance for supporting electricity infrastructure may be equally important.

This is an issue that already affects the HYBRIT project in that the transition to EAF at SSAB’s site in Oxelösund hinges on the completion by 2025 of a new distribution-grid connection to enable a sufficient increase in power capacity (TT 2019). We argue that this is a factor that will be very important for the size of the demonstration plant. If the demonstration plant will be of a scale that requires expansion of power transmission and an extensive permitting process, the significant time frames involved could disrupt the overall HYBRIT time plan.

S3. Climate policy
Not only will the demonstration phase entail a substantial increase in capital expenditure compared to the pilot phase (see B3), the demonstration phase will also have greater component of operational expenses (OPEX). This could be challenging given that costs of production from a first-of-a-kind plant will likely be uncompetitive compared to mature production processes. As the HYBRIT process matures and moves into commercial operations, the impact of CO$_2$ prices on fossil-based steel could be an important factor in favour of HYBRIT, but this may not be sufficient at the demonstration phase.

For the demonstration phase, higher OPEX costs would need to be covered either through public funding (e.g., EU innovation fund) or by finding customers that are willing, or required by regulation, to pay a premium for fossil-free steel. This is an important factor for the decision on scale. If (at least) one of these two options are in place, this speaks in favour of a large demonstration plant (see also B2).

Business case and financial risks

B1. Internal coordination and cross-value chain optimization
The HYBRIT project not only consists of several different technological subsystems, it is also run as a joint venture that includes three large companies, each with their unique business logic, ownership and organizational structure. This means that internal coordination is as much a matter of organization as it is a matter of technology. In general, this is a challenge that grows with the size of the effort and larger economic stakes (Merrow 2011). Internal coordination and a shared view across the consortium of how to move forward is very important for the move to the demonstration phase. This is especially so for a large demonstration plant, although we deem it to be a necessary condition independent of the size of the demonstration plant.

B2. Marketing “green” steel
We argued in section 3 that SSAB could be well-positioned to bundle high sustainability credentials into its existing offering of premium high-quality steels. However, a question that remains is how much extra customers are willing to pay for “green” steel (Vogl and Åhman 2019),
and conversely, how costs of early HYBRIT steel volumes compare with the incumbent blast furnace route. The pre-feasibility study (HYBRIT 2018b) points towards 20–30% higher costs than the blast furnace-basic oxygen furnace process, although this obviously depends on a range of factors, especially capital costs of electrolyzers and market prices of electricity, coking coal and CO₂ emission credits. In addition, the 20–30% range may not be valid for early volumes produced in a demonstration plant. On the demand side, HYBRIT has received plenty of positive attention and is an early mover in terms of implementation of deep decarbonization in heavy industry, which should improve demand prospects. If there are strong indications from market actors and/or policymakers that high initial demand for fossil fuel free steel is likely, this speaks in favour of a larger demonstration plant.

### B3. Financial risks and costs of capital

The largest percentage increase in cost for HYBRIT DRI steel compared to the blast furnace-basic oxygen furnace process stems from increased capital costs (HYBRIT 2018b). In a similar way that wind and solar power energy requires higher capital expenses (CAPEX) but lower operational expenses (i.e. no fuel cost), this makes HYBRIT comparatively more sensitive to challenges related to financing. It is thus very important to reduce uncertainties around assumptions about, for example, the lifetime of equipment, which could be possible to demonstrate with both a “small” or a “large” demonstration plant.

However, there will probably be a substantial differences between the two in terms of financial risk and associated challenges, especially when it comes to availability of different sources of funding. Whereas a “large” demonstration plant will probably have to rely on conventional “commercial” sources of funding, a “small” demonstration plant will be more akin to an R&D facility and it is therefore more likely that it would be eligible for, and potentially depend on, funding from the national level or EU innovation support (e.g. the EU Innovation Fund). However, even if investment support might be available for a large-scale demonstration plant, it likely has to operate under commercial conditions, and although some public sources of funding include provisions to provide OPEX support (European Commission 2019a), it is not a given that this is available. The kinds of funding options available is thus a very important factor in deciding on the size of the demonstration plant.

In addition, there are key uncertainties around access to and the cost of capital (weighted average cost of capital). However, as we noted in section 3.2, increased interest among other steel companies in H-DR steel could reduce perceptions of risk among investors and so reduce the cost of capital (cf. Egli et al. 2019). Furthermore, a continuously changing policy landscape that favours stronger regulation of climate change should mean that risk factors applied in capital cost calculations for low-carbon technology will go down, and risk factors for fossil fuel steel should go up. Indications of reduced risk perception among investors speaks in favour of a larger plant.

Another approach that could potentially reduce risk for HYBRIT in both a large-scale demonstration phase and commercial operation, is to consider investments in renewable electricity and hydrogen production as a bundled business case. Electricity is a key factor in the overall cost calculation for HYBRIT (Vogl et al., 2018), but also one that can be quite uncertain given the substantial variation in electricity prices. An opportunity to address this is to vertically integrate investments and develop new wind energy using power purchase agreements between HYBRIT and electricity providers. This has the potential to reduce the risk for both parties. If low-cost wind energy can be developed through large power purchase agreements, this points in favour of a larger demonstration plant.

In summary, we find that the non-technical risks (i.e. societal/political and business/financial) are the ones where the choice between “small” and “large” are most important. An overview of these assessments can be found in Table 4.
Table 4. Overview of non-technology risk factors and how they influence decisions in terms of demonstration plant size

<table>
<thead>
<tr>
<th>Risk category</th>
<th>Risk factor</th>
<th>Importance for demo size</th>
<th>Comments</th>
<th>Assessment based on current indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Societal/ political</td>
<td>S1. Electricity supply</td>
<td>High</td>
<td>Availability of large power capacity crucial for H-DR, could become a bottleneck and a central design factor for the demo.</td>
<td>Two cases: if transmission expansion necessary regardless for both small and large – build large demo. If small demo can be built without transmission expansion - consider small demo.</td>
</tr>
<tr>
<td>Societal/ political</td>
<td>S2. Permitting and stakeholder relations</td>
<td>High</td>
<td>Permitting and stakeholder relations crucial for S1. See S1.</td>
<td></td>
</tr>
<tr>
<td>Societal/ political</td>
<td>S3. Climate policy</td>
<td>High</td>
<td>Public support needed to co-fund demo CAPEX and possibly also OPEX.</td>
<td>Build large demo.</td>
</tr>
<tr>
<td>Business/ financial</td>
<td>B1. Internal coordination</td>
<td>High</td>
<td>Common strategic view on business model &amp; ownership structure becomes more important with larger demo and larger economic stakes.</td>
<td>Uncertain. If agreement on key strategic issues – build large demo.</td>
</tr>
<tr>
<td>Business/ financial</td>
<td>B2. Marketing “green” steel</td>
<td>Medium-high</td>
<td>A larger plant enables establishment of a foothold as leader in green steel, but comes with higher OPEX risks.</td>
<td>If customers indicate demand for early HYBRIT steel (especially at premium), build large demo.</td>
</tr>
<tr>
<td>Business/ financial</td>
<td>B3. Financial risks &amp; costs of capital</td>
<td>High</td>
<td>HYBRIT relatively more CAPEX-intensive than the blast furnace-basic oxygen furnace process, hence cost of capital important. Different forms of funding available depending on demo size. Larger demo likely more reliant on commercial funding.</td>
<td>Stronger global emphasis on climate action should reduce relative cost of capital of HYBRIT compared to fossil-based steel. If this shift is already apparent in discussions with funders, build large demo.</td>
</tr>
</tbody>
</table>

4.4 “Large” and “small” demonstration plants – different risks, different rewards?

Table 5 illustrates how first the pilot plant, and the two alternative types of demonstration plant could enable the HYBRIT consortium to realize different levels of learning on the route to full commercialization. The role of the pilot plant should be to remove key uncertainties pertaining to technology, whereas the demonstration phase should be more about testing the concept more broadly. A “small” demonstration plant can provide learning across several non-technical risk factors, but, as is illustrated in Table 5, it could be too small to assess other key factors, especially relating to business model setup, infrastructure and permitting.
5. Discussion

5.1 In this case, bigger seems to be better
In this working paper, we have drawn on research from the innovation systems literature to discuss how decisions that relate to scale and capacity of the HYBRIT demonstration plant influence a) the learning value of the demonstration phase towards full commercialization, and b) the risks associated with the deployment of the demonstration plant itself.

With the aim of making this discussion more tangible, we have centred our analysis around two different hypothetical HYBRIT demonstration plant alternatives: one “small”, which is more of a large pilot plant (80 MW electrolysis capacity) and one “large” that is of a size (320 MW electrolysis capacity) closer to commercial scale. Note that we do not consider that both of these would be built – rather, we see it is a decision of going for either small or large.

Our analysis finds that in the choice between the two alternatives, there is much that points in favour of building a large demonstration plant. We argue that the key challenges that need to be addressed in the demonstration phase are related not only to technological aspects but also – and perhaps to a greater extent – to societal integration, supply chain coordination and business models. These are areas where the lessons learned from a “small” demonstration plant might not be sufficient in terms of risk reduction for a subsequent move to full commercialization. Building a “large” demonstration plant would initiate important collaborations with authorities and society at large, and could enable important first-mover advantages linked to the introduction of fossil-free steel in product markets.

Table 5. Illustration of how different steps in the HYBRIT innovation process could realize different levels of learning on the road to full commercialization. Light green = partial learning and dark green = substantial learning.

<table>
<thead>
<tr>
<th>Step Description</th>
<th>Pilot</th>
<th>“Small” demo</th>
<th>“Large” demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>B3. Financing and cost of capital</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2. Marketing “green” steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1. Cost optimization and value chain viability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3. Climate policy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2. Permitting and stakeholder acceptance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1. Electricity supply</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3. Process integration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2. H₂ production and storage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1. Hydrogen direct reduction of iron</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
At the same time, Nemet et al. (2016) note that scaling up demonstration plants too rapidly is “asking for trouble” (p.33). As we have discussed, choosing the “large” demonstration plant will also entail challenges for the HYBRIT project, especially if the accelerated time plan announced in September 2019 is to be followed. We argue that risks pertaining to ensuring sufficient electricity supply capacity for a “large” demonstration plant could be particularly challenging. This is because of the very long time periods that may be needed for to gain permits for and to deploy power transmission infrastructure. In addition to the risk of delaying the overall HYBRIT time plan, a drawn-out permitting process might also include conflicts with local and regional stakeholders. If the “large” alternative is chosen, it is crucial to promptly initiate planning and consultation processes with authorities and key local stakeholders to reduce the risk of regulatory issues becoming bottlenecks.

5.2 Demonstration and scale-up for industrial decarbonization

A central theme that has run through this analysis is that to reduce risk you have to take risk. In other words, it is necessary to take a certain amount of risk in the formative phase of an innovation process so that once the step to full commercialization is taken, the amount of remaining risk has been minimized and the likelihood of the full-scale investment being a success is maximized. In certain respects, technological development in recent decades has enabled the early costs and risks of innovation processes to be reduced, because things like chemical processes and energy flows within industrial equipment can now be simulated in computer models, which enables learning at relatively low cost without having to build the physical equipment itself.

However, when it comes to the issue of transitioning heavy industry to technological pathways that align with global climate change mitigation ambitions, full understanding of the underlying science and the technological systems still leaves substantial amounts of uncertainty about the viability of the concept as a whole. Small pilot plants are important when it comes to improving confidence in the technological side of the innovation, but this is only one component of many that need to be in place for commercial viability. In the highly capital intensive and often very competitive world in which heavy industry companies operate, processes and equipment will have to be in operation at high capacities for years or even decades, product quality needs to be consistent and internal and external material flows need to run smoothly (cf. Gertenbach and Cooper 2009). These are areas where key challenges may only be revealed once a certain scale is reached; one that allows continuous operations under close-to-commercial conditions. In addition, then, several issues linked to interactions with markets, regulation and external stakeholders require a certain scale to be tested in a way that enables learning that has true value for the eventual step to commercialization.

In section 2.4, we reasoned that it is not self-evident that the H-DR/EAF process will be characterized by the same sort of logic in terms of technological economies of scale as the incumbent blast furnace-basic oxygen furnace process. However, we still found the “large” demonstration plant to be the more attractive option for HYBRIT, and this largely based on a list of predominantly non-technical aspects, where we argued that there are notable gains from greater scale in the form of reduced uncertainties. This is a reflection of the multifaceted nature of the “economies of scale” concept as highlighted by Buzacott et al. (1982), who describe economies of scale as playing out differently on different levels in an organization, from the component/unit level, to plant/site level, to the level of the organization/company and finally to the industrial or societal level. The compound logic of these different levels will vary not only between industries but between jurisdictions as well, which means it is difficult to see how it would be possible to devise simple rules-of-thumb for demonstration plants in the broader context of industrial decarbonization. On the whole, however, it is becoming increasingly important that policymakers and business leaders alike shift their view of deep decarbonization in heavy industry and move away from conceptual discussions to on-the-ground deployment.

6 Here, experiences from CCS projects in the 2000s and early 2010s give clear examples of how technological aspects can be far from being the most important obstacles (Russell et al. 2012).
References


