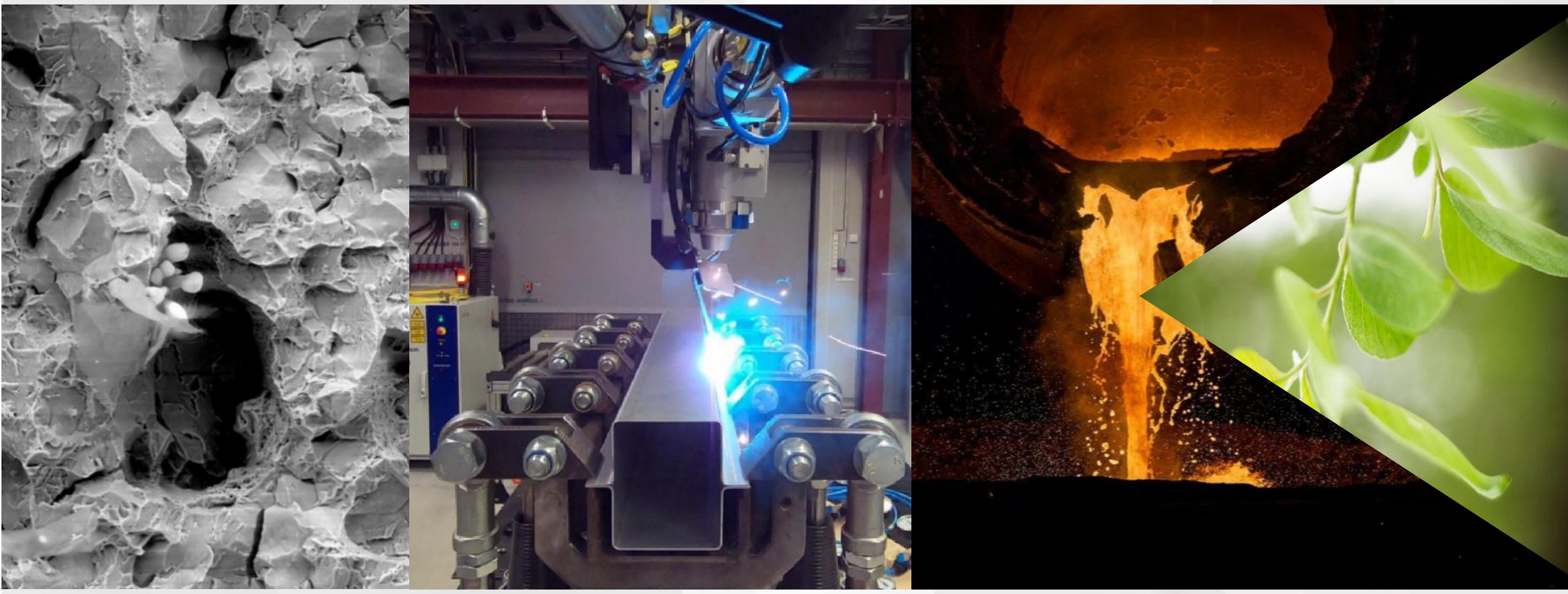

Final report HåBiMet - Social perspective

Erland Nylund, Tova Jarnerud Örell, XingQiang Song, John Pettersson, William Di Francesco

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Research Report

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Final report HåBiMet - Social perspective

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Report number Swerim-2025-221

Customer value

HåBiMet – social perspective **has investigated the potential challenges and opportunities related to social acceptance and skill supply of the supply chain for metallurgical biocarbon in Sweden. The project findings indicate that social acceptance is not a major barrier to developing the supply chain currently, but there are opportunities to ensure that metallurgical biocarbon is well received and provides societal benefits.**

The project has identified how different actors can contribute to using opportunities and improving the social impact and conditions for metallurgical biocarbon:

- **Greater exchange of knowledge and information between actors in the metallurgical biocarbon supply chain would aid further development**
- **Lack of standardisation and coordination is a barrier to adoption, market development and acceptance**
- **There is considerable knowledge sharing between some actors, and in particular utilisation of research opportunities. In the future wider training and upskilling related to metallurgical biocarbon may be needed across several industries.**
- **Establishing best practices and better understanding of fire safety and workplace safety when handling biocarbon is a high priority for most stakeholders.**
- **Further research should seek to better understand the social and environmental impacts of metallurgical biocarbon compared to other biomass- and biocarbon uses. Regional development and social benefits from biocarbon should be better understood.**

Abstract

The *HåBiMet – Social Perspective* project investigates the social dimensions of establishing a sustainable supply chain for metallurgical biocarbon in Sweden. As the metal industry transitions toward fossil-free production, biocarbon is emerging as a critical enabler in processes where hydrogen cannot fully replace carbon. This feasibility study focuses on two key social factors: public acceptance and the availability of relevant skills across sectors.

Through stakeholder interviews, workshops, and a master's thesis, the project identifies current perceptions, institutional barriers, and opportunities for collaboration. The findings suggest that while social acceptance is currently not a major obstacle, it remains vulnerable to misinformation and biomass competition. Similarly, skill supply is adequate but requires strategic development, particularly in fire safety, process optimization, and cross-sectoral knowledge.

The study emphasizes the importance of knowledge sharing, standardization, and regional development. It highlights the potential for biocarbon production to contribute to rural job creation and industrial symbiosis, especially in forest-rich areas. The project concludes by recommending further research into social and environmental impacts, and by proposing collaborative initiatives to ensure that metallurgical biocarbon contributes meaningfully to Sweden’s green transition.

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1 Background

As Swedish metal producers are transitioning toward fossil-free production methods, various options for replacing fossil materials such as coal and fuel gases are being explored. The largest steel producer in Sweden, SSAB, will replace their coal-based Blast Furnace – Basic Oxygen Furnace (BF-BOF) process with Electric Arc Furnaces (EAF) fed with sponge iron that will be produced by LKAB using green hydrogen. Stegra is building a combined Direct Reduction of Iron (DRI) and EAF steel mill plant in Boden, that will use green hydrogen produced on-site for reduction. These initiatives will replace most of the fossil coal currently used in Swedish steel production with hydrogen. However, there will still be a need for carbon as an alloying element and a process aid in EAF steelmaking, as well as in several other metallurgical processes where hydrogen is not an easy replacement.

EAF steelmakers, and actors running processes such as Vargön Alloys' ferrochromium production and Höganäs Direct Reduction iron powder production are turning to biogenic carbon products to fill this gap and speed up their defossilisation. Solid biogenic carbon products (biocarbons) can be produced from most types of biomasses using thermochemical processes such as pyrolysis, gasification, torrefaction or hydrothermal carburisation (HTC). However, the most promising results for producing the high-quality biocarbon required for metallurgical applications come from high-temperature pyrolysis of woody biomass. Ideally, this biomass should be sourced from residue streams within forestry and forest industries, to avoid increased extraction pressure on forests. Nevertheless, building a value chain for production of metallurgical biocarbon will have an impact both on metal industries and on the sectors currently utilising large volumes of woody biomass – district heating, pulp and paper and lumber industries.

In the development of a metallurgical biocarbon industry, new knowledge will be required in industries changing to new input materials, as well as for biomass suppliers gaining a new customer segment. New production facilities may find advantages in being located in rural, biomass rich areas, or by being integrated with existing industries such as pulp mills or steel plants. At the same time, the forestry sector and the role of forests in advancing carbon neutrality are subjects of significant political contention. Initiatives that may increase lumber harvests or cause deforestation are closely scrutinised and often criticized by local residents and civil society. If local communities or political actors distrust the use or production of metallurgical biocarbon, this could be a significant barrier to continued development.

The HåBiMet - Social Perspective project has aimed to better understand the challenges and opportunities related to supplying the new supply chain with skilled workers, as well as the social acceptance for production and use of metallurgical biocarbon. This has resulted in consortiums and applications for further research projects addressing specific needs identified in this study.

2 Project overview

The project *HåBiMet – Social perspective* was a feasibility study project conducted as part of the Impact Innovation research program Swedish Metals and Minerals – a joint initiative by the Swedish Energy Agency, Formas, and Vinnova. Funding was obtained through the call "Impact Innovation: Feasibility studies and projects within Social Action Areas in the program Metals & Minerals" and received additional funding from Swerim's Metallurgy Program Council. The consortium consisted of:

Swerim AB (coordinator)

Energiforsk AB

Höganäs AB

Vargön Alloys AB

Envigas AB

The HåBiMet projects consists of *HåBiMet -Technical perspective*, *HåBiMet - Social perspective* (which this report pertains to), and *HåBiMet - Policy perspective*. By working in parallel, the three projects strengthen the overall systems perspective. The study aims to accelerate the transition to climate neutrality in Swedish metal industry by identifying and addressing challenges to a sustainable supply of biogenic carbon materials, with a focus on social challenges.

2.1 Motivation

Supplying the Swedish metal industries with biocarbon will require the coordination of a number of sectors that do not currently have strong networks or connections. Social acceptance, skill supply and knowledge sharing will be necessary for the emerging metallurgical biocarbon industry. During the project an understanding emerged about the need for this sector to take a proactive approach regarding the different demands on biomass.

2.2 Challenges addressed and objectives

The project activities have identified and evaluated challenges relating to social acceptance and skill supply in the metallurgical biocarbon supply chain.

The objectives of the project were to:

- To identify social challenges to the metallurgical biocarbon supply chain
- To propose future actions that could mitigate social challenges and support the development of metallurgical biocarbon supply chains in Sweden

2.3 Work plan and execution

This section presents how the project plan was divided into work packages, linked activities, and when they were completed. Communication and dissemination efforts related to the project are also discussed.

2.3.1 Work packages

The project was divided into four Work Packages, presented in Table 1. Since HåBiMet – social perspective was conducted as one out of three concurrent HåBiMet-projects, there were considerable synergies in workshop and seminar activities. The social acceptance topic in particular benefited from activities including both policy and social perspectives.

Seminars and workshops were coordinated by Erland Nylund from Swerim, and Anna Steorn from Albaeco. Two thesis workers were recruited to form part of the project, conducting a joint thesis project "*Technological Innovation System Analysis and Dynamic Capabilities for Progressing Green Innovations*" (Appendix 2), covering several of the research aims of the overall project, but in several respects going further than the initial research scope. Interviews were conducted by MSc thesis workers John Pettersson and William Di Francesco.

Table 1: Description of work packages in the HåBiMet social project

Work Package	Description	Start	End	Completed activities
1. Project management		2024-11-01	2025-06-30	• Monthly project consortium meetings • Project plan established in November • Workshop and seminar program established in January • Supervision of MSc thesis students • Creating a project website • Reporting to Vinnova and Impact Innovation
2. Social Acceptance	Externally aimed work package that invites actors from civil society as well as industry to map barriers to social acceptance of metallurgical biocarbon. A combination of workshops and interviews, with results and analysis presented in a concluding seminar.	2024-12-01	2025-06-30	• Crash course in metallurgy, 25 participants – 21/1 & 23/1 • State-of-research seminar, 27 participants – 30/1 • Workshop about acceptance and conflicts of interest • 6 Explorative interviews • 21 semi-structured interviews • Sustainability Compass workshop, 16 participants – 9/4 • Concluding seminar with open discussions, 38 participants – 13/5
3. Skill supply and employer attractiveness	A series of workshops and dialogues with representation from all industrial actors across the biocarbon value chain, aimed at identifying challenges related to attractiveness and skill supply. Results and analysis presented in a concluding seminar.	2024-12-01	2025-06-30	• State-of-research seminar – 30/1 • Workshop about skill supply and employer attractiveness – 19/3 • 6 Explorative interviews • 21 semi-structured interviews • Sustainability Compass workshop, 16 participants – 9/4 • Concluding seminar with open discussions, 38 participants – 13/5
4. Developing consortia and applications	Formulate continuation projects, establishing consortia and preparing applications	2025-02-01	2025-06-30	• "Metallindustrins Sociala Symbios" (not submitted) • "HåBiMet safe management" (submitted 30/4) • WIP: "Societal benefit from a regional biocarbon value chain"

2.3.2 Communication and dissemination

Achieving a diversity of perspectives and experience in the workshops and interviews of the project was a high priority. A joint communication strategy was deployed for the three HåBiMet projects, using a common webpage (www.swerim.se/habimet) to publish results as well as information about upcoming activities. Website visitors were invited to join a HåBiMet newsletter, and to register for workshops and seminars of interest.

LinkedIn was used as a primary social media platform, with posts informing about activities such as the initial state-of-research seminar, a Webinar hosted by Energiforsk, and the chance to join the concluding seminar. This combination of outward-facing activities, communication through established channels, and personal invitations to key stakeholders within and outside existing networks achieved a diverse group of participants in HåBiMet activities.

During the spring of 2025, around 60 different people participated in the project activities, representing many different types of stakeholders, including universities and research institutes, steel and alloy producers, energy companies, biocarbon producers, technology providers, raw material suppliers, foresters and forest industries, industry organizations and more.

Toward the end of the project, preliminary results and experiences from the project structure were presented as an academic poster at the European Biomass Conference and Exhibit (EUBCE 2025) in Valencia. Furthermore, public presentations of the MSc thesis project were done both aimed at interviewees and consortium partners (27/5) and in a public defence at Luleå Technical University (4/6).

2.4 Deliverables

In the project application, a number of expected deliverables were presented. In addition to the originally expected deliverables, a MSc thesis and corresponding executive summary were also produced. All seven deliverables are included in this report, as summarised in Table 2.

Table 2: Summary of project deliverables

Deliverables	***Can be found in***
A report summarizing the work done.	Swerim-2025-221
Workshop on employer attractiveness and skill supply	Section 3.1.1
Workshop on social acceptance for metallurgical biocarbon	Section 3.1.2
Executive summary MSc thesis report	Section 3.2
At least one project consortium and project plan for further application	Section 6
Presentation of results from concluding seminar	Appendix 1
Cross-sector supply chains for metallurgical biocarbon (poster presented at European Biomass Conference and Exhibition 2025 in Valencia)	Appendix 2
MSc thesis report – analysis of Technological Innovation system	Appendix 3

3 Results

This section will summarize outcomes from the seminar and workshop activities conducted in the project, as well as the exploratory and in-depth interviews conducted.

3.1 Workshops and seminars

As listed in Section 2.5, a workshop on the topic of social acceptance and conflicts of interest was held on the 10/3, with 30 participants from metal industry, the energy sector, agricultural companies, forestry actors and more. The group was divided into four sub-groups, to enable more in-depth discussions.

On the 19/3, a workshop was held specifically dedicated to the question of skill supply and the attractiveness of employers in the metallurgical biocarbon supply chain. This workshop had 16 participants.

Both the workshops 10/3 and 19/3 were advertised on the HåBiMet project webpage, over LinkedIn, and in personal correspondence.

A workshop using the Sustainability Compass method was held on 9/4, investigating the potential social impacts and benefits from some proposed continuation projects – using the Sustainable Development Goals as a framework.

Finally, a seminar presenting preliminary results for review and discussion was held on 13/5. The seminar was advertised on the HåBiMet project website, on Swerim's website, over LinkedIn, and by invitations to Swerim's program council for metallurgy. The main findings from these activities are summarised in the following section.

3.1.1 Skill supply and employer attractiveness

Overall, throughout the interviews and workshops, skill sharing and production of knowledge was actually identified as one of the strengths of the Swedish biocarbon innovation system. On an academic level, a number of research projects have been conducted in collaboration between research institutions and industrial actors, generating knowledge and experience of production of use of metallurgical biocarbon. There are several pilot-scale biocarbon production facilities in Sweden aiming to produce metallurgical-grade products. So far, skill supply does not seem to have been a limiting factor for these companies. On the other hand, the metal industry overall does struggle with attracting enough high-skilled workers especially in fields of research and engineering.

Metal industry representatives expressed a desire for more students choosing technical fields, and in particular for more students to choose technical specialties such as metallurgy or materials science. Representatives from forestry and agricultural sectors expressed similar challenges. When discussed in the workshop in March, at least part of the reason for this seems to be an image of these industries as being old-fashioned or uninteresting. Part of the challenge may also be a simple lack of insight into career options in these fields.

Though not currently a major barrier to industry expansion, creating an efficient and sustainable supply chain for metallurgical biocarbon in Sweden will require training and learning across multiple sectors. For most of the 1900s, biomass producing sectors have not been closely linked to metal production but now many factors in production and conversion of forestry biomass may have an impact on the quality of input materials in metal industries. To make the best use of biomass resources, and produce high-value products, the function of metallurgical biocarbon needs to be understood in those sectors supplying them. Skills relating to the safe handling of biocarbon materials will also be needed by new groups of employees. An overview of skill and knowledge needs across sectors is presented in Table 3. To a large extent, the same kind of knowledge and skills are needed by many different actors. This indicates that future upskilling initiatives may be useful to many actors.

Table 3: Key competence requirements for the metallurgical biocarbon supply chain. The actors with an expected use for each competence is indicated with X.

Skill	Description	Actors				
		Biomass producers	Biocarbon production	Metallurgical use	Regulators/ policymakers	Others
Safe handling of biocarbon	Mitigating dust- mold- and fire risks, knowledge of fire and worker health hazards.	X	X	X	X	Emergency services, logistics providers
Process optimisation	Adjusting processes for correct product quality and optimal yields	X	X	X		
Metallurgical quality requirements	Knowledge of quality criteria and specifications for different metallurgical uses of biocarbon	X	X	X	X	
Coproduct handling	Handling and successful valorisation of byproducts from biomass industries and pyrolysis	X	X			
Compaction/ agglomeration	Agglomerations methods such as briquetting, pelletisation, extrusion, enabling more efficient transport and metallurgical use		X	X		
Soil amendment quality requirements	Biocarbon specifications and quality requirements for soil uses. These are a potential use for biocarbon or biomass fractions that don’t meet metallurgical criteria.	X	X	X	X	

As indicated by Table 3, one set of skills that was brought up frequently relates to fire safety and knowledge of how to safely handle and store biocarbon. Biocarbon materials undergo self-heating processes that can lead to self-ignition. The products also produce dust in handling and use, which may have health implications for workers. Finally, some biocarbon materials may also suffer from mould, which is also a health and safety issue for workers in logistics and storage.

The continuation project "HåBiMet - Säker hantering" / "HåBiMet - Safe management" was proposed to investigate these risks and develop a best practice for handling metallurgical biocarbon materials. This project consortium included RISE, LTU, Swerim, Höganäs, Vargön Alloys, Kvasir technologies, Envigas and Eramet, and was submitted to the call "Impact Innovation: The interaction between humans and technology – Swedish Metals &Minerals" in April.

3.1.2 Social acceptance

The second main track of investigation for the project involved understanding the social acceptance of metallurgical biocarbon, to what extent lack of acceptance may limit market development, and what kind of initiatives may support improved acceptance.

The participants indicated that the understanding of why biocarbon is required by metal industries is not widespread. Once acquainted with information about metallurgical biocarbon such as that it is a chemical reagent rather than a fuel, no great opposition to this use of biomass was presented by any participants in the workshop. However, there are many conflicts of interest surrounding forest biomass in Sweden, and even if metallurgical uses are accepted, there is not necessarily support for biomass being produced specifically for production of metallurgical biocarbon. Actors from most sectors seemed in agreement that the use of secondary biomass streams is greatly preferable (and likely more profitable) than primary production of wood for pyrolysis.

Currently, social acceptance does not seem to be a major barrier to developing the metallurgical biocarbon industry, but it could become so if biomass competition intensifies, or the function of biocarbon is not communicated well to relevant stakeholders.

There are also opportunities for creating greater social benefits and acceptance for metallurgical biocarbon. For instance, the district heating sector in Sweden is very large, and has a strong reliance on biofuels – primarily burning woody residues such as tops and branches. District heating is also facing a profitability crisis, partly driven by higher biomass prices. Some of the existing heat plants could be used to produce biocarbon materials, enabling them to run at higher capacity for longer periods each year, while also providing a secondary revenue stream. Furthermore, an increased demand for tops and branches could create rural job opportunities in regions such as Västerbotten and Norrbotten, where this resource is currently underused. The term "underused" should be understood from an isolated industry perspective. From an ecological perspective the tops and branches play a role in the ecosystem.

Thus, metallurgical biocarbon supply chains implemented in the right way may create jobs where they are needed and improve profitability and reliability of energy supplies. This represents opportunities for improving acceptance not only for metallurgical biocarbon but also for metal and energy industries, if communicated well to the public. Further studies on this topic may improve the chance of benefiting from these opportunities.

An overarching theme of the discussions on social acceptance is that biomass should be used where it creates the most benefit. Co-utilization and synergies with other industries are key to achieving credible and efficient solutions. However, value chains should be evaluated both from an environmental and an economical point of view. To this end, social and environmental life cycle analyses should be conducted to compare biocarbon production and use in metallurgical uses to alternative biomass or biocarbon uses, as well as considering the role of biomass/carbon in standing forests..

3.2 Executive summary for HåBiMet – Social perspective project report

This section was written by John Pettersson and William Di Francesco to present how the findings of their MSc thesis project, including 27 interviews, relates to the research objectives of HåBiMet – Social perspective. The full thesis is available as Appendix 2 to this report.

3.2.1 Purpose

This study analyses the dissemination and development of biocarbon for metallurgy in Sweden. The aim is to map what is driving and hindering the technological innovation system for metallurgical biocarbon (TIS-MB), assess the functionality of the TIS-MB, and which firm-level dynamic capabilities are needed to commercialize biocarbon.

3.2.2 Method

Using an abductive, qualitative case study approach, we conducted 27 interviews and applied two rounds of thematic analysis; first to identify mechanisms influencing the TIS-MB and assess system functions, and second to operationalize dynamic capabilities.

3.2.3 Findings and conclusions

Our analysis highlights six driving mechanisms and six hindering mechanisms. We assess the system's functionality and identify resource mobilization and market formation as weak functions. To address this, we find dynamic capabilities among key actor groups to strengthen the innovation system.

3.2.4 Contributions to HåBiMet – Social perspective project goals

As part of the social perspective of the HåBiMet project, the study aimed to provide system-level insights and actions related to the project's overarching goals. This was achieved through evaluation of the system functions in the TIS analysis which provided the base through which the challenges tied to social acceptance and competence provision within the TIS-MB could be identified. While all evaluated functions are not directly connected to the project goal, it is important to note that further developing the system as a whole indirectly contributes to the improvement of the aforementioned factors.

Social acceptance

The social challenges identified in the study are, in this case, tied to the hindering mechanisms: Lack of formal institutions (rules, laws, regulations, standards) and Reluctance to share information, as defined in the original study.

The lack of formal institutions contributes to perceived decreased legitimacy of biocarbon as well as related technologies and processes, among system actors and potential system entrants. These uncertainties, while not in focus of the study, may affect the social acceptance among external actors and the general public. Without clear, recognized frameworks that define what constitutes sustainable and safe biocarbon, it becomes more difficult for external stakeholders to assess the credibility and viability of the technology. This lack of clarity can lead to hesitation, reduced willingness to support biocarbon-related initiatives, and in the long term, hinder the broader social acceptance necessary for scaling the technology. In parallel, the reluctance among larger organizations to be transparent towards biocarbon actors further obstructs legitimation. Respondents noted that visible support and open engagement from influential firms would help validate biocarbon as a credible alternative. Their reluctance to share information sends mixed signals to other stakeholders, slowing momentum and reducing confidence in the transition. In this way, addressing internal system uncertainties through both the development of formal institutions and increased transparency among key actors is not only critical for strengthening market legitimacy among existing actors but also for building the wider societal trust and support required for successful industrial development.

In addition to formal structures, social acceptance is influenced by informal institutions such as shared perceptions, norms, and public debates. The study identified three such institutions. Firstly, there is a misconception that hydrogen-based steel making eliminates the need for biocarbon altogether. Secondly, there is a lack of awareness of the difference in emissions between Swedish, European, and particularly Asian metal producers. Lastly, there is a debate about whether woody biomass should be used for biocarbon production or for other uses from a societal perspective. Firms need to actively influence both formal and informal institutions by engaging in targeted knowledge distribution, participating in public debates, and collaborating with stakeholders beyond the immediate value chain. By providing clear, accessible information and contributing to shaping public discourse, firms can reduce misconceptions, build trust, and strengthen the legitimacy of biocarbon as part of the broader green transition.

Skill supply and employer attractiveness

The development of metallurgical biocarbon and its integration into the metal industry is closely linked to the challenge of skill supply. As highlighted in this study, the emerging biocarbon industry requires new knowledge, skills, and collaboration across previously disconnected sectors such as forestry, energy, and metallurgy. This creates both a demand for specialized technical competence and an opportunity to increase the attractiveness of the industry as an employer. In particular, the need for cross-industry understanding, spanning everything from biomass sourcing to metallurgical processes highlights the importance of building new competence profiles that combine sustainability knowledge with technical and industrial expertise. System actors have already taken steps to strengthen competence, for example through targeted recruitment and participation in research collaborations. However, to ensure long-term attractiveness and a competitive workforce, further efforts are needed to position the biocarbon industry as part of the broader green transition, offering meaningful, innovative career opportunities. To accomplish this, system actors need to increase their visibility and inform the broader market of their biocarbon initiatives. With sustainability trends driving the development of the TIS-MB and biocarbon initiatives, system actors should take advantage of the positive image a green transition represents in their advertising.

4 Discussion

This section presents some further analysis on how different actors can act to strengthen the production of metallurgical biocarbon from a social point of view, and the challenges and opportunities to form further research consortiums.

4.1 Key takeaways for different stakeholders

Section authored by John Pettersson and William Di Francesco

To further concretize the implications of our findings, we provide some key takeaways for three different actor categories; metal producers, biocarbon producers, and forestry firms, and display how these takeaways are anchored in our findings regarding dynamic capabilities, as shown in Table 4.

Table 4 – Key takeaways for specific industrial actors, and the dynamic capabilities they are best posed to contribute to the overall innovation system.

Actor category	Key takeaway	Market screening	Customer and supplier scouting	Updating technological competences	Influencing institutions	Establishing strategic alliances	Developing organizational agility
Metal producers	Share requirements and participate in setting standards						
	Sign off-take agreements with biocarbon producers						
Biocarbon producers	Explore potentially symbiotic side streams						
	Strengthen supply, and interact more with forestry firms						
Forestry firms	Investigate by-product availability						
	Update knowledge of technical properties of assortment						

4.1.1 Metal producers

Firstly, metal producers should focus efforts on signing off-take agreements with biocarbon producers as this is key for financing the upscaling of biocarbon production. A prerequisite of signing off-take agreements for metal producers is ensuring that their technological competences regarding biocarbon is updated by experimenting and running pilot tests, in order to, when necessary, develop their processes for biocarbon. They also need to scan the market to identify and engage with potential suppliers, as well as advertise their own biocarbon efforts in order to send credible signals and open up to being approached by biocarbon producers. Lastly, metal producers must align their internal perceptions of biocarbon, especially from company leadership, and foster an acceptance of risks associated with early investments. The biocarbon market is in need of early adopters who lead by example, sending signals that boost the perceived legitimacy of biocarbon for other actors and catalyze market development.

Second, metal producers should prioritize sharing requirements of biocarbon and participate in setting quality standards. As part of this, firms should update their specifications of biocarbon to ensure the technical performance and safety requirements of metallurgical applications. They should also evaluate if there are some requirements of carbon that can be loosened in order to facilitate the use of a wider range of feedstock and production processes for biocarbon. Informal and formal collaborations with biocarbon producers, other metal producers, networks and interest groups should be utilized to coordinate these efforts. Therefore, an openness to these types of collaborations is crucial.

4.1.2 Biocarbon producers

Biocarbon producers should explore symbiotic side stream applications. Monetizing the by-products from the pyrolysis process, syngas and bio-oil, is critical to find the business case of upscaling production. Technical advancements and market research are needed to realize the production of refined products such as chemicals, methane, hydrogen and renewable fuels. Moreover, there are possible cross-industry symbiosis implications where biocarbon production could be adapted or integrated into district heating and energy production.

Moreover, there is high competition for biomass, meaning that biocarbon producers need to focus efforts on securing supply. Close collaborations with the forestry industry are needed to explore by-product availability of tops, branches and saw dust, and construct the supply chain.

4.1.3 Forestry firms

Forestry firms themselves have an important role in this. They should focus efforts on investigating by-product availability. Tops and branches have largely stopped being harvested, especially in northern Sweden, and could be utilized in biocarbon production. Moreover, sawdust and wood chips from sawmills are by-products with clear potential for biocarbon applications. Understanding the volume and availability of these materials is the first step in enabling their use.

Lastly, forestry firms have their expertise in traceability and woody biomass sourcing but need to update their knowledge of the technical properties of their assortment. Since the metal industry has strict requirements of the material properties of their carbon inputs, forestry firms should map the composition of their biomass to ensure it can meet these requirements. This will strengthen their position as reliable suppliers in the growing biocarbon value chain.

4.2 Forming research consortiums

Many of the opportunities for social impact projects relating to metallurgical biocarbon connect to regional development, in particular rural development. Though several metal actors have shown an interest in contributing to such initiatives, as part of ensuring that their companies produce social as well as economic benefits, they are not accustomed to participating in such projects. The regular research organizations of metal companies, biocarbon producers or biomass producers may be able to contribute to social projects, but they should also involve functions such as communications or HR.

Furthermore, municipalities and counties in Sweden typically have a great interest in regional development opportunities and would be key enablers of social research projects.

5 Conclusions

The HåBiMet – Social perspective pre-study has provided valuable insights into the social dimensions of developing a sustainable supply chain for metallurgical biocarbon in Sweden. The findings suggest that while neither social acceptance nor skill supply currently pose major barriers, both areas require proactive attention to ensure long-term success and societal benefit.

- **Social acceptance is currently sufficient, but fragile**. There is no widespread opposition to metallurgical biocarbon, especially when its role as a chemical reagent rather than a fuel is clarified. However, misconceptions persist – such as the belief that hydrogen-based steelmaking eliminates the need for carbon entirely. Without clear communication and engagement, social acceptance could erode, especially in the face of biomass competition or environmental concerns.

- S**kill supply as adequate but need strategic development.** The current workforce is managing the transition well, but cross-sectorial knowledge and new competences will be essential. Upskilling in areas such as fire safety, process optimization, and biocarbon quality standards will be critical across forestry, energy, and metallurgical sectors.
- **Knowledge sharing and coordination are crucial.** A lack of standardization and fragmented communication between actors hinders progress. Better transparency, shared standards, and collaborative platforms are needed to build trust, align expectations, and accelerate innovation.
- **Safety and handling require immediate focus.** Fire safety, dust control, and health risks associated with biocarbon handling are top concerns among stakeholders.
- **Regional development**. Biocarbon production has real potential to boost local economies – especially in forest-rich areas like Västerbotten and Norrbotten. Co-utilization with district heating and other industries could enhance profitability and social value, improving public support and trust.
- **Further research is needed**. Life cycle assessments (LCA), social impact evaluations, and comparative studies of biocarbon versus other biomass uses are necessary to guide policy and investment. Understanding the full spectrum of environmental, economic, and social impacts will support more informed decision-making.

The project has laid a strong foundation for integrating social considerations into the development of metallurgical biocarbon. By fostering collaboration, addressing safety and knowledge gaps, and aligning with regional and societal needs, the industry can position itself as a key contributor to Sweden´s green transition. Continued research, communication, and stakeholder engagement will be essential to maintain momentum and ensure that the benefits of biocarbon are realized across society.

6 Suggested continued work

Within the project, several continuation project ideas have been formulated and pitched. A major interest from most participating actors was better understanding of safe handling and fire safety relating to biocarbon. This resulted in the application “HåBiMet – Safe management”, submitted to the Impact and Innovation call “The interaction between humans and technology - Swedish Metals & Minerals”.

Two continuation projects have been conceptualized focusing on regional development, and how metal industries and biocarbon producers can contribute to local communities. The first, “The social symbiosis of the metal industry” aimed to connect popular education actors and civil society with local metal industries. It was circulated but did not attract enough industrial partners to go through with an application for the intended call in April.

The second project concept relates to the “Social benefit of metallurgical biocarbon” and aims to quantify and better understand the impact on local economy and local society from biocarbon production initiatives.

There is also a new idea being explored around partnering with district heating plants to co-produce metallurgical biocarbon. This could help improve energy efficiency and create new revenue streams for existing infrastructure.

Overall, there is need for further research into LCA of metallurgical biocarbon, different ways of quantifying and prioritizing the effects of biocarbon production and utilization. A greater understanding is needed for the social impacts of biocarbon projects, and there will be a need for greater skill development and diffusion within and between industries.

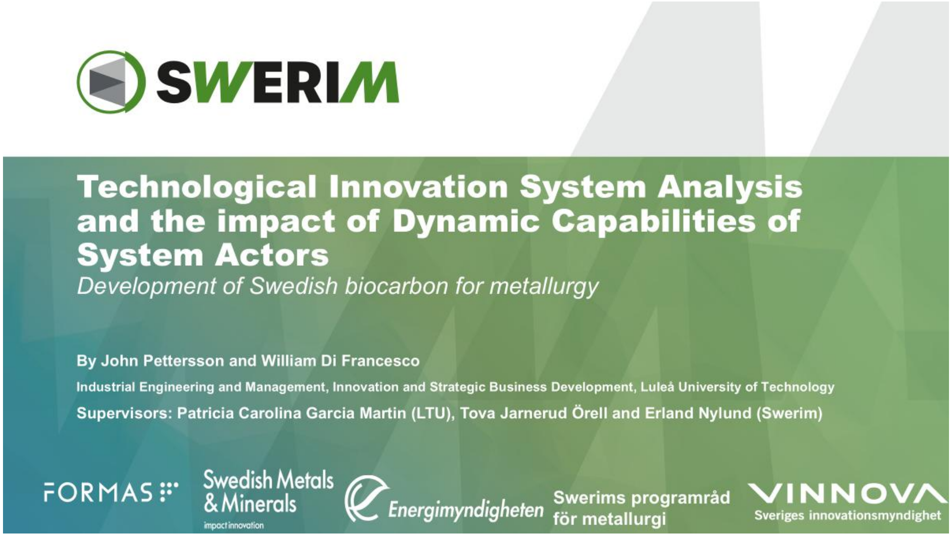
7 Acknowledgments

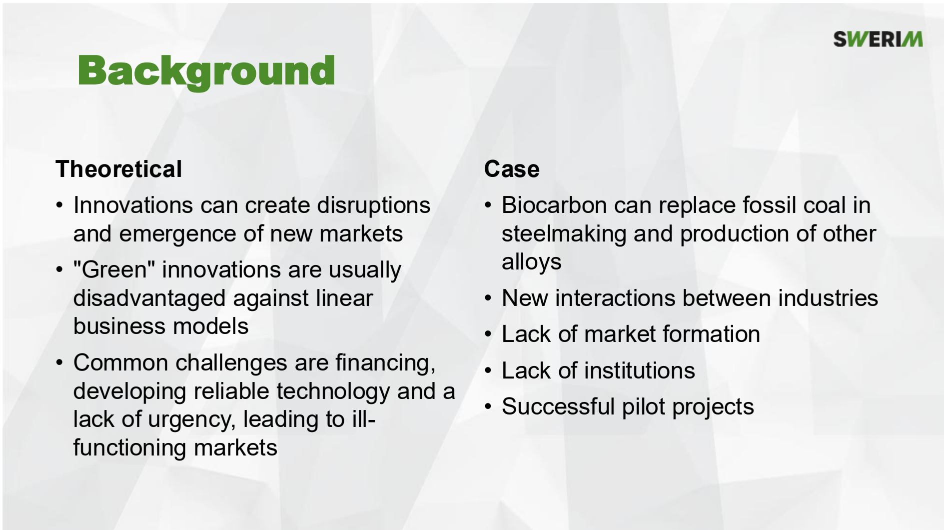
This project was made possible through funding from the Impact Innovation program, a joint initiative by the Swedish Energy Agency, Formas, and Vinnova. We are grateful for their support in establishing research that bridges technology, society, and sustainability. We would also like to thank the members of Swerim´s Metallurgy Program Council for their economical support as well as for valuable input, feedback, and engagement throughout the project. Their perspectives have been instrumental in shaping the direction and relevance of our work.

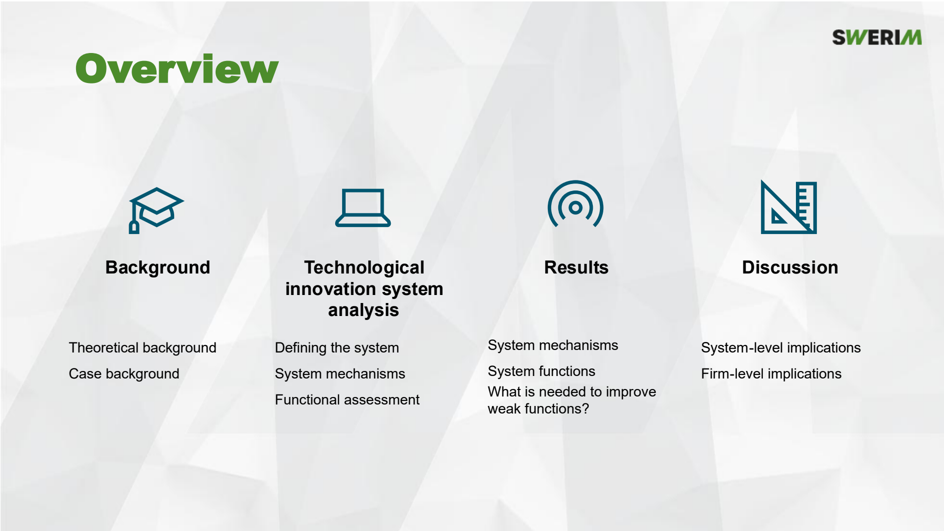
Appendices

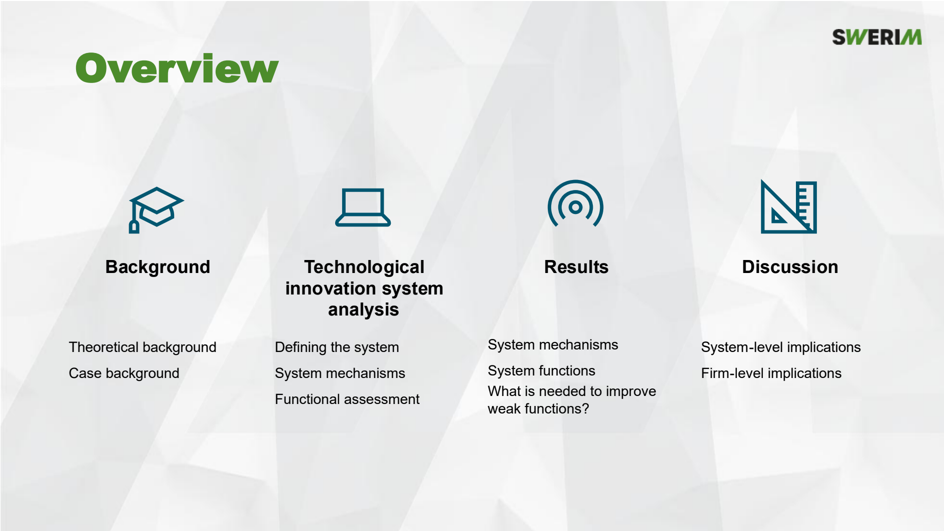
Appendix 1: Presentation of results from concluding seminar

Initial slides presented by John Pettersson and William Di Francesco






SWERIM
Overview
Background
Theoretical background
Case background
Technological innovation system analysis
Defining the system
System mechanisms
Functional assessment
Results
System mechanisms
System functions
What is needed to improve weak functions?
Discussion
System-level implications
Firm-level implications


SWERIM
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System-level implications
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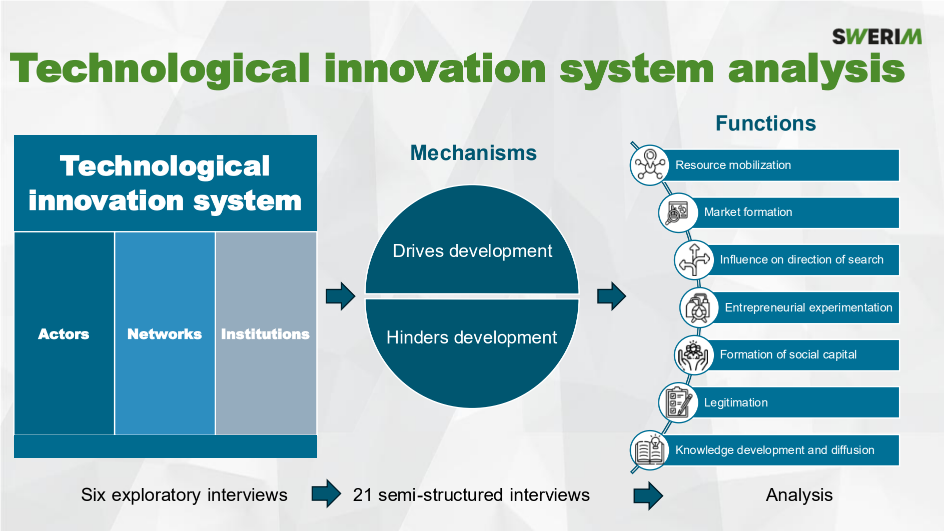
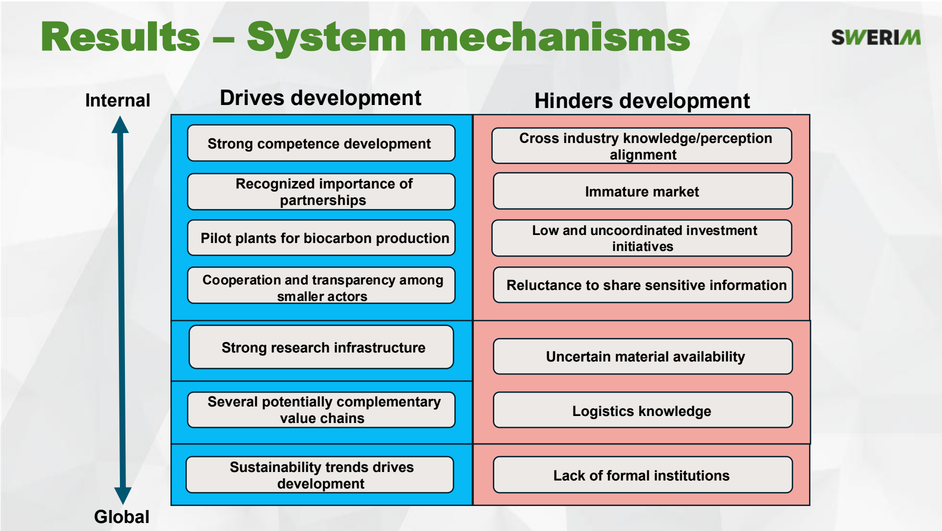
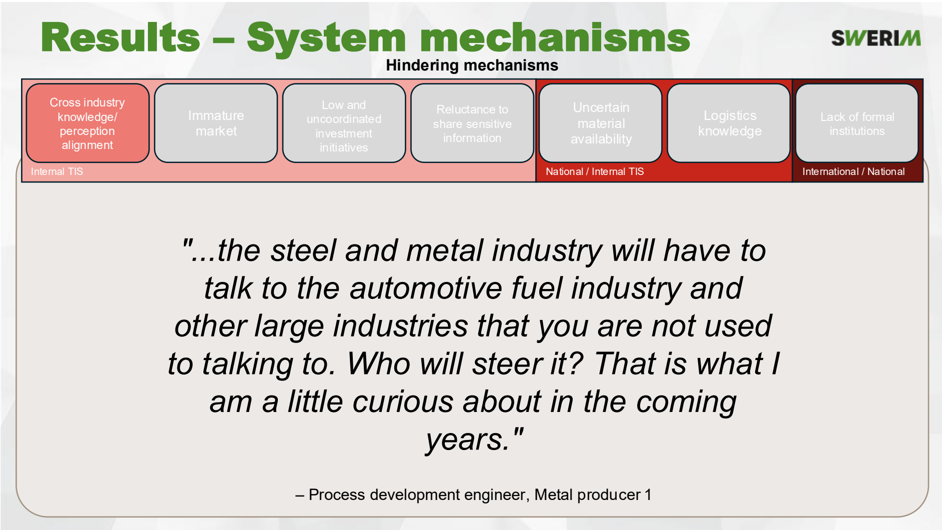
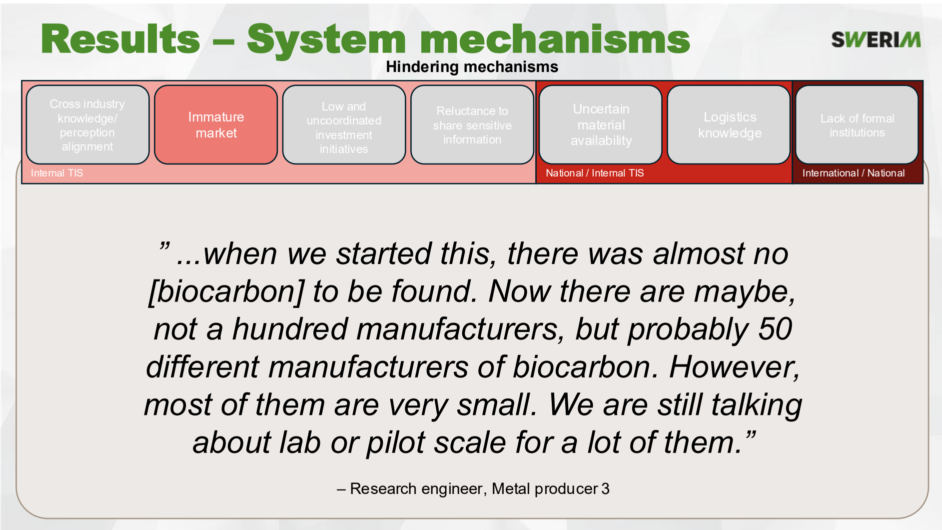
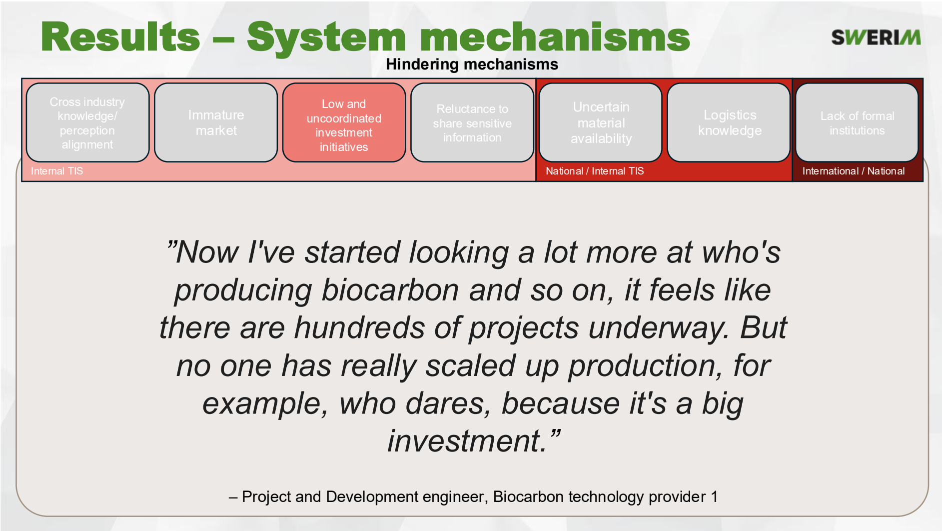
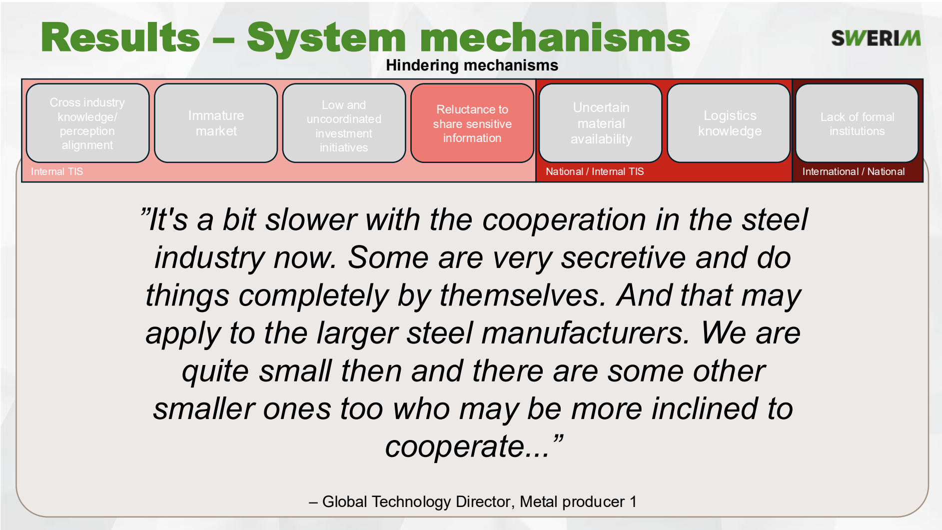

SWERIM
Technological innovation system analysis
Technological innovation system
Actors
Networks
Institutions
Mechanisms
Drives development
Hinders development
Functions
Resource mobilization
Market formation
Influence on direction of search
Entrepreneurial experimentation
Formation of social capital
Legitimation
Knowledge development and diffusion
Six exploratory interviews
21 semi-structured interviews
Analysis

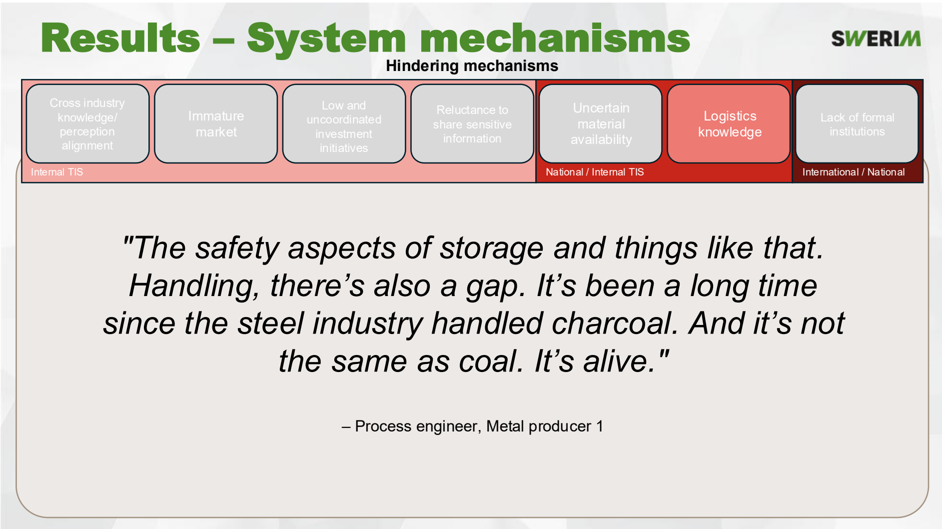

Results – System mechanisms
SWERIM
Internal
Global
Drives development
Strong competence development
Recognized importance of partnerships
Pilot plants for biocarbon production
Cooperation and transparency among smaller actors
Strong research infrastructure
Several potentially complementary value chains
Sustainability trends drives development
Hinders development
Cross industry knowledge/perception alignment
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions


Results – System mechanisms
SWERIM
Hindering mechanisms
Cross industry knowledge/ perception alignment
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions
Internal TIS
National / Internal TIS
International / National
"...the steel and metal industry will have to talk to the automotive fuel industry and other large industries that you are not used to talking to. Who will steer it? That is what I am a little curious about in the coming years."
– Process development engineer, Metal producer 1


Results – System mechanisms
SWERIM
Hindering mechanisms
Cross industry knowledge/ perception alignment
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions
Internal TIS
National / Internal TIS
International / National
” ...when we started this, there was almost no [biocarbon] to be found. Now there are maybe, not a hundred manufacturers, but probably 50 different manufacturers of biocarbon. However, most of them are very small. We are still talking about lab or pilot scale for a lot of them.”
– Research engineer, Metal producer 3


Results – System mechanisms
SWERIM
Hindering mechanisms
Cross industry knowledge/ perception alignment
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions
Internal TIS
National / Internal TIS
International / National
"Now I've started looking a lot more at who's producing biocarbon and so on, it feels like there are hundreds of projects underway. But no one has really scaled up production, for example, who dares, because it's a big investment."
– Project and Development engineer, Biocarbon technology provider 1


Results – System mechanisms
SWERIM
Hindering mechanisms
Cross industry knowledge/ perception alignment
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions
Internal TIS
National / Internal TIS
International / National
"It's a bit slower with the cooperation in the steel industry now. Some are very secretive and do things completely by themselves. And that may apply to the larger steel manufacturers. We are quite small then and there are some other smaller ones too who may be more inclined to cooperate..."
– Global Technology Director, Metal producer 1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SWERIM
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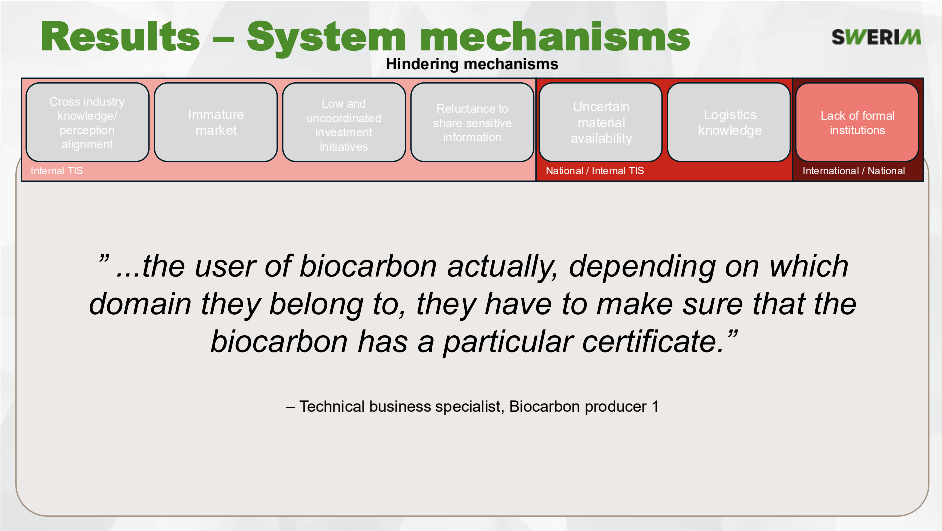
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions
Internal TIS
National / Internal TIS
International / National
"The safety aspects of storage and things like that. Handling, there's also a gap. It's been a long time since the steel industry handled charcoal. And it's not the same as coal. It's alive."
– Process engineer, Metal producer 1


Results – System mechanisms
SWERIM
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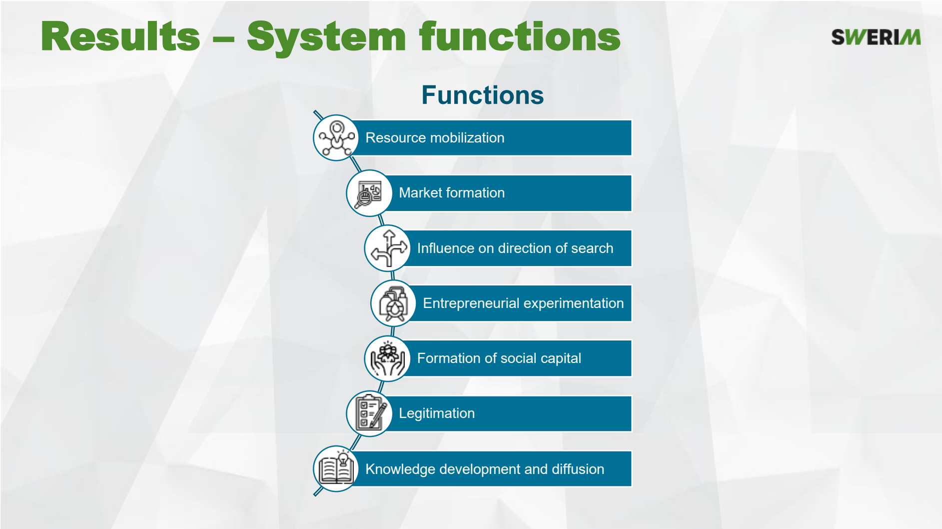
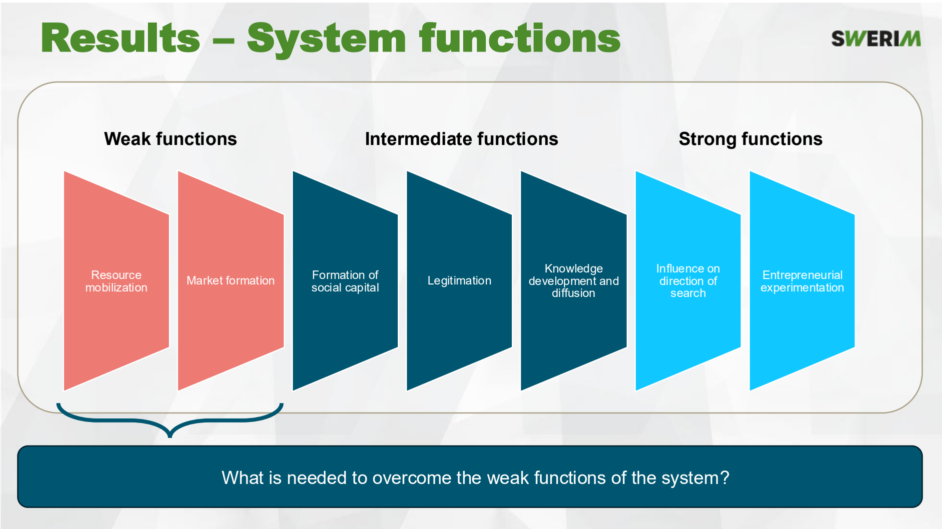
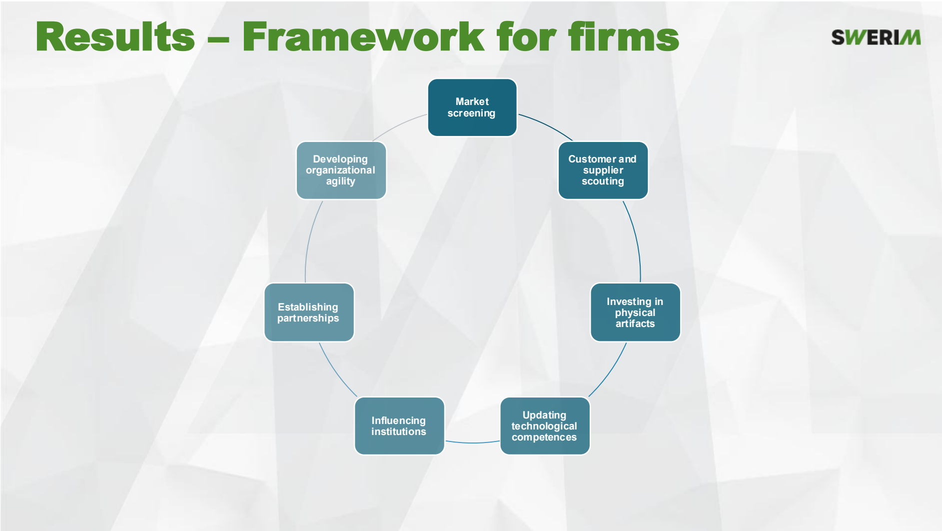
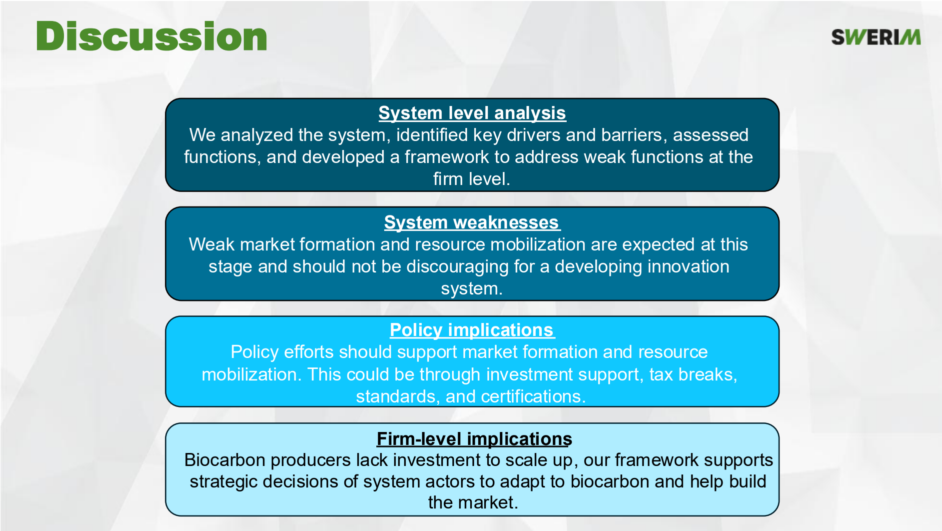
Cross industry knowledge/ perception alignment
Immature market
Low and uncoordinated investment initiatives
Reluctance to share sensitive information
Uncertain material availability
Logistics knowledge
Lack of formal institutions
Internal TIS
National / Internal TIS
International / National
” ...the user of biocarbon actually, depending on which domain they belong to, they have to make sure that the biocarbon has a particular certificate.”
– Technical business specialist, Biocarbon producer 1

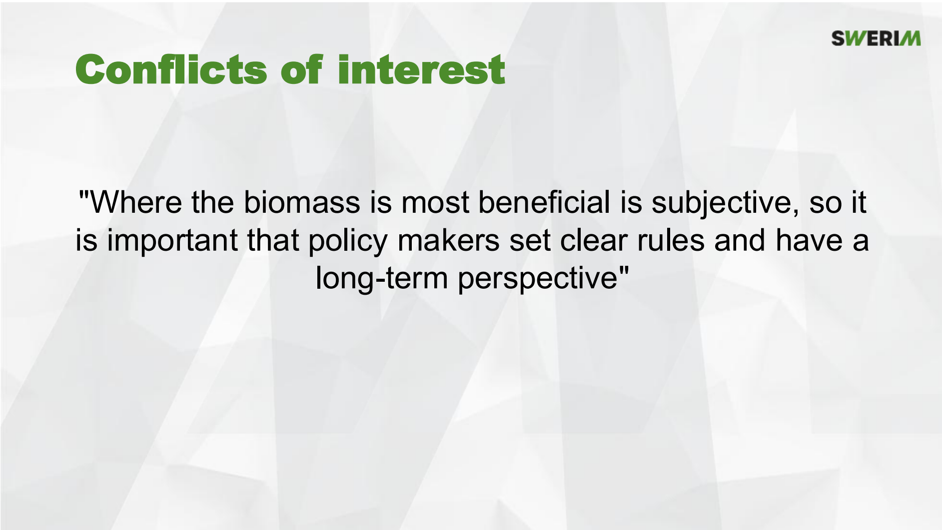

Results – System functions
SWERIM
Functions
Resource mobilization
Market formation
Influence on direction of search
Entrepreneurial experimentation
Formation of social capital
Legitimation
Knowledge development and diffusion


Results – System functions
SWERIM
Weak functions
Intermediate functions
Strong functions
Resource mobilization
Market formation
Formation of social capital
Legitimation
Knowledge development and diffusion
Influence on direction of search
Entrepreneurial experimentation
What is needed to overcome the weak functions of the system?





The following slides were presented by Anna Steorn, summarizing the findings from workshops 10/3 and 19/3.



SWERIM

Conflicts of interest

- High demand for biomass - likely to increase
- Uncertainty about future regulations leads to caution in developing and investing
- Resistance between sectors is largely due to lack of understanding - agriculture and industry require different biomass
- Factors affecting how biomass is used:
  - ❖Material characteristics
  - ❖Geographical location
  - ❖Price
  - ❖Willingness to pay

SWERIM

Competence requirements

- In general, a **high level of competence** is recognized and knowledge and experiences are shared
- Competence on **security risks** and how to manage them has been built and shared but needs to be continuously updated and adapted to new technologies, policies and management
- Knowledge is lacking or inadequate among **policy makers**

SWERIM

Competence requirements

- High competition for **the right skills**
- **Academic programs need to be updated** to match modern technologies - and include biochar
- Terminology is important here too!
- Working in this field should be attractive - **use storytelling and popular culture!**

Competence requirements

"you have to distinguish what is required in order not to spoil the product from what you want or are used to"

The following slides were presented by Tova Jarnerud Örell, summarizing results from the Sustainability Compass 9/4.

Sustainability compass

Sustainability compass

In this case, the Sustainability Compass was used to give information about how initiatives focused on how

- A) work environment, fire safety and sustainable logistics
- B) local and regional collaborations respectively
- C) techno-economic solutions related to creating a sustainable bio-value chain

Were perceived to be able to favour or hinder the different sustainability goals and in that way create societal benefit.

SWERIM

Sustainability compass

- The HåBiMet project proposals would, if successful, create a good security, regional collaboration and techno-economic breakthroughs related to biocarbon, in line with UN Global goals:
- Goal 13 – **reduced climate emissions**
- Goal 9 – **sustainable infrastructure, industry and innovations**
- **Goal 12 – sustainable production and consumption**
- And also give positive contributions to other goals related to regional economic growth, energy and sustainable communities, not least in rural areas and forest-rich regions.
- Risks related to biocarbon identified by the compass were primarily related to a possible increased **harvest of biomass, impacting land econsystems**, but also **security and work safety aspects** related to dust and fire hazards.

SWERIM

Virtuous circles where investments into stronger work safety and ensured competence supply can yield investments and jobs ((SDG 3, 4, 8 & 9), which in turn supports additional SDGs.

In this way, biocarbon initiatives can also support SDGs 1, 7, 10, 11, 16, 17 and through in particular goal 12 indirectly impact even more goals.

These virtuous circles would benefit from cooperation with:

SINTEF (LTU)
RISE, IVL, SWERIM, Energiforsk
Karolinska (physicians)
Politicians in relevant regions and committees
The academy in relevant fields: SLU, LTU, KTH, ..
Unions
Svenskt näringsliv/industry associations
Steel- and forestry company leadership
The chemical industry
Foundries
Permitting agencies
Technichal areas within Jernkontoret
State/regional financers of pilot projects
Raw material actors – forestry, agriculture, ore, energy
Companies of interest along the entire value chain
Biocarbon fraction stakeholders of all kinds

63

A possible vicious circle in two steps which the following actors could help mitigate

What actors could take part in risk mitigation initiatives to manage challenges in the biocarbon value chain:

Ecologists, biologists, SLU forestry and soil
Farmers and foresters
Water- and environmental researchers
Municipalities, sewage and water treatment plants
Environmental protection agencies
Work safety authority
Civil defency authorities and fire safety experts
Research institutes: RISE, IVL, Swerim, Energiforsk
Carbon sequestration actors
Politicians in relevant committees and regions
Academic actors in relevant fields
Unions
Svenskt näringsliv /inudstry associations
Steel- and forestry leadership
Permitting authorities
Technical areas and networks in Jernkontoret
State/regional financiers of pilot facilities
Raw material actors – forestry, agriculture, ore, energy
Companies of interest along the entire value chain
Biocarbon fraction stakeholders of all kinds

The following slides were presented by Erland Nylund, summarizing future research needs and opportunities for consortium formation identified in the project.

SWERIM

Identified needs

- Collaboration across a broader value chain
- Deeper understanding of possible supply chains
- Market developing initiatives
- Practical understanding of logistical solutions
- Reinforce understanding and acceptance

SWERIM

Technical-social-policy

- Policy issues and conflicts of interest are central
- Technical challenges in the steel industry are not the main barriers
- Social initiatives easiest to develop when closely related to the industries
- Policyfrågor och intressekonflikter centrala
- Tekniska utmaningar i metallindustrin inte största behovet
- Sociala frågor enklast när de ligger nära industrierna

SWERIM

Social goals of Metals and Minerals

Outside of the typical research scope

Socio-technical:

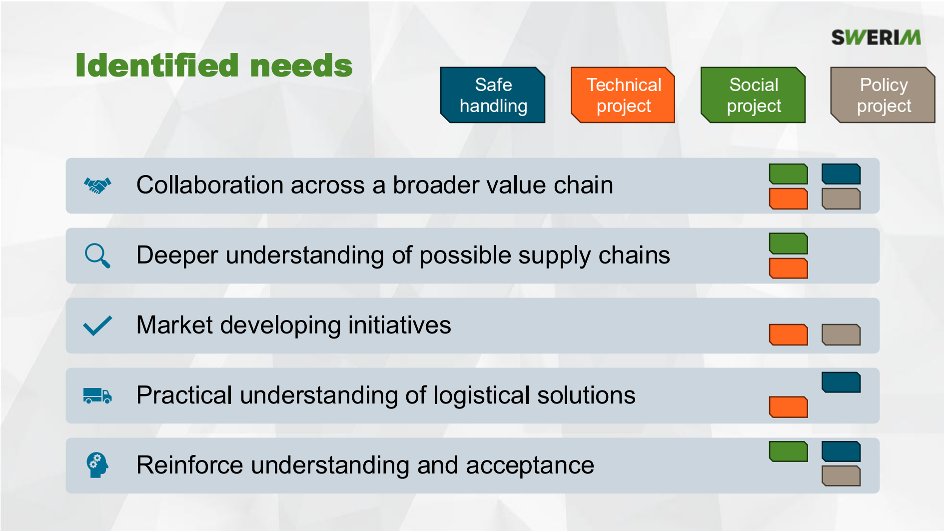
- Safe handling

Social impact:

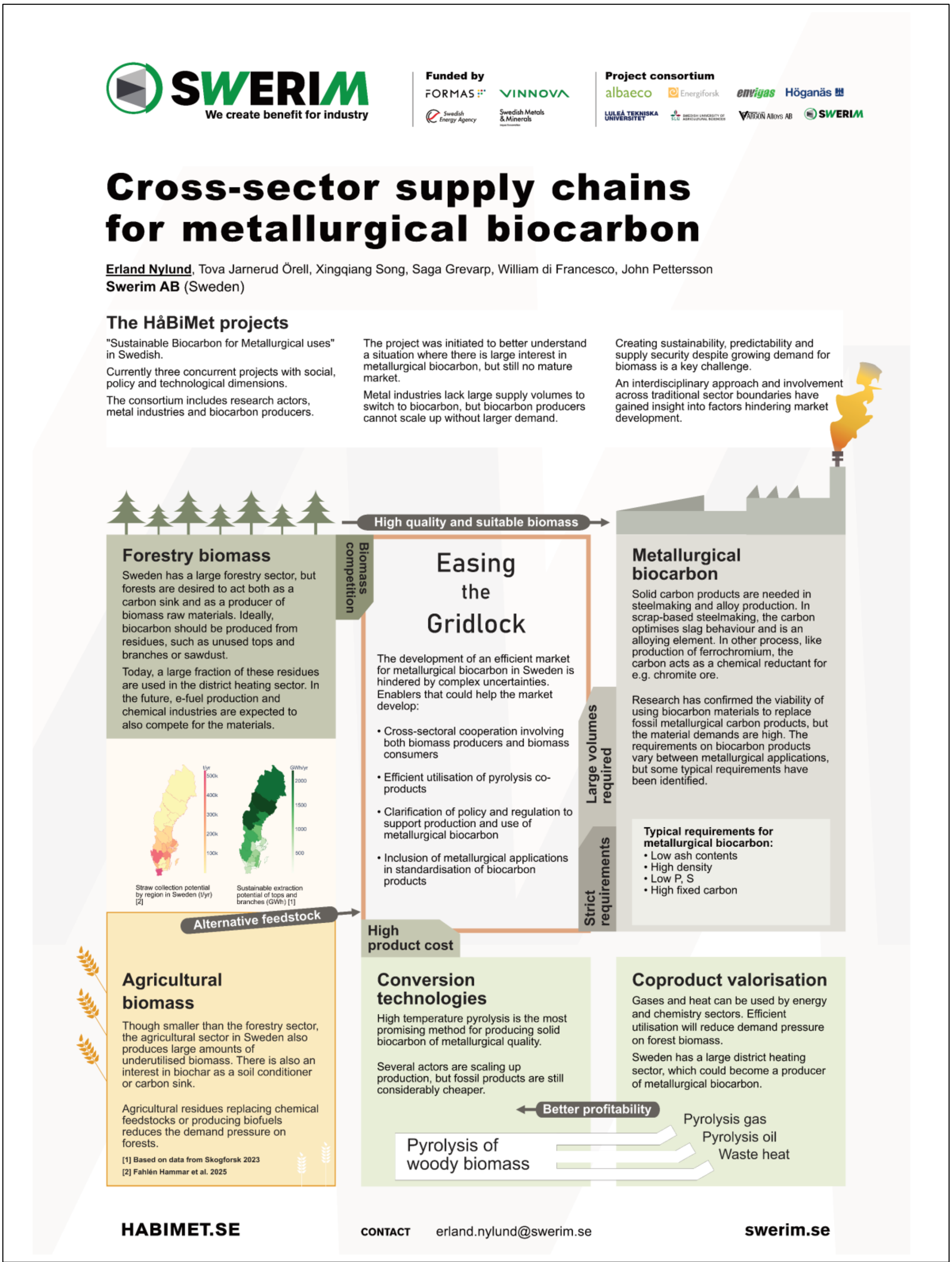
- Social symbiosis
- Regional development

Policy impacts

- Support and incentives
- Conflicts of interest – how to create social benefit, environmental benefit


SWERIM
Identified needs
Safe handling
Technical project
Social project
Policy project
Collaboration across a broader value chain
Deeper understanding of possible supply chains
Market developing initiatives
Practical understanding of logistical solutions
Reinforce understanding and acceptance

Appendix 2: Cross-sector supply chains for metallurgical biocarbon (Poster)



Appendix 3: Technological Innovation System Analysis and Dynamic Capabilities for Progressing Green Innovations: Development of Swedish biocarbon for metallurgy

MSc thesis by John Pettersson and William Di Francesco

Abstract

Purpose - This study analyses the development of biocarbon for metallurgy in Sweden. The aim is to map what is driving and hindering the technological innovation system for metallurgical biocarbon (TIS-MB), assess the functionality of the TIS-MB, and which firm-level dynamic capabilities are needed to commercialize biocarbon.

Method - Using an abductive, qualitative case study approach, we conducted 27 interviews and applied two rounds of thematic analysis; first to identify mechanisms influencing the TIS-MB and assess system functions, and second to operationalize dynamic capabilities.

Findings - Our analysis highlights six driving mechanisms and six hindering mechanisms. We assess the system's functionality and identify resource mobilization and market formation as weak functions. To address this, we find dynamic capabilities among key actor groups to strengthen the innovation system.

Theoretical contributions - The findings contribute to the literature on TIS by introducing a firm-level perspective and studying mechanisms affecting resource mobilization and market formation. It also contributes to theory on dynamic capabilities for green innovations.

Practical contributions - The findings highlight how firms can leverage dynamic capabilities to support market formation and resource mobilization in formative technological innovation systems. For policy makers, the findings highlight the need for targeted support efforts.

Limitations and future research - The focus on the national context of Sweden inhibits the generalizability of the findings. The absence of further downstream actors limits the perspective on demand factors. Future studies should include multiple cases and try to validate the dynamic capabilities in other contexts.

Keywords - Technological innovation system, Dynamic capabilities, Green innovation, Green transition, Sustainability, Biochar, Biocarbon, Biogenic carbon, Metallurgy.

DEGREE PROJECT

Technological Innovation System Analysis and Dynamic Capabilities for Progressing Green Innovations

Development of Swedish biocarbon for metallurgy

John Pettersson
William Di Francesco

Industrial and Management Engineering, master's level
2025

Luleå University of Technology
Department of Social Sciences, Technology and Arts

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ABSTRACT

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We would like to thank everyone who has contributed to this thesis and supported our work.

First, we express our gratitude to our supervisor at Luleå University of Technology, Patricia Carolina Garcia Martin, for always being engaged, available to advise us, and challenging us to find ways to improve our report. Second, we want to thank our case company supervisors for their invaluable support, perspectives and knowledge of the metal industry. We also want to thank all of the respondents who shared their time, insights, for showing interest in our study and participating in interviews, workshops and presentations. Lastly, we want to thank our family, friends and partners for supporting us throughout writing this thesis.

We also want to thank Vinnova, the Swedish Energy Agency, Formas, Swedish Metals & Minerals and the case company who funded the research project that made this thesis possible.

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1 *INTRODUCTION*

Innovations can disrupt existing markets, occasionally leading to the emergence of entirely new markets, leaving many legacy firms unable to adapt due to increased uncertainties (Flaig et al., 2021; Furr & Shipilov, 2018). According to Schmidt and Druehl (2008), the cause of this is that disruptive innovations often initially under perform in the primary attribute of established products but excel in an alternative attribute, thereby giving rise to a new market. Over time, these innovations improve in the primary attribute and eventually surpasses the incumbent product in preference. Failure to capture the value of such innovations can result in reduced market share, lowered status or even death of firms (Bower & Christensen, 1995). Certain kinds of innovations may come with additional unique challenges. Green innovations is one such case and refers to innovations that minimize waste and pollution while generating financial and representational benefits when effectively implemented (Ullah et al., 2022). Unlike traditional innovation efforts, green innovations are often catalyzed by additional, sustainability tied factors such as regulatory pressure, consumer demands and reduction of carbon emission (Ullah et al., 2022). While initially facing performance and cost challenges, green innovations have the potential to reshape industries by aligning economic and environmental objectives.

Recently, bankruptcies of start-ups focusing on green innovations, such as Northvolt and Renewcell which previously have been hailed as success stories, have raised questions on how to realize such green innovation transitions. When these transitions are led by firms, they face essential challenges of business management: securing financing, developing and investing in reliable technology, generating profits and increasing market share (Corvellec & Stowell, 2024; Grafström & Aasma, 2021). These innovations are however usually disadvantaged against linear business models in terms of scale, costs and institutional legitimacy (Corvellec & Stowell, 2024; Kanda et al., 2024; Vermunt et al., 2019) and systems of actors will only emerge around the green innovation if all actors find a business case (Corvellec & Stowell, 2024). These challenges often lead to a lack of urgency from actors (Masi et al., 2018) as well as ill-functioning markets with lacking supply (Vermunt et al., 2019), competition, and entrepreneurial entrants (Grafström & Aasma, 2021).

An exciting green innovation in the Swedish metals industry is causing disruptions to the market with some promising implications. The application of biogenic carbon for metallurgical purposes, henceforth biocarbon, leverages a trend of sustainability in the industry by contributing to defossilization of production processes (Kim et al., 2022). Biocarbon is derived from renewable biomass and is usually produced by pyrolysis which in broad terms entails heating the material under anaerobic conditions. The pyrolysis process also produces oil and syngas as by-products with potential applications such as district heating and jet fuel production (Wei et al., 2024). Biocarbon has the potential to significantly reduce net greenhouse gas emissions while maintaining the characteristics required for metallurgic application (Kim et al., 2022; Suopajärvi et al., 2017; Wei et al., 2024).

This green innovation is a part of an ongoing transition towards defossilization, driven by the overarching goals of achieving net zero emissions by 2050, in accordance with the Paris Agreement (Lopez et al., 2023). While Stegra and Hybrit have shown that hydrogen reduction has strong potential for decarbonization, carbon still remains a need in steel making and other metallurgical processes as a reducing agent, alloying element or functional material. Here, biocarbon could play an important role (Kim et al., 2022). Implementation of biocarbon in the metals industry is still in its early stages and while the technical potential is promising (Wei et al., 2024), the market is still immature, with mostly small pilot plants, high prices and limited market data (Salo et al., 2024). The most common feedstock is woody biomass, already being harvested close to sustainable levels and risking significant price hikes if demand increases (Lundmark et al., 2024; Salo et al., 2024). Safety and transportation hazards also exist as biocarbon has self-igniting properties leading to spontaneous fires (Restuccia et al., 2019). Since these issues come from a wide variety of sources, they require deeper systemic understanding and analysis from a theoretical point of view. To achieve this, we apply technological innovation system (TIS) theory, which has been used extensively by researchers on innovation, especially to study green innovation transitions (Bergek, 2019; Markard & Truffer, 2008). The TIS framework is used to analyze the dynamics and mechanisms which drive or hinder key processes, or "functions", that affect the performance of an innovation system (Bergek et al., 2008b), and can thereby be used to evaluate the development and diffusion of biocarbon for metallurgical use in Sweden, on a system-level.

While TIS theory, in most previous studies, has been applied to deduce policy implications (Bergek et al., 2008b), there have been calls for research on firm-level implications (Markard et al., 2015; Ortt & Kamp, 2022; Planko et al., 2017). There is a need for knowledge of how individual firms or actors can directly influence the development of the innovation system as well as how they successfully adapt their business to the technological change. To answer this call, we integrate dynamic capabilities theory, which focuses on a firm's ability to adapt to changing business environments (Teece et al., 1997), into our analysis. We thereby introduce a firm-system perspective to the TIS framework where dynamic capabilities are connected to specific system functions to capture the complexity associated with green innovation transitions and to concretize implications at the firm-level. In doing so, we also contribute to the nascent research field of dynamic capabilities for green innovations, which recently has been proposed to be a promising way to support early-stage green transitions, but needs further conceptualizations (Di Vaio et al., 2022; Hällerstrand et al., 2023; Liboni et al., 2023).

The purpose of this study is to analyze both the current state and future potential for the development of biocarbon in Sweden. We delineate the technological innovation system for metallurgical biocarbon (TIS-MB) around the development of biocarbon adapted for metallurgical use, such as steel making or production of other alloys in Sweden. This includes the sourcing of feedstock, specifically woody biomass due to its beneficial chemical composition for metal production, the development of the biocarbon itself, and the development of metallurgical production processes for the integration of biocarbon. As part of the TIS analysis, this thesis identifies mechanisms that either drive or hinder the development of biocarbon, and maps these to assess the functionality of the TIS-MB. This provides insight into what is currently being achieved in the TIS-MB, highlights both the external and internal factors influencing its progress and contribute to the theoretical understanding of specific system functions (Bergek, 2019; Bergek et al., 2008b). Furthermore, we answer calls for a firm-level perspective to TIS (Markard et al., 2015; Ortt & Kamp, 2022; Planko et al., 2017) by identifying dynamic capabilities that strengthen system functions and support green innovation ventures. The study aims to provide both theoretical insights into green innovation transitions and practical implications for industry actors and policy makers, leading to the following research questions:

RQ1: *What are the driving and hindering mechanisms of the TIS-MB?*

RQ2: *What are the weak, intermediate and strong functions of the TIS-MB?*

RQ3: *Which dynamic capabilities are needed to strengthen the weak functions of the TIS-MB?*

2 *THEORETICAL BACKGROUND*

This chapter introduces the concepts of technological innovation systems and dynamic capabilities to provide an overview of the existing literature which form a basis for the analysis and results of this study.

2.1 Technological innovation systems

The TIS approach was from its inception developed for describing the development and diffusion of technological innovations, from a systems perspective (Carlsson & Stankiewicz, 1991; Carlsson, 2012). Rooted in innovation, evolutionary, and institutional economics, it was developed by Swedish policy makers to analyze technological and industrial dynamics (Bergek, 2019; Smits et al., 2010). A technological innovation system is a sociotechnical system, defined as *"a dynamic network of agents interacting in a specific economic and industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology"* (Carlsson & Stankiewicz, 1991). Although TIS theory was not developed with a focus on sustainability, the majority of studies conducted using TIS has been on green innovations (Bergek, 2019), indicating a relevance for innovations such as biocarbon.

Key to a TIS analysis is the functions approach which treats functions as sub-processes of the overall innovation system (Bergek, 2019). These functions are important to understand, both for policy makers and firms, in order to evaluate system strengths and weaknesses which may drive or hinder the development of the system (Bergek et al., 2008a; Hellsmark et al., 2016). In this thesis, we use the functions based on Bergek et al. (2008a), Bergek et al. (2008b) and adapted by Hellsmark et al. (2016). These are **resource mobilization** (F1), **market formation** (F2), **influence on direction of search** (F3), **entrepreneurial experimentation formation of social capital** (F5), **legitimation** (F6) and **knowledge development and diffusion** (F7), as seen in Table 1 below.

Table 1: Definitions of system functions within the Technological Innovation System (TIS) framework (Hellsmark et al., 2016).

Function	Definition
F1: Resource mobilization	The extent to which actors within the TIS are able to mobilize human and financial capital, as well as complementary assets such as products, services, network infrastructure, etc.
F2: Market formation	The factors that stimulate the emergence of markets for new products. These include articulation of demand from customers, institutional change, and changes in price and performance of the products. Market formation normally goes through different stages, i.e. demonstration projects, niche market, and mass markets.
F3: Influence on the direction of search	The incentives for organizations and actors to enter the technological field. These incentives may stem from visions, expectations of a growth potential, policy instruments, technical bottlenecks, etc. In an early phase, it also includes how prime movers manage to define technological opportunities and make it attractive for other actors to enter the field.
F4: Entrepreneurial experimentation	The testing of new technologies, applications, and markets whereby new opportunities are created and a learning process unfolds. This includes the development and investments in artifacts such as products, production plants, and physical infrastructure.
F5: Formation of social capital	Social relationships among key actors. This includes trust, mutual dependence, shared norms, authority, and a sense of togetherness in the TIS. This type of social capital facilitates network building, knowledge diffusion, and collective action.
F6: Legitimation	The social acceptance of the technology and the actors and compliance with relevant institutions. Legitimacy is formed through conscious actions by organizations and individuals, and this process may often be complicated by competition (and lobbying) from adversaries defending existing technologies and regimes.
F7: Knowledge development and diffusion	The breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the TIS. Various types of knowledge serve as inputs for innovation, including that generated from R&D and different learning processes (i.e., learning-by-doing, learning-by-using).

Each function is evaluated in terms of strength to assess the functionality of the TIS (Bergek et al., 2008b). One way of making this assessment is through identifying mechanisms, also conceptualized by some researchers as events (Hekkert et al., 2007) or strengths and weaknesses (Hellsmark et al., 2016), that either drive or hinder the development of the TIS. These mechanisms, which can be internal dynamics within the system or exogenous factors from the larger national or international context surrounding the system, result in what is being achieved in the TIS. Moreover, mechanisms can drive or hinder several functions at once, emphasizing the value in mapping and explaining these connections (Bergek et al., 2008b).

Some examples of mechanisms which have been identified in previous TIS studies are actors participating in international R&D projects and collaborations with universities contributing to **knowledge development and diffusion** in the TIS for Swedish marine energy (Andersson et al., 2017), testing complementary value chains contributing to **entrepreneurial experimentation** in the TIS for Swedish biorefineries (Hellsmark et al., 2016), development of standards contributing to **market formation** (Lee et al., 2017), EU directives and legislation contributing to **influence on direction of search** in the TIS for high voltage direct current technology (Andersen, 2014), public funding contributing to **resource mobilization** in the TIS for Norwegian biofuel industry (Fevolden & Klitkou, 2017), and the national research infrastructure affecting **legitimation** of the TIS for wind energy in Portugal (Bento & Fontes, 2015). In summary, the TIS literature provides the foundations for the systemic analysis of biocarbon for metallurgy in Sweden. In addition to this systemic perspective, we address the need of a firm-level analysis, building on dynamic capabilities research.

2.2 Dynamic capabilities

Dynamic capabilities were defined by Teece et al. (1997) as "the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments" and can be categorized into the ability to "*sense* and shape opportunities and threats, to *seize* opportunities, and to maintain competitiveness through enhancing, combining, protecting, and, when necessary, *reconfiguring* the business enterprise's intangible and tangible assets". Dynamic capabilities are especially beneficial in highly changing business environments (Linde et al., 2021; Zahra & George, 2002) where disruptive innovations induce systemic changes and several inventions must be combined to create an offering which fills the customers needs (Teece, 2007). Eisenhardt and Martin (2000) and Smart et al. (2007) argue that dynamic capabilities are not necessarily firm specific but can be duplicated across firms and that doing so has an inherent value as a source of competitive advantage.

Sensing has to do with discerning new opportunities related to the changes in the business environment and ecosystem, not only from a technological R&D perspective (Helfat, 1997), but also from a customer need and commercialization perspective (Teece, 2007). Firms can sense opportunities from customers as they often are the first to identify the potential of an innovation. Moreover, the understanding of customer or user needs has consistently been shown to be correlated with the likelihood of commercial success of an innovation. Suppliers can also be the origin of innovation as appropriating an upstream innovation before ones competitors can be a source of great competitive advantage (Teece, 2007). Zott (2003) describes competitors as another source of opportunity but gathering information for imitation is often costly. In many cases, sensing is not only about discovering new innovation, but collaborating with suppliers, complementors and customers to combine several innovations into a cohesive offering which fulfills a customer need (Helfat et al., 2009; Teece, 2007).

Seizing means being able to address a sensed opportunity through new processes, products or services (Teece, 2007). This capability depends on investments in development and commercialization and includes incorporating acquired knowledge into operations (Teece, 2007; Zahra & George, 2002). Firms need to update technological competences, invest in the technologies and design which they deem most promising in terms of market acceptance, and get the timing right (Teece et al., 1997; Zott, 2003). Firms can invest early and place a "risky bet" with potentially large rewards associated with early adoption, or they can wait until a dominant design has emerged. As important as the technological competences, is deciding the business model of how to commercialize the innovation. Large incumbent firms often fail to invest in sensed business opportunities related to innovations since bureaucratic features in hierarchically organized firms are usually biased against radical innovations as compared to more incremental improvements. Future cash flow projections as part of business models can therefore, as an example, be used to justify investments into a sensed business opportunity. The design of business models also defines the value proposition and will bring an increased understanding of customer needs as well as capabilities within the ecosystem (Teece, 2007).

Reconfiguring assets entails recombining assets and organizational structures as markets change or the firm grows (Karim, 2006; Teece, 2007). This could be reconfiguring internally developed or acquired business units, internal units being more slow to reconfigure

(Karim, 2006). To increase the speed of reconfigurations, firms can foster an acceptance of change by promoting a culture where the departure of institutions such as internal routines, rules or social norms are embraced within the organization (Ambrosini & Bowman, 2009; Teece, 2007; Zahra & George, 2002). Rigidness of such institutions can limit the organizations responsiveness to changes and, in combination with strong hierarchies, could make employees obligated to management only, instead of the customer (Teece, 2007). Because of this, bringing management closer to the market and technology by decentralizing the organization is preferred, and management leadership skills as well as attitudes are important to facilitate renewal of assets and institutions (Ambrosini & Bowman, 2009; Aragón-Correa & Sharma, 2003; Teece, 2007). Reconfiguring assets can also include the change in business models, mergers or acquisitions as part of management of the ecosystem (Bowman & Ambrosini, 2003; Karim & Mitchell, 2000; Teece, 2007).

In recent years, academic literature has recognized the applicability of dynamic capabilities for green innovations, e.g. (Burki et al., 2019; Buzzao & Rizzi, 2021; Hällerstrand et al., 2023; Ma et al., 2025). Dynamic capabilities are key to be able to commercialize green innovations by screening for business and technology opportunities, scouting for partnerships, orchestrating financing, and value chain, adapting business models and aligning internal and external resources (Hällerstrand et al., 2023). Buzzao and Rizzi (2021) found that dynamic capabilities for green innovations are characterized by added complexity, as compared to dynamic capabilities related to mainstream innovations. They involve systems thinking, extensive and socially convoluted innovation management, production processes such as cross-industry coordination and cross-stakeholder management, e.g. evaluating environmental impact of production processes by incorporating suppliers' knowledge. In line with this reasoning, Burki et al. (2019) argues that dynamic capabilities for green innovation allow for the identification of green supply chains and that when each actor in the supply chain strives for dynamic capabilities to increase sustainability, cross-industry coordination becomes crucial. These aspects align with the core elements of TIS, which also emphasizes the systemic nature of innovation, cross-industry collaborations, and institutional work (Bergek, 2019). This study therefore proposes dynamic capabilities as a lens to understand how firms successfully adapt to and commercialize green innovations within such systems.

3 *METHODOLOGY*

This chapter explains the chosen methodology of the study by describing the research approach, data collection, and data analysis.

3.1 Research approach

To answer our research questions, we utilize qualitative analysis in conjunction with an abductive research approach. As there is currently a gap in the literature connecting the systematic perspective of the TIS-framework and dynamic capabilities, qualitative analysis was deemed suitable as it allows for a deeper and more nuanced understanding of these themes. (Dierckx de Casterlé et al., 2012). The iterative nature of an abductive research approach was used to systematically combine theory and gathered data to create a greater understanding, since neither theory nor empirical findings may represent the full scope of the researched phenomenon on their own (Dubois & Gadde, 2002). An overview of the scientific method can be seen in Figure 1.

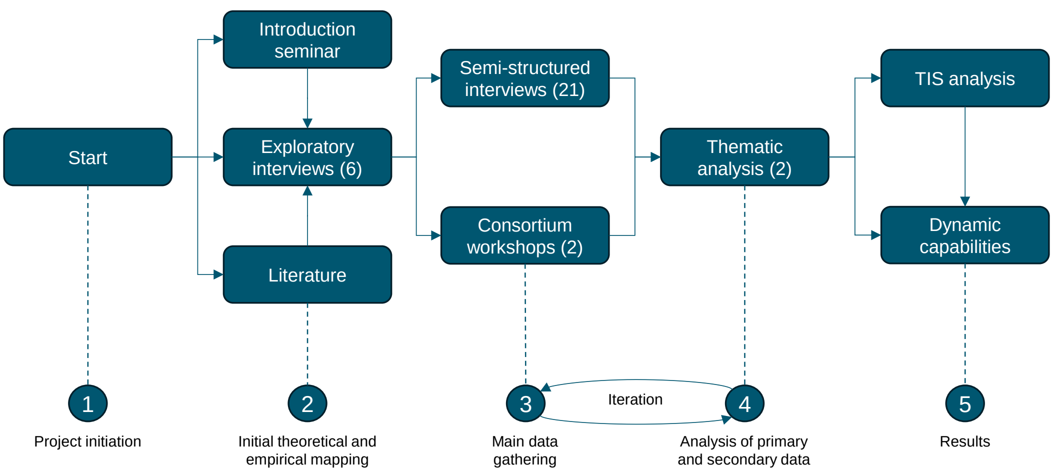

Figure 1: Scientific method.

3.2 Case selection

This study was conducted in collaboration with a Swedish research institute within a publicly funded project aimed at facilitating the implementation of biocarbon for metallurgical applications. The project is structured around three perspectives: (1) *Technological*, focusing on industry requirements and producer capabilities; (2) *Policy*, addressing regulatory conditions, conflicts of interest, and enabling policy changes; and (3) *Social*, to which this thesis contributes, exploring how to build knowledge, acceptance, and collaboration for sustainable biocarbon value chains and the green transition from fossil coal. While rooted in the social perspective, this thesis also has implications for the technological and policy perspectives. The research institute is working to establish a consortium of relevant stakeholders across the value chain, and the project is expected to serve as a foundation for future initiatives within the field.

This case was chosen because it met a predetermined criteria set by the authors. First, it represents the implementation of a green innovation. Second, it captures a technological innovation system in its formative phase, allowing analysis of early-stage market and system development. Third, the case consortium provides access to a broad range of relevant stakeholders engaged in the TIS-MB with varying backgrounds. Respondents' roles included strategic decision makers such as global technology directors, sustainability directors, and heads of business development; academic experts including professors and senior lecturers; as well as process-oriented professionals like process engineers, metallurgists, and technical specialists. This diverse set of respondents enabled this study to capture perspectives from different organizational levels and functions, ranging from long-term strategic planning and policy influence to technical implementation and research.

To define the structural components of the TIS; actors, networks, and institutions (Bergek et al., 2008b), we applied the four minimum conditions for the existence of a TIS, as outlined by Markard et al. (2015).

1. Encompassing a variety of different actors with different innovation strategies and/or control a set of *different resources, united by shared expectations or a shared vision for the respective innovation field.*

In the TIS-MB, actors share a vision of biocarbon as a sustainable replacement for fossil coal in metallurgical processes, contributing to the defossilization of the metal industry.

Biocarbon producers convert sustainably sourced biomass into renewable carbon materials. While some initially targeted agricultural markets, many are shifting focus toward metallurgical applications. Technology providers deliver pyrolysis systems, increasingly tailored for metallurgical biocarbon. In some cases, these systems were originally developed for bio-gas production but have since been adapted to produce biocarbon for metallurgy. Metal producers, under increasing regulatory and societal pressure to reduce greenhouse gas emissions, are testing biocarbon as a substitute in the production of "greener" steel, ferrochromium and other alloys. Industry associations advocate for the sector at national and EU levels and mobilize actors for research development around biocarbon. Forestry firms have not been as actively involved in the development of biocarbon, but are included in the TIS-MB since they control the biomass and their knowledge of biomass supply chain development. Academia contributes essential research in biocarbon production and metallurgical applications.

2. Having a certain division of labor between actors, meaning an innovation value chain or innovation networks with different types of actors focusing on different innovation tasks

Within the TIS-MB, biocarbon producers and technology providers are collaborating with academia and industry in research groups, particularly concerning the applications of biocarbon by-products. Metal producers also engage in development projects, often in partnership with research institutes and universities, and typically publicly funded. These projects focus on testing biocarbon in metallurgical processes, which differ depending on the alloy produced and production process, and logistics. Collaborative networks include publicly funded research projects and interest groups. Other partnerships involve commercial arrangements, including off-take agreements and equity transactions.

3. Having a variety of internal institutions

Institutions, formal and informal rules that shape behavior (Scott, 2013; Vargo et al., 2015) in the TIS-MB, include the Paris Agreement, the Swedish Climate Law, and the European Union Emissions Trading Scheme (EU ETS). The EU ETS sets a cap on the total amount of greenhouse gases that can be emitted by firms covered by the system. Firms receive or buy emission allowances at auction, each one representing one ton of carbon dioxide equivalents, and may sell or keep an eventual surplus for the future (European Commission, n.d.). Recent revisions impose stricter emission targets, increased the annual reduction rate and set an end date for new allowances after 2039 (Naturvårdsverket, 2024). These developments create pressure on emission-intensive industries such as the metal industry, which contributed 37% of Sweden's industrial emissions in 2023.

Regarding informal institutions, Sweden is distinguished by wide-spread public awareness and support for environmental policy (Harring & Jagers, 2018). TIS-MB actors are united by a shared vision of biocarbon as a way to defossilize the metal industry, in line with the metal industry's 2050 vision, "Steel shapes a better future", which aims to achieve a fossil-free steel industry by 2045.

4. Being characterized by a certain degree of market transactions, although the market might be immature

Although the market for metallurgical biocarbon is still emerging, there is evidence of early-stage commercial activity. *Biocarbon producer 1* is up-scaling through financing by *Metal producer 3* who in 2023 invested 9,9 MEUR in the firm, acquiring a 20% ownership and off-taking 50% of their biocarbon supply until the upscale is complete (Envigas, 2023). *Metal producer 3* have also invested 40 MEUR in their own biocarbon plant in Germany, which will have an annual capacity of 15,000 tons and which is also set for completion in 2026. The biocarbon produced in this facility will be delivered to their 30 MEUR compaction facility which is being constructed in Tornio, Finland and is expected to be completed mid-2025 (Outokumpu Corporation, 2024). However, most biocarbon producers remain small-scale and face challenges related to financing and the complexities of the technology. These challenges were exemplified by the bankruptcy of Cortus Energy in March 2025, one of

Sweden's largest producers (Dagens Industri, 2024).

3.3 Data collection

The primary data for this study were gathered through interviews with respondents possessing suitable roles in stakeholder organizations as can be seen in Table 2. All interviews were conducted and recorded digitally via Microsoft Teams. The recordings were then transcribed, assessed and analyzed by both authors.

Table 2: Overview of the interviews and informants.

Respondent ID	Role	Company	Country (Language)	Date	Duration (min:sec)	Transcribed words
Explorative interviews						
R1 & R2	Process engineer & Global technology director	Metal producer 1	SWE (Swe)	2025-02-13	36:49	4080
R2, R3 & R4	Global technology director, process development engineer & Energy coordinator	Metal producer 1	SWE (Swe)	2025-02-14	54:10	6662
R5 & R6	Metallurgist & Metallurgy process manager	Metal producer 2	SWE (Swe)	2025-02-14	45:21	5445
R7	Professor of economics	University 1	SWE (Eng)	2025-02-17	36:50	3697
R8	Technical business specialist	Biocarbon producer 1	SWE (Swe)	2025-02-18	39:13	4240
R9 & R10	Research manager & research manager	Metals producer association	SWE (Swe)	2025-02-20	52:38	6799
Semi-structured interviews						
R11	Director of sustainable business development & strategy	Forestry firm 1	SWE (Swe)	2025-03-10 & 2025-03-17	53:20 & 29:41	5738 & 3410
R12	Marketing manager	Biocarbon seller 1	SWE (Swe)	2025-03-11	46:47	6654

R13	Head of business development, former CEO	Biocarbon producer 1	SWE (Swe)	2025-03-11	57:37	7730
R14	Project and development engineer	Biocarbon technology supplier 1	SWE (Swe)	2025-03-14	43:51	6881
R15	Program manager, Heat & Power	Energy sector research institution	SWE (Swe)	2025-03-14	63:15	5365
R16	Global business developer	Biocarbon producer 2	SWE (Swe)	2025-03-17	44:23	5032
R17	Senior lecturer in bioenergy systems	University 2	SWE (Swe)	2025-03-17	28:02	2418
R10	Research manager	Metals producer association	SWE (Swe)	2025-03-17	50:32	6389
R5	Metallurgist	Metal producer 2	SWE (Swe)	2025-03-18	65:35	8962
R2	Global technology director	Metal producer 1	SWE (Swe)	2025-03-18	54:35	6543
R8	Technical business specialist	Biocarbon producer 1	SWE (Eng)	2025-03-18	49:51	5234
R18	Senior process engineer	Metal producer 4	SWE (Swe)	2025-03-19 & 2025-04-02	56:08 & 41:26	6854 & 6210
R19 & R20	Group business controller & Sustainability director	Forestry firm 2	SWE (Swe)	2025-03-20	33:53	3648
R1	Process engineer	Metal producer 1	SWE (Swe)	2025-03-20	62:44	7572
R21 & R22	Sustainability director & VP and Head of business development	Biocarbon technology producer 2	SWE (Swe)	2025-03-21	46:46	5645
R3	Process development engineer	Metal producer 1	SWE (Swe)	2025-03-21	44:57	3744
R23	Sales manager	Biocarbon seller 1	SWE (Swe)	2025-03-21	58:17	6408
R24	Research engineer	Metal producer 3	SWE (Swe)	2025-03-31 & 2025-04-01	58:51 & 20:08	5968 & 2104
R25	Energy project manager	Metal producer 4	SWE (Swe)	2025-04-25	43:33	5107

3.3.1 Exploratory interviews

To support the early stages of our research process and guide the refinement of our research focus, we conducted a series of exploratory interviews (Appendix A). These interviews served as a means to gain a preliminary understanding of the context, identify relevant stakeholders as well as uncover key issues and dynamics related to the introduction of biocarbon on the Swedish market and the development of the associated TIS. During this phase of our data collection we focused on actors that were already active within the case projects consortium. This included customers, producers, actors from academia, and a trade association for the metallurgy industry. Six exploratory interviews were conducted with a total of ten respondents.

3.3.2 Semi-structured interviews

To deepen our analysis of the TIS-MB, we conducted 21 semi-structured interviews with a diverse set of system actors. This method was selected for its ability to elicit in-depth insights while maintaining a degree of consistency across interviews. This interview format enabled us to ask comparable questions across respondents, while also allowing flexibility to probe interesting or unexpected points raised during each conversation (Louise Barriball & While, 1994). An interview guide (Appendix B) was developed based on our initial theoretical understanding of TIS, insights from the exploratory interviews, and observations from the introductory project seminar. Throughout the process, the interview guide was iteratively refined to better capture emergent themes and to ensure relevance across the diverse set of respondents. The interview sample included representatives from a broad range of organizations, varying in both size and sector, to reflect the heterogeneous nature of stakeholders in the TIS-MB. Care was taken to ensure balanced representation across identified stakeholder categories and value chain position, allowing us to build a more complete picture of the system and minimize the risk of overrepresenting any single actor category.

3.3.3 Secondary data and validation activities

To support our case study and enrich our understanding of the empirical context of the case project, we participated in a series of events: one seminar and two workshops. First, an introductory "Current Situation Seminar," which included presentations and a workshop session. This seminar served as a foundation for understanding the background, objectives, and current challenges. Subsequently, we attended two workshops focused on specific themes relevant to our study, conflicts of interest and, competence supply. These events included actors from within and outside the project consortium, including metal industry, district heating and academia.

To ensure the robustness and relevance of our analysis, we presented our research design, methodological approach, and preliminary findings at multiple stages throughout the thesis process. These sessions, held with members of the case project consortium, provided iterative feedback that shaped the development of our analysis. Toward the end of the project, we conducted a final presentation for a select group of external respondents to gather their reflections on our conclusions. This validation step ensured that our interpretations resonated with stakeholder experiences and were grounded in the practical realities of the TIS-MB.

3.4 Data analysis

The analysis of the gathered empirical data followed a three-phase qualitative approach, grounded in thematic analysis. Thematic analysis was chosen due to its flexibility in identifying, analyzing, and interpreting patterns within qualitative data (Braun & Clarke, 2006).

3.4.1 Phase 1: Mapping of system mechanisms and dynamic capabilities

In the first phase, two separate thematic analyses were conducted. The first, to identify hindering and driving mechanisms as conceptualized within the TIS framework (Bergek et al., 2008b). This process was initiated by the pre-selection of two themes, (1) driving mechanisms and (2) hindering mechanisms, after which the more traditional thematic analysis process was applied by first identifying representative quotes. The quotes were then grouped together into thematic codes, which were subsequently grouped into sub-themes. For example, the sub-theme and driving mechanism *Sustainability trends drive development* was generated by quotes such as *"The need for biocarbon primarily came from a sustainability perspective"* [R1].

The second thematic analysis was conducted with the same primary data as the previous one, but with a focus to identify the dynamic capabilities that support the development of the TIS-MB. In this stage, we grouped quotes where respondents either (1) described what types of dynamic capabilities are missing in the TIS-MB, or (2) how their organization had succeeded in leveraging dynamic capabilities for biocarbon efforts, into codes. These were then sorted into the sub-themes, which became the dynamic capability conceptualizations, and were sorted into themes for dynamic capability categories. For example, the sensing capability *market screening* from quotes such as "*Well, it was at the same time that we read some articles where people started talking about the possibility of replacing coal both for metallurgical applications...*" [R12].

3.4.2 Phase 2: Functional assessment of the TIS-MB

During phase 2, the identified mechanisms from the initial thematic analysis were applied to asses the functional pattern of the TIS-MB. While the traditional application of the TIS framework involves first evaluating the performance of system functions and then identifying associated hindering and driving mechanisms (Bergek et al., 2008b), our analysis has taken a reversed but methodologically reasoned approach. The mechanisms were systematically mapped to corresponding TIS functions based on their correlation with the function definitions in Table 1. This alternative ordering allowed us to stay close to the empirical expressions of system dynamics, while still maintaining analytical alignment with the TIS framework. Through this mapping, we could evaluate each of the seven functions of the TIS-Mb, assigning them a rating of either strong, intermediate, or weak.

3.4.3 Phase 3: Dynamic capabilities for weak system functions

After identifying relevant dynamic capabilities and evaluating the system functions, where *market formation* (F2) and *resource mobilization* (F1) emerged as weak, we combined the two analyses to explore how specific capabilities could support these functions. By examining the context of quotes linked to each capability, we connected them to the system's functional challenges. The mapping focused on how each capability helped overcome barriers or enabled progress in F1 and F2, such as addressing resource constraints, attracting stakeholders, or reducing market uncertainty. Capabilities were grouped by their category, whether enabling actors to *sense* opportunities, *seize* opportunities, or *reconfigure* assets.

3.5 Quality enhancing measures

To ensure that this study is of high quality, we engaged in several quality improving measures. These can be categorized into the four criteria of trustworthiness presented by Guba (1981): (1) *Credibility*, (2) *Transferability*, (3) *Dependability*, and (4) *Confirmability*.

Credibility refers to how well the results accurately reflect the reality of the studied phenomenon (Graneheim & Lundman, 2004). To increase the credibility of this study we interviewed people from different industries, with different backgrounds and experiences in order to capture varied perspectives. Regular engagement with the actors within the established project consortium allowed us to get a thorough understanding of their perspectives and priorities, related to the implementation of biocarbon for metallurgy. Finally, to reduce the risk for mistranslation of interview quotes from Swedish and thus misrepresentation of the data, we used software and discussed the translations ability to convey original information.

Transferability refers to the extent to which findings can be applied to other contexts or settings (Graneheim & Lundman, 2004). In this study, transferability is supported by the use of a well-established theoretical frameworks, which offer a structured and generalizable approach to analyzing the development of emerging innovation systems. This study includes a diverse range of stakeholders and, although characterized by the specific institutional environment of Sweden, this diversity increases the transferability to other green innovation contexts

Dependability relates to the stability of data over time and how well the research process is documented (Graneheim & Lundman, 2004). To increase dependability, thorough descriptions and visualizations of the different methodological steps taken during the writing of this thesis are included. While only the final versions of utilized interview guides are provided (Appendix A, B), the structure and key questions asked remained the same throughout the data gathering process. However, irreplicable findings may occur due to the nature of semi-structured interviews. This study is performed to the specific formative stage of the TIS for biocarbon in Sweden which may experience significant changes over time. However, the findings will still be relevant for other innovation systems in a similar stage.

Confirmability is the degree to which the results could be confirmed or corroborated by other researchers (Graneheim & Lundman, 2004). To increase the level of confirmability, the methodology and results were discussed with supervisors at the case company and validated through regular presentations for actors from both within and outside the project consortium. Finally, limitations of the study are adressed in the discussion chapter.

4 *RESULTS*

In this chapter, the results of the study are presented. First, driving and hindering mechanisms for the TIS-MB have been identified, these are then used to assess the functional pattern of the TIS-MB, and lastly, conceptualizations of dynamic capabilities for weak system functions are presented.

4.1 Mapping of driving and hindering mechanisms

In this section, driving and hindering mechanisms (DM and HM) of the TIS-MB are identified, shown in Figure 2 below. Our findings highlight that what is being achieved in the TIS-MB is, on the one hand, as a result of internal factors within the system, and on the other hand, exogenous factors on a national and international level.

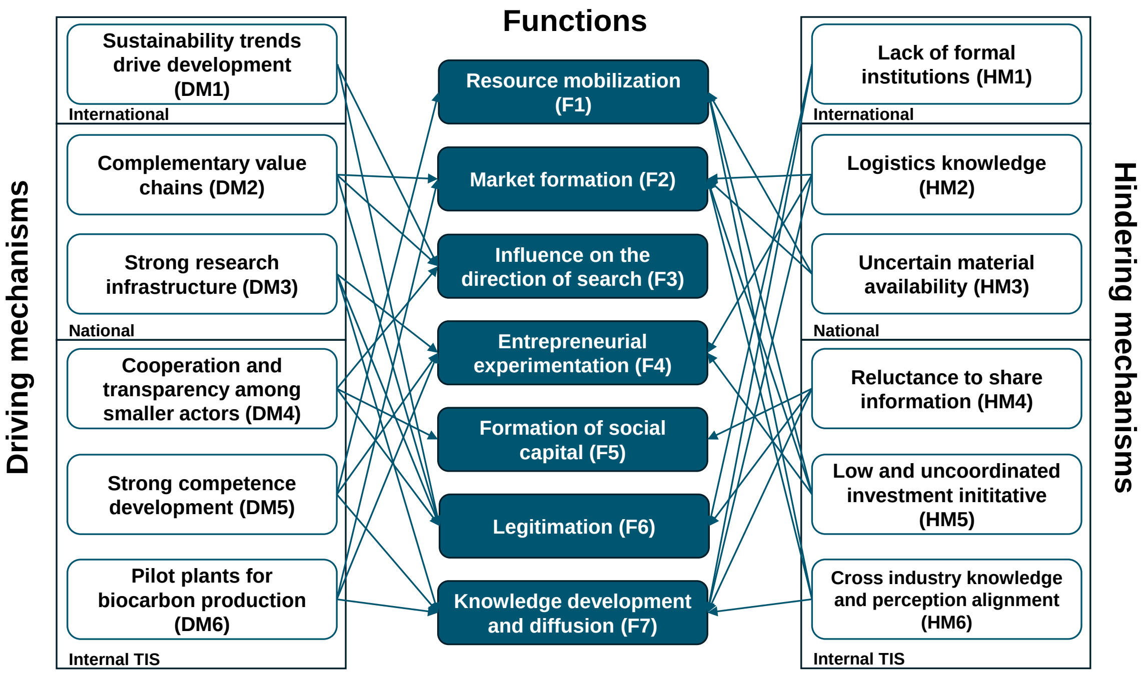

Figure 2: Mapping of driving and hindering mechanisms

4.1.1 Driving mechanisms

International driving mechanisms

Sustainability trends drives the development (DM1) represents the fact that system actors universally agree that the main driving force behind the formation of the TIS-MB is the sustainability trends and the related pressures of formal and informal institutions. Social awareness and pressures of sustainability are high as firms are expected from the public to lower emissions and become more sustainable. Related policies and regulations also act as a driving force largely due to a lack of viable alternatives to fossil carbon in metallurgical processes. Frequently mentioned by respondents was the EU ETS, which places regulatory pressure on the metals industry by attaching a cost to emissions, adding a financial incentive to defossilize the industry.

> *"Right now we have free emissions rights, but this is kind of to face what happens if you don't have free emissions rights anymore. That we are ready for that."* - R24

Moreover, biocarbon producers, technology providers and, to some degree forestry firms, are realizing that this is a business opportunity and see growth potential in the market. These trends therefore drives the development of the TIS-MB by contributing to the social acceptance and **legitimation** (F6) of the technology. It is also linked to **influence on the direction of search** (F3) by incentivizing new entrants to join the system and incumbent actors to adapt their business to integrate biocarbon.

National driving mechanisms

One key driving mechanism identified in the TIS-MB is the presence of *several potentially complementary value chains* (DM2) connected to biocarbon production. Respondents emphasized that the biocarbon production process, particularly in pyrolysis or gasification systems, generates multiple outputs beyond biocarbon. These include process heat, bio-oils and syngas. System actors, specifically biocarbon producers, are currently looking for profitable areas of use for these side streams to enhance the economic viability of production facilities. Furthermore, the forestry firms are particularly interested in the potential use of underutilized biomass sources for biocarbon production, proving that the potential for symbiotic business cases are present throughout several levels of the TIS-MB value chain.

These opportunities **influence the direction of search** (F3) by encouraging actors to explore diversified business models. Co-locating production with industries such as district heating or agriculture was highlighted as a strategy to enhance integration and efficiency.

This cross-sector potential also supports **market formation** (F2) by embedding biocarbon production within existing infrastructures, lowering risk, and enabling more robust business cases. At the same time, the visibility of multiple benefits enhances **legitimation** (F6), making the technology more attractive to stakeholders and policy actors.

> *"And have some combustion process where you can put a little more biomass in and then a new kind of product comes out that's pretty close to what you've done before. Stop the full combustion so you're just taking out the heat. End it too early and you can sell the residual product instead. That feels like the most reasonable"* – R10

Strong research infrastructure (DM3) refers to the robust foundation of academic and applied research supporting innovation within the TIS-MB. Several actors, both public and private, have actively contributed to and participated in research projects aimed at solving technical challenges related to biocarbon production, metallurgical applications, logistics, and handling.

These collective, though at times fragmented, efforts play a key role in advancing **knowledge development and diffusion** (F7) by generating new insights, validating technological options, and serve as platforms for shared learning between actors and sectors. The research infrastructure also facilitates **entrepreneurial experimentation** (F4) by providing access to test environments, analytical capabilities, and expert networks. Several pilot activities have been enabled through collaborations with universities and research institutes, allowing actors to test biocarbon solutions in realistic settings with lower risk. In parallel, strong involvement from recognized research institutions contributes to **legitimation** (F6). Scientific engagement signals credibility, increases stakeholder trust, and helps position biocarbon as a legitimate, evidence-based alternative to fossil carbon.

> *"Then what we have been working on a lot is that we work with research and development projects like this. For companies, it is partly financed by, for example, the Energy Agency, Vinnova, the Swedish Research Council, these different sources, so to speak."* – R14

Internal driving mechanisms

An important driving mechanism in the TIS-MB is the high degree of *cooperation and transparency among smaller actors* (DM4). Many of the system actors actively participate in initiatives aimed at building and sharing both technical and contextual knowledge related to biocarbon production, applications, and supply chain development.

Formal and informal learning environments, such as pilot projects, inter-organizational collaborations, and the establishment of interest groups, have proven especially valuable. These spaces have contributed to building competence and a collaborative culture where actors are open about challenges, results and learnings. This strengthens the **formation of social capital** (F5) within the TIS-MB by building trust, reciprocity and interactions among actors who might otherwise be isolated. It also **influences the direction of search** (F3) by highlighting promising development paths and encouraging alignment around shared challenges and opportunities. Moreover, the visible collaboration contributes to **legitimation** (F6). When smaller actors coordinate efforts and share progress, it signals credibility and seriousness to external stakeholders, reinforcing biocarbon's role as a viable alternative.

> *"Above all, we are quite open about what we do. We have come out and said that we have built a demo facility where we invited both users and equipment suppliers to show that this is actually something that we do and that works reasonably well. And we have received a lot of feedback from suppliers, among other things."* - R2

The presence of *strong competence development* (DM5) is another key driving mechanism. This growing knowledge base is particularly valuable in the early stages of system formation, as it enhances the ability to experiment, adapt technologies, and engage with actors in adjacent sectors. Competence is developed in different ways depending on actors' roles. Metal producers often invest in internal research and testing, allocating staff and resources to build in-house capabilities, supporting both **entrepreneurial experimentation** (F4) and **resource mobilization** (F1). Other actors, like *Biocarbon Producer 1*, focus on recruiting specialized personnel, while some broaden their activities to neighboring sectors to gain complementary knowledge. These strategies contribute to **knowledge development and diffusion** (F7) and strengthen the system's overall innovation capacity.

> *"We've been building this for a few years now and we have a bunch of PhDs that we've*

recruited over the years, so I think we've probably filled the gaps that we might have had before." – R13

The establishment of *pilot plants for biocarbon production* (DM6) is an important driving mechanism in the TIS-MB, enabling applied learning, collaboration, and system development. Many actors across the value chain have participated in pilot projects to test and adapt biocarbon solutions relevant to their role. These pilots support **entrepreneurial experimentation** (F4) by allowing actors to address practical challenges such as handling, densification, and logistics. For example, *Biocarbon Producer 1* is demonstrating production scalability, while others tackle transport-related constraints. By generating real world insights, pilot plants contribute to **knowledge development and diffusion** (F7), especially as many of the challenges are systemic rather than firm-specific. They also aid **market formation** (F2) by validating processes, reducing uncertainty, and signaling technological readiness to potential users and investors.

"So that's why we attempt to scale up from 5,000 tons to 30,000 tons. And actually the next production plant of 30,000 tons, we see it as a proof of concept that, yes, the market is there... So this will be a proof of concept to increase more our capacity later to 150,000 tons in 2030." – R8

4.1.2 Hindering mechanisms

International hindering mechanisms

The *lack of formal institutions* (HM1), such as quality standards, certification systems, and clear legislation, have been identified as a key hindering mechanism hindering the development of the biocarbon innovation system. This lack of institutional infrastructure impacts both **knowledge development and diffusion** (F7) and the **legitimation** (F6) of the technology.

Several respondents highlighted that the absence of shared quality standards for biocarbon complicates efforts to development and compare knowledge across actors. Without common reference points, it becomes difficult to asses the performance or suitability of biocarbon for specific applications, which in turn hampers collaborative learning and knowledge accumulation. Similarly, the lack of recognized certification systems was described as a bottleneck that limits trust in biocarbon among potential producers, users and surrounding actors. Legislation was also frequently mentioned as an area of uncertainty. In some cases, biocarbon does not clearly fall under existing regulatory frameworks, leading to confusion about how it should be handled, applied, or reported. This regulatory ambiguity weakens the perceived legitimacy of the technology and limits incentives for further investment or experimentation.

Taken together, the lack of formal institutions appears to stall both the generation and circulation of knowledge and the broader process of market legitimation.

> *"...standardization of how to evaluate, test and qualify biocarbon as a product. This needs to happen, because there are currently no standards for biocarbon. Then it is clear what biocarbon producers who supply us with biocarbon, what they need to do, what product they should have, so that we are interested."* –R3

National hindering mechanisms

A large share of respondents emphasized uncertainties related to the *logistics knowledge* (HM2) of biocarbon. Dustiness and self-combustion tendencies of the material poses significant safety hazards during storage and transport as fires have already occurred at storage sites. Although some actors have developed technical solutions to mitigate these hazards, there is still no standardized approach for safe handling. In addition, the biological nature of biocarbon introduces the risk of molding during long-term storage, making consistent handling practices even more critical.

> *"The safety aspects of storage and things like that. Handling, there's also a gap. It's been a long time since the steel industry handled charcoal. And it's not the same as coal. It's alive."* –R1

Another major challenge lies in the low bulk density of the material. In addition to contributing to dustiness, the low density makes transportation costly, especially as metal producers require increasingly large volumes. The solution is to compress the biocarbon in dedicated compaction facilities, allowing each shipment to carry more usable material. However, there is no consensus among actors on how these facilities should be integrated into the value chain. Some suggest placing compacting units at production sites, making producers responsible for densification. Others argue for centrally located facilities closer to biomass sources to streamline upstream logistics.

> *"A huge challenge with everything that comes from biomass is the biomass itself and access to the biomass. It is extremely expensive to transport biomass… it feels like it will never be worthwhile to have a huge production site somewhere that does not have biomass"* -R14

These findings highlight a significant knowledge gap regarding logistical solutions, which has implications across multiple system functions. First, the lack of standardized handling procedures and shared understanding of logistics inhibits **knowledge development and diffusion** (F7), as lessons and best practices are not systematically captured and shared. Second, the absence of clear pathways for how logistics could be organized creates uncertainty, weakening the **direction of search** (F4) by making it harder for actors to identify promising investment areas or coordinate efforts. Finally, unresolved logistical challenges make it difficult to develop cost-effective and scalable supply models, delaying **market formation** (F2) and deterring engagement from potential producers, users, and investors.

The hindering mechanism *uncertain material availability* (HM3) refers to the widespread concern about the availability of biomass suitable for producing biocarbon with the qualities needed for metallurgical applications, such as low phosphorus content and high carbon content. Respondents highlighted a lack of clarity around both the total supply of viable biomass and the share that meets these technical standards. Competition for woody biomass, currently one of the few suitable sources, is already high due to demand from sectors like energy and pulp and paper. This competition contributes to limited availability and drives up prices, making biocarbon three to four times more expensive than fossil carbon, according to several respondents. As a result, alternative biomass sources such as branches and tree tops left from traditional wood harvesting, are being explored.

"...it's the whole mass balance puzzle, as I call it. That you should probably increase biomass extraction or change biomass extraction." – R10

This mechanism also includes the low biocarbon supply which impedes **market formation** (F2), since industrial users requests stable long-term supply before committing to procurement or process changes. Lastly, **resource mobilization** (F1) is constrained, as potential investors are reluctant to fund technologies with low production capacity and uncertain raw material availability.

"Before you start taking steps towards more investments, you need to see that there are volumes available." –R3

Internal hindering mechanisms

While cooperation and openness were described as strengths among smaller actors, this transparency often stops when it comes to commercially sensitive information. Larger firms were frequently mentioned as particularly *reluctant to share information* (HM4), unless an established partnership exists. This limits system development in several ways. First, it hinders **knowledge development and diffusion** (F7). Without access to key insights, such as procurement needs or technical requirements, smaller actors struggle to align their innovation efforts, slowing collective learning. Second, this behavior weakens the **formation of social capital** (F5). Limited trust and low levels of informal exchange between small and large actors create a fragmented system, reducing opportunities for collaboration and mutual support. Third, it obstructs **legitimation** (F6). Respondents noted that visible support and open engagement from large firms would help validate biocarbon as a credible alternative. Their silence or closed-off stance sends mixed signals to other stakeholders, slowing momentum and reducing confidence in the transition. Several smaller actors expressed a desire for these influential firms to assume a leadership role in guiding the biocarbon transition. In particular, they emphasized the importance of larger firms clearly stating what they are willing to pay for biocarbon, as this would reduce uncertainty and guide investment and development efforts.

"Until people have had to confess their business in terms of what they are willing to pay, the business model has too many uncertain variables" – R10

Lack of openness and leadership from key industry players not only hampers trust and coordination but also contributes to broader system fragmentation. One critical consequence is *low and uncoordinated investment initiatives* (HM5), which further limits the system's ability to progress beyond early-stage development. Across the TIS-MB, there is a noticeable and expressed lack of targeted, system-wide investments to support the scale-up of biocarbon production. Producers consistently emphasized the need for financing to expand capacity, with off-take agreements seen as a critical enabler.

This dynamic constrains **resource mobilization** (F1), as investors remain cautious without clear signs of market maturity. The limited number of buyers willing to commit also makes it difficult for producers to justify capital-intensive expansion. Some isolated efforts exist, such as *Metal Producer 3*'s off-take agreements and internal investments, but these are primarily aimed at securing internal supply rather than supporting a broader, open market. The lack of coordinated investment and demand aggregation directly undermines **market formation** (F2). Without reliable supply-demand structures, price formation, and long-term business relationships, actors across the value chain hesitate to engage. A fragmented investment landscape also constrains **entrepreneurial experimentation** (F4). Emerging producers face high financial barriers to testing and scaling biocarbon solutions, and the lack of coordinated funding or support mechanisms increases the risk of stagnation or exit from the system.

The hindering mechanism *cross-industry knowledge and perception alignment* (HM6) refers to the gap in mutual understanding and expectations between actors across different parts of the biocarbon value chain. Respondents emphasized the increasing need to understand both upstream and downstream processes, such as biomass sourcing, biocarbon production, and industrial application, at a deeper level than before the TIS-MB began to emerge.

Beyond technical knowledge there is also misalignment in perception regarding what biocarbon should be used for and which biomass types are appropriate. While some actors see biocarbon as an input for metallurgy, others view it as a lower-value energy product.

This hinders **knowledge development and diffusion** (F7) by limiting shared learning and slowing system-wide understanding. It also affects **market formation** (F2). Without alignment on uses, feedstocks, and quality expectations, actors struggle to coordinate around standards, pricing, and long-term roles, delaying the structuring of functioning markets. Finally, the misalignment weakens **resource mobilization** (F1). Uncertainty about value chain interactions and future roles creates hesitation among investors and supply chain partners. This barrier is particularly evident in discussions around symbiosis potentials. Utilizing side streams across sectors could improve profitability and lower biocarbon prices, but realizing these opportunities requires cross-sector coordination that is currently lacking.

> *"...the steel and metal industry will have to talk to the automotive fuel industry and other large industries that you are not used to talking to. Who will steer it? That is what I am a little curious about in the coming years."* -R3

4.2 Assessing the functional pattern

In this section, the functional pattern of the TIS is assessed, based on the identified driving and hindering mechanisms. In other words, how well the TIS-MB is performing based on seven key system functions, as defined in Hellsmark et al. (2016) and illustrated in Figure 3.

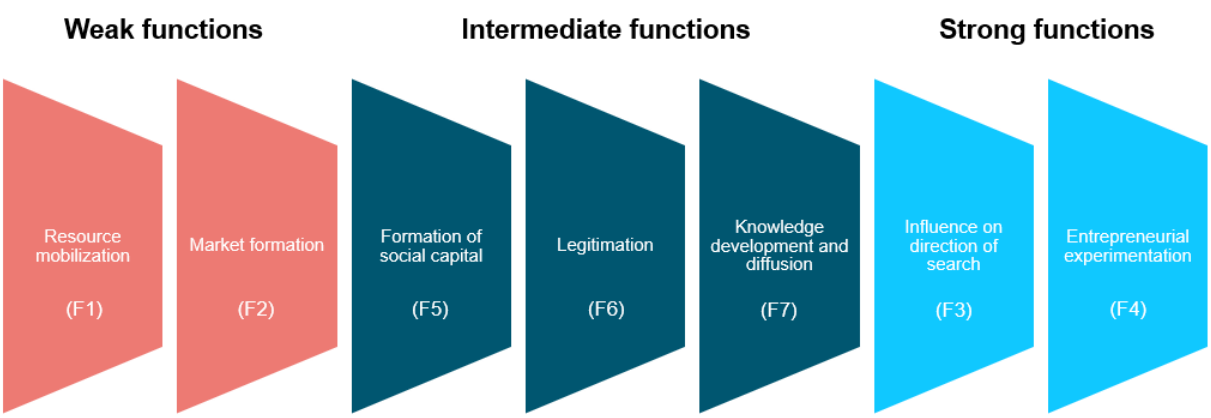

Figure 3: Assessment of functions

4.2.1 Weak functions

Resource mobilization (F1) and **market formation** (F2) are identified as weak within this system. F1 is weakened by a low supply of biocarbon (HM3) and lack of cross-industry knowledge and perception alignment (HM6), leading to an unwillingness to invest in up-scaled biocarbon production facilities (HM5). Financial resources are not being mobilized to a high degree, largely because of the lack of suppliers and competition as well as uncertainties regarding by-product applications and lack of cross-industry symbiosis. F2 is hindered by unresolved supply chain related challenges (HM2) and high competition of suitable biomass. High biomass prices contributes to a biocarbon product that costs about three to four times as much as fossil carbon and these prices transfer down in the value chain toward the metallurgical end product. Prices are also affected by underutilized side streams (HM6). F2 is also weakened by the lack of investments (HM5), leading to a paradoxal situation of smaller biocarbon producers being unable to produce the required higher volumes of biocarbon (HM3) because of financial constraints and investors being unwilling to invest in facilities that do not already have a large production capacity.

4.2.2 Intermediate functions

Knowledge development and diffusion (F7) is rated as intermediate since the system, on the one hand, has a robust knowledge development infrastructure (DM5) in terms of applied research (DM3), trial tests of biocarbon production (DM6) and biocarbon applications in different metallurgical processes. The nature of the early phase of the technology does however mean that there are knowledge gaps, mainly around sourcing of biomass (HM3) as well as transportation, handling and storage of biocarbon (HM2). For this function to be strengthened, knowledge development needs to be continued, dissemination of knowledge (HM4) must increase, production needs to be up-scaled and standards (HM1) must be developed. **Legitimation** (F6) is also intermediate and relates to the issue of up-scaling and standardization. While there are strong networks (DM4), research (DM3) and unified visions (DM1) for biocarbon, the acceptance of the technology is lowered by a reluctance by industry leaders to share information (HM4) and formal institutions (HM1). The last intermediate function, **formation of social capital** (F5) stems from the strong networks (DM4) that that have been built within the TIS-MB, and the fact that actors recognize the importance of partnerships for development to continue. With this said, firms must balance cooperation and secrecy when it comes to information that might be sources of competitive advantages. Larger firms in particular, tend not to be as open as their smaller counterparts (HM4), which hinders the development of the system as a whole.

4.2.3 Strong functions

On the other hand **influence on direction of search** (F3) and **entrepreneurial experimentation** (F4) are considered strong. F2 is highly affected by sustainability trends (DM1) and related policy instruments, such as EU ETS, as an incentive for new entrants to join the system. Metal producers realize that they will pay a high fee for their emissions in the future and see biocarbon as a way to meet reduction targets. Biocarbon producers, technology providers and, to some degree forestry firms, are realizing that this is a business opportunity and see a growth potential in the market (DM2). Moreover, many actors are quite open about their efforts (DM4) and are thereby raising the awareness of and activating other actors to get involved. These efforts are investments and developments into the production (DM6) and application of biocarbon contributing to F3. Metals producers have conducted pilot tests for the application of biocarbon in their processes for several years (DM3, DM5) and their technical competence of how biocarbon should be integrated is therefore quite high. Investments are also being made in the infrastructure of how to receive and handle biocarbon, and on the producer side, there is a clear research infrastructure with institutes and universities.

4.3 Dynamic capabilities for weak system functions

In this section, the results from the functional assessment as well as driving and hindering mechanisms are used to narrow down the analysis to the firm-level. We delimit ourselves to the weak functions **market formation** and **resource mobilization** and discuss what dynamic capabilities are needed for forestry firms, biocarbon producers, -sellers, and -technology providers, as well as metal producers to navigate and strengthen these weak functions.

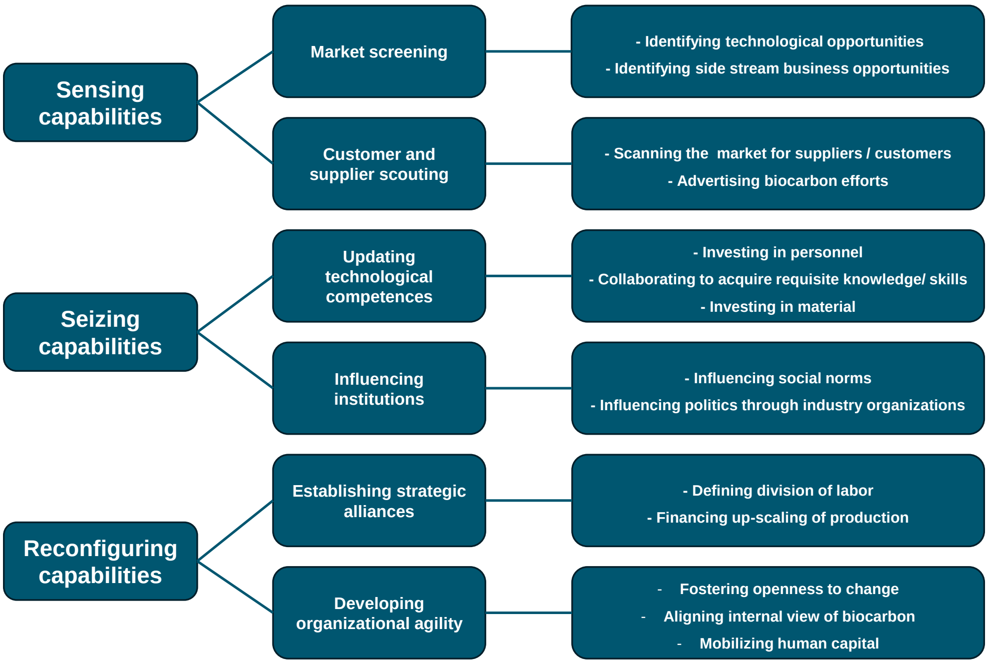

Figure 4: Dynamic capabilities for weak system functions

As seen in Figure 4 above, six dynamic capabilities for TIS-MB actors have been identified. The sensing capabilities identified are *market screening* and *customer and supplier scouting*. The seizing capabilities identified are *updating technological competences* and *influencing institutions*. The reconfiguring capabilities that have been found are *establishing strategic alliances* and *developing organizational agility*.

4.3.1 Sensing capabilities

Market screening is the dynamic capability of being able to identify technological and business opportunities. We found that leading firms are able to recognize and evaluate emerging trends, innovations and side-stream opportunities to "sense" potential areas for both advancements in technology and strategic business growth. This is done through customer requests, academic research, consulting reports, and market reports.

Market screening contributes to **resource mobilization** by inducing strategic shifts that mobilize financial and human resources towards biocarbon, both internally and externally.

Furthermore, by identifying side-stream applications, resource use can be made more efficient, financially viable, or even critical for survival. It also contributes to **market formation** by mapping the possible applications and demand of biocarbon, its by-products and related services. Furthermore, it acts as a basis for actors to identify new business models and enter the market.

For instance, forestry firms have recognized that biocarbon presents an opportunity to make better use of by-products like sawdust, wood chips, and tops and branches. Traditionally, these materials were sent to district heating plants. However, in northern Sweden, the practice of harvesting tops and branches has significantly declined. As R11 explained, this is a result of contractors being layed off in the 2010s, triggered by the heating sector's transition to alternative fuels. Thus, much of this biomass is now left unused, highlighting a potential opportunity to utilize it through biocarbon applications. Another example is that biocarbon producers and technology providers have been able to identify the importance of monetizing by-products in order to be able to scale up production.

> *"...if someone produces biocarbon, they will for sure produce oil and gas and they have to do something with this. If they don't know what to do with this, then the industry will fail because they will not be able to financially support the production of biocarbon."* – R8

Respondents had identified possible applications of bio-oil and syngas to include district heating, energy production and the production of refined products such as chemicals, methane, hydrogen and renewable fuels, including jet fuel.

Customer and supplier scouting refers to the capability to identify and engage with potential customers and suppliers in the market. This involves scanning the market to locate actors who might be interested in biocarbon products or services, as well as advertising biocarbon efforts to raise awareness. The aim is to send credible signals about emerging opportunities in the TIS-MB to attract and activate these stakeholders.

This dynamic capability contributes to **resource mobilization** by helping to secure the necessary inputs such as raw materials, logistics services, technologies, and knowledge. At the same time, it builds demand by identifying customers who are not only interested in biocarbon products but also potentially willing to pay a "green premium" for sustainable alternatives. In doing so, it unlocks financial, material, and human resources essential to scale up innovation efforts. Customer and supplier scouting also facilitates **market formation** by shaping both the supply and demand sides of the value chain. On the demand side, early adopters of biocarbon products are identified. On the supply side, it engages suppliers who can support the up-scaling of production. As more market participants are engaged, transactions increase and the market matures.

Customer and supplier scouting is essential throughout the entire value chain, from forestry firms, biocarbon producers to metal producers. As an example, leading biocarbon producers and metal producers are learning to target specific customer segments that are more motivated to pay a green premium for sustainable products.

> *"We've looked at it and we can see that from some applications you can charge more, from some it's probably more difficult."* – R1

Firms are also considering diversifying their offerings. For example, producing different grades of "green" alloys with varying amounts of biocarbon content, at different prices.

4.3.2 Seizing capabilities

Updating technological competences entails being able to "seize" the sensed business opportunities by experimenting and conducting pilot tests, collaborating with other actors to acquire knowledge, and investing in skilled personnel.

Updating technological competences improves **resource mobilization** by acquiring human capital to address knowledge gaps and drive innovation. Moreover, by using collaborations, firms can share knowledge and the risks and costs of R&D. By addressing knowledge gaps, firms are more likely to mobilize financial capital and committing to large investments related to biocarbon. Updating technological competences contributes to **market formation** since it ensures that biocarbon meets the technical performance and safety requirements of metallurgical applications. Furthermore, standards and specifications can be developed to reduce uncertainties. This contributes to the commercialization of biocarbon and facilitates market transactions.

Forestry firms reported having expertise in traceability and woody biomass sourcing but identified a need to deepen their understanding of material properties relevant to metallurgical use, as expressed by R11. Biocarbon producers are focused on refining by-products and improving safety and handling. Metal producers are also exploring logistics but also emphasize the need for further pilot tests to adapt their processes and define biocarbon specifications. We found that these efforts both contribute to shared knowledge within the TIS-MB, and, as noted by R24, gaining competitive advantages through cutting edge internal research.

The majority of respondents mentioned finding and using collaborations as a key capability to expand knowledge. All actors who are participants in the value chain needs to be involved to solve the challenges of transportation and storage, at different stages. A vast majority of respondents mentioned research projects together with or orchestrated by universities and research institutes as a great source of technical developments, especially for those smaller actors who do not have the resources for extensive internal R&D. These collaborations could also be more informal meetings and correspondence, through interpersonal relations.

> *"We have been involved in projects with Biocarbon producer 1 and Metal producer 1. And Metal producer 3 is also involved in a project. It is a project that is not funded. It is just a council where people just discuss and talk once a quarter. And then we have discussions about different safety things and how we view things, which has been very rewarding." - R5*

Another part of updating technological competences is investing in personnel. Leading biocarbon producers and metal producers have recruited highly qualified individuals, such as PhD´s and researchers, over the years. This has been driven by the recognition of technical knowledge gaps within their organizations. These individuals are not only addressing knowledge gaps immediately with their knowledge and experience, but are in many cases also driving the development of new knowledge.

Influencing institutions includes both being able to identify and affect social norms and perceptions around biocarbon, biomass, metal products, and influencing policies and standards through industry organizations and interest groups.

Influencing institutions contributes to resource mobilization since the development of standardizations and certifications have been expressed by respondents to increase access to investments, both from TIS-MB actors, and from external investors. Moreover, it facilitates **market formation** by establishing the legitimacy of biocarbon among metal producers and defining product standards which can ease the entry of entrepreneurial firms and increase the comparability between biocarbon producers.

We found that firms have been able to identify informal institutions that affect the use of biocarbon. Firstly, there is a misconception that hydrogen-based steel making eliminates the need for biocarbon altogether. Secondly, there is a lack of awareness of the difference in emissions between Swedish, European, and particularly Asian metal producers. These perceptions can hinder the development of the TIS-MB if they persist among private consumers, or especially B2B-purchasers. Lastly, there is a debate about whether woody biomass should be used for biocarbon production or for other uses from a societal perspective. Firms discover and affect these informal institutions through interactions with stakeholders such as conferences and meetings, as well as through industry organizations who represent their interests.

Insights from respondents showed that most biocarbon and metal producers depend on industry organizations to advocate for their interests at both the national and international level, thereby influencing formal institutions. An important part of formal institutions is the standardization and certifications effort, where networks and interest groups are emphasized as being important pathways for actors to collaboratively exert their influence.

"...someone who can really coordinate this knowledge or specifications or who could write

their norms or standards that might somehow have the knowledge to set it up. I think these Biochar Europe are on the way to that." - R14

4.3.3 Reconfiguring capabilities

Establishing strategic alliances is the dynamic capability of finding and establishing partnerships such as joint ventures and acquisitions. This is important in order to finance the up-scaling of production of biocarbon, constructing the supply chain, and defining a clear division of labor and risks

Establishing strategic alliances improves **resource mobilization** by facilitating access to financial capital, knowledge and organizational capabilities that otherwise would be unavailable to a single firm. For example, partnerships such as off-take agreements and acquisitions provide funding and reduce uncertainties, enabling biocarbon producers to scale operations. In the same vein, it also contributes to **market formation**, but it also aligns interests between partners and thereby facilitates product qualification, the development of supply chains.

We found that *Biocarbon producer 1* was able to finance the up-scaling of their production by signing an off-take agreement with *Metal producer 1*, who also acquired shares in the firm. R8 explained that off-take agreements are a key source of financing for them now and in the future and also emphasized the value in having a customer as a partner to create insight in qualifying the biocarbon for specific applications and how value chains have to change. R24 explained the reasons why *Metal producer 3* acquired shares in *Biocarbon producer 1*, before constructing their own biocarbon production facility.

> "When we [bought shares in Biocarbon producer 1], they had the best product. I think we did it to buy know-how and gain insight into the suppliers' opportunities and challenges." - R24

Several other respondents from both metal producers and forestry firms had identified joint ventures or partial acquisitions as being possibilities for them in the future. The reasons mentioned were to catalyze the development of production, attract external investors, to share risks, but also to facilitate collaboration and knowledge sharing. Another benefit of establishing strategic alliances is a clear division of labor, delineating which actor should be responsible for which area of development, at what stage of the supply chain.

Developing organizational agility refers to fostering an internal openness to risk and change, as well as aligning the internal perceptions of biocarbon, especially within company leadership. Our research revealed that an internal openness to change was an important driver of developing organizational agility. Firms who had a culture which promoted experimentation, new ideas and had a history of making organizational and operational changes were among the leaders in biocarbon initiatives.

Developing organization agility contributes to **resource mobilization** by allowing firms to rapidly respond to investment opportunities and allocate resources internally. Firms that possess this capability are positioned to pursue development internally, which reduces risks associated with investments, but conversely are also willing to take on certain risks related to to scaling biocarbon production. It also contributes to **market formation** by driving critical financial commitments such as off-take agreements and investments in pilot facilities. Moreover, agile organizations can lead by example, sending signals that boost the perceived legitimacy of the market for other actors, thereby catalyzing market development.

A recurring theme from the respondents was that metal producers need to be willing to take on the risks associated with investing in biocarbon. R5 noted that the metal industry tends to be risk averse and conservative while R13 pointed to uncertain macroeconomic and geopolitical factors contributing to restraint from actors. Several respondents mentioned that metals producers need to be able to look beyond these inhibitions and dare to sign off-take agreements in order to drive the market formation.

> *"..if you take the first step, it's always a risk. Risk costs money. And those who take the first step have to be prepared for it. Instead of waiting for others to make the mistake and then jumping on the bandwagon. But if everyone waits, nothing will happen."* -R2

Another aspect of developing organization agility is being able to align the internal perception of biocarbon, cultivating a shared vision and perceived value throughout the organization and management. Respondents from smaller firms expressed that aligning the view of biocarbon was easier than for larger firms due to their flatter organization structures. R5 shared that *Metal producer 2* have been unable to conduct certain trials because ownership did not approve internal funding. R12 mentioned some frustrations from *Biocarbon seller 1*'s board about the lack of short-term financial returns on biocarbon. R3 explained that it has taken *Metal producer 1* several years of development, from lab-scale to industrial scale to convince decision makers at the firm to view biocarbon as a viable alternative. R24 explains that *Metal producer 3*, which many respondents recognize as the leading metal producer when it comes to biocarbon, has benefited from extensive commitment from management regarding investments in biocarbon, following successful pilot projects.

5 DISCUSSION AND CONCLUSION

This chapter discusses the results of the study, presents key conclusions, contributions, limitations, and future research.

In this thesis we have analyzed the technological innovation system around the green innovation biocarbon (TIS-MB), identified mechanisms that either drives or hinders the development of biocarbon (RQ1), assessed the functionality of the innovation system (RQ2), and identified dynamic capabilities which can help firms take strategic decisions to adapt their business to biocarbon and contribute to strengthened resource mobilization and market formation (RQ3).

A common oversight by researchers is not considering the development phase of the TIS, when evaluating the functionality. Weak resource mobilization (F1) and market formation (F2), is typical of an innovation system in a formative stage (Bergek et al., 2008b) and does not indicate that the overall potential of biocarbon as an innovation is weak. Hence, current actors and potential entrants of the TIS-MB should not be discouraged. However, moving into a growth phase will require significant improvements in resource mobilization (F1) and the effective formation of markets (F2) to facilitate scaled-up production and large-scale diffusion of the innovation.

In addition, entrepreneurial experimentation (F4) must be maintained as a strong function in order to facilitate knowledge development and diffusion (F7) in a number of innovation areas such as the refinement of by-products of pyrolysis, the sourcing of biomass, and safe handling and transportation of biocarbon. Influence on direction of search (F3) must also be upheld and further strengthened by legitimation (F6) through the development of standards, certifications and legislation, and increased openness and collaboration, in order to attract more actors to enter the TIS-MB.

5.1 Theoretical implications

This thesis addresses two significant gaps in the TIS literature. First, it contributes to understanding the mechanisms behind **market formation** and **resource mobilization** functions. While prior TIS research has given limited explanations of **market formation** (Bergek, 2019; Bergek et al., 2008b), this study emphasizes both which mechanisms and dynamic capabilities affect market formation, while giving a holistic view of related by-products and market implications for stakeholders across the value chain. **Resource mobilization** has been extensively described in previous TIS literature (Bergek, 2019), but almost the entirety of focus has been on public funding, e.g. Andersson et al. (2017). While our findings contain implications for public funding, a significant focus has been placed on private funding mechanisms and implications.

Researchers benefit from this by gaining a more nuanced framework for analyzing formative technological innovation systems, facilitating hypothesis development and comparative studies. Furthermore, the emphasis on by-products and cross-industry implications broadens the scope, allowing future studies to incorporate overlooked aspects such as supply-chain integration and knowledge development processes across industry boundaries.

Second, the study adopts a firm-level perspective, beyond the system-level perspective of TIS. Responding to calls from Markard et al. (2015), Ortt and Kamp (2022), and Planko et al. (2017), our analysis of dynamic capabilities within the wider framework of TIS contributes to the understanding of firm-system fit, where capabilities are connected to specific system functions. This approach offers more actionable insights by identifying the dynamic capabilities needed to strengthen weak system functions. We encourage researchers to adopt multiple perspectives to address the complexity associated with green innovations.

Our findings confirm arguments of previous research, e.g. Corvellec and Stowell (2024) and Grafström and Aasma (2021), who assert that green innovation transitions led by firms face challenges of financing, investing in reliable technology and several actors needing to find a business case. Moreover, we have found supporting evidence that these challenges lead to a lack of urgency (**resource mobilization**) (Masi et al., 2018) and ill-functioning markets (**market formation**) (Vermunt et al., 2019). This fact suggests that our findings contribute to the literature on dynamic capabilities for green innovations. Moreover, our conceptualized dynamic capabilities align with other green dynamic capability conceptualizations and micro-foundations, for instance, the study developed by Hällerstrand et al. (2023) in the context of the biofuel, bioenergy, biochemistry, and biomaterial sectors.

5.2 Practical implications

This study provides system actors and researchers with a structured overview of the TIS-MB, identifying key mechanisms, assessing functional performance, and at the firm-level, our findings identify key dynamic capabilities to enhance the development of the system. These findings can inform strategy development and investment decisions.

Bankruptcies of green innovation start-ups have highlighted the business management challenges attached to green innovation transitions. Managers involved in green innovation, both within and beyond the TIS-MB, can use our findings on dynamic capabilities to better align their business strategies with the demands of green innovation. By assessing their internal capacity against the identified dynamic capabilities, they can evaluate which capabilities to develop or acquire. By developing capabilities to sense, seize, and reconfigure, firms can play a more effective role in driving **market formation** and **resource mobilization**. These capabilities are essential not only for advancing commercialization and securing financing, but also for realizing the broader societal impact of green innovations. Importantly, this should be seen as an ongoing, iterative process rather than a one-time or linear effort.

Policy makers can benefit from our findings by realizing that they should prioritize focused efforts to strengthen the weak functions resource mobilization and market formation. While we have highlighted the importance of some key matters, such as certifications and standards, further policy instruments will have a critical role in enabling the development of the TIS-MB in the future, and must not be overlooked. Potential initiatives might include providing investment support or offering tax breaks to stimulate investment initiatives and market growth.

5.3 Limitations and future research

The TIS analysis offers a snapshot of the rapidly evolving business environment within our case system. However, the study was limited by the timeframe of a master's thesis. As the innovation system continues to develop, further assessment will be needed, particularly as it transitions from a formative to a growth stage. Moreover, further dynamic capabilities may be needed over time which is why it is important to continue sensing, seizing and reconfiguring assets to adapt to the changing business environment.

One limitation affecting the generalizability of our findings is the study's focus on the national context of Sweden. Additionally, certain actors such as customers of the metal industry, including the automotive sector, were not included in the TIS. These actors are likely to play a key role on the demand side for green alloys and, by extension, for biocarbon. As this study is based on a single case of green innovation, we encourage future research to examine additional cases across different national contexts to test the validity of our findings. We also recommend investigating failed green innovation transitions to better understand how such failures might have been avoided. Furthermore, our novel approach of integrating dynamic capabilities into TIS analysis, introducing a firm-level perspective, should be further validated through additional studies of green innovation transitions.

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Appendix A – Interview guide for exploratory interviews

Introduction

Introduction of interviewer and project background

Confidentiality and permission to record the interview

– What is your name, position and experience with metals industry, biocarbon and related areas?

Collaboration and networks

– In your opinion, what does the current network/ecosystem look like in the metals industry?

– What is your perspective on the biocarbon market today?

– What types of resources or knowledge related to biocarbon do you currently lack?

– Who are potentially important partners for the implementation of biocarbon? Why?

– Who must cooperate with each other? Who had collaborated with each other in a dream scenario?

– What factors would drive or hinder such collaboration?

– Do you see any clear leader for a potential ecosystem formed around metallurgical biocarbon? Who has the most power/influence?

– Who are the key players that have the most influence when it comes to the work related to the implementation of biocarbon?

– What would have been the consequences if actors in the metallurgical industry did not cooperate with each other regarding the implementation of biocarbon?

Challenges with the implementation of biocarbon in the metallurgy industry

Technical

- How do you define carbon? What are the general guidelines and requirements for carbon?
- What different process steps do you have in which carbon is used? What is the function of that carbon? Requirement specifications?
- How is biocarbon defined? What does the standard look like in classifying?
- What are the technical challenges with biocarbon?
- How do you produce biocarbon? Which raw materials/biomass do you use?
- How do you classify biomass, what kind of classification do you have?
- What processes are there to make biocarbon?
- What are the difficulties in making metallurgical biocarbon?

Managerial

- What are your biggest challenges with biocarbon? How can these be resolved?
- Have you come across any conflicts in the view of biocarbon?
- What do you think is the value of using metallurgical biocarbon?
- What would be the consequences of not implementing metallurgical biocarbon?
- What are the biggest non-technical challenges to metallurgical biocarbon implementation? Solution?

Future

- How do you see the market for biocarbon developing in the next 5-10 years? Technically? Financially?

- What steps do you think are necessary for biocarbon to become a viable alternative in the metallurgical industry? Technically? Financially?

Closing

- Is there something we haven't covered that you want us to include in our work going forward?

- Is there any material (industry reports, scientific articles, etc.) you would recommend us to read?

- Do you have any suggestions for other people or organizations that might be interesting to interview?

Appendix B – Interview guide for semi-structured interviews

Introduction

– Can you introduce yourself briefly?

– Can you tell us about your organization and your connection to biocarbon?

– What is your opinion on biocarbon and metallurgical biocarbon?

Description of our project

Information about anonymization and recording

Biocarbon drivers and hinders

– How did you identify biocarbon as a business opportunity? (Internal, through a supplier, customer or other?)

– What is the driving force for you to implement/contribute to biocarbon?

– How does biocarbon affect your value proposition? In what way does it affect your business models?

– How would you describe your strategy for your work related to biocarbon?

– What first steps do you think are most important for biocarbon to become more established on the market?

– What is the biggest obstacle to the implementation/production/support of biocarbon for your/your industry?

Investments

– What kinds of investments have you made around biocarbon and for what purpose?

- What kind of future investments will be required of you around biocarbon and what conditions have you identified to be willing to make those investments?

- In what way have you experimented/been involved in pilot projects with biocarbon?

- What pilot projects do you have planned going forward?

Institutions

- How do regulations, laws and policies around biocarbon affect you?

- How do you work to influence these rules, laws and policies?

- How do norms, perceptions and different practices affect the implementation of biocarbon?

- How do you work to influence these norms?

Knowledge gathering and organizational factors

- What has your process been like for gathering knowledge about biocarbon? (Internal/in collaboration with others)

- Do you consider that you share the same view of biocarbon as other actors in the value chain or neighboring value chains?

- In what way can the image of biocarbon differ internally within your organization?

- How do you view openness with information towards suppliers, competitors and customers?

- How would you assess that from an organizational and cultural perspective you can handle changes in the business, i.e. changed routines and work processes?

Partnerships and networks

- What resources and or competences regarding biocarbon are missing in your network of collaborators?

- Which types of actors do you think have the greatest influence in shaping the biocarbon market? (e.g. firms, authorities, research institutions)

- How should efforts be coordinated to introduce biocarbon to the market?

- What challenges do you see when it comes to getting more actors to use or produce biocarbon (participate in the value chain)?

- How can these obstacles be overcome?

- How has your process been for finding partners and which partners have you found in your work with biocarbon? Have you turned down any potential partners and, if so, for what reasons?

- What advantages and disadvantages do you see of acquiring other players in the market / establishing joint ventures?

- How can business, academia and public actors work together to create a stable foundation for the biocarbon market?

- How does the implementation of biocarbon affect your dynamics with suppliers and your customers when it comes to biocarbon?

- From a systems perspective, how would you like to define your organization's role in the development of biocarbon?

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