



Master Thesis in Material Design – Technical and Sustainable materials

Advanced 30Hp

Sustainable biocarbon for metallurgical application

Investigation of the enablers and barriers to sustainable biocarbon – A case study for the Swedish metal industry

SAGA GREVARP



Sweden
2025-08-22
Royal Institute of Technology, Swerim AB
Material Design - Technical Materials: Sustainable Materials
(CMATD – TTMVM: SUMA)
Supervisors: Yu-Chiao Lu, Tova Jarnerud Örell, Erland Nylund
Examiner: Pär Jönsson

Acknowledgement

I would like to extend a warm big thank you to supervisor Yu-Chiao Lu from the university for her continuous feedback, commitment and support throughout the work. As well as to supervisors at the company Tova Jarnerud Örell and Erland Nylund, for their commitment, support and their valuable views during the project of the work and contributing to me doing this work. Thanks also to the examiner Pär Jönsson for incredible support and recognition. As well as the working group at the company and the project consortium, also to all participation in the report through interviews, extremely grateful, thank you a lot. Thanks to thesis colleagues, friends and family for unforgettable support, energy retrieval, encouragement and guidance throughout the project period.

Thank you Swerim AB for an exciting and developing degree project.

Abstract

The Swedish metal industries are facing increasing demands to reduce their climate impact. One possible solution in this transition is to replace or dilute fossil carbon in metallurgical processes with bio-based alternatives, such as biocarbon. This study aims to investigate the potential of using biocarbon in the electric arc furnaces (EAF) process, direct reduction process (tunnel furnace, TF), and submerged arc furnaces (SAF) process. This report will present a technical comparison of quality requirements for biocarbon (for metallurgy and soil improvement) versus the properties of biocarbon available in Sweden, and an overview of wood-based biomass availability in Sweden.

The method is based on literature reviews and interviews with stakeholders from the metallurgical sector, biocarbon production, and forestry industries, as well as researchers from various universities. The focus has been on identifying the quality requirements for metallurgical biocarbon (e.g., particle size, fixed carbon, ash content, P) and evaluating which types of biocarbon can meet the requirements, as well as forest biomass contained in relation to these requirements, and how the application requirements for soil improvement differ.

The results from this study show that biocarbon has the technical potential to replace fossil coal in some metallurgical applications, but variations in raw materials and production methods affect the quality of the produced biocarbon. Also, soil improvement applications and metallurgical applications usually require opposite properties.

A conclusion that can be drawn from the interviews with metal producers is that the utilization of biocarbon largely meets the metallurgical process requirements. Improved sorting of biomass can help generate more suitable feedstocks for metallurgical biomass. Furthermore, biocarbon for metallurgy and for soil improvement do not compete for the same material, except potentially in the context of carbon sequestration in soil. These conclusions can help act as drivers towards fossil-free development in the Swedish metal industry.

Sammanfattning

Den svenska metallindustrin står inför ökande krav på att minska sin klimatpåverkan. En möjlig lösning i denna omställning är att ersätta eller späda ut fossilt kol i metallurgiska processer med biobaserade alternativ, såsom biokol. Denna studie syftar till att undersöka potentialen för att använda biokol i ljusbågsugnsprocesser (EAF), direktreduktionsprocesser (tunnelugnar, TF) och nedsänkta ljusbågsugnar (SAF). Denna rapport kommer att presentera en teknisk jämförelse av kvalitetskrav för biokol (för metallurgi och jordförbättring) kontra de egenskaper hos biokol som finns tillgängliga i Sverige, och ge en översikt över tillgången på ved baserad biomassa i Sverige.

Metoden är baserad på litteraturgenomgångar och intervjuer med intressenter från metallurgisk sektor, biokolproduktion och skogsindustrin, samt forskare från olika universitet. Fokus har varit att identifiera kvalitetskraven för metallurgiskt biokol (t.ex. partikelstorlek, fixerat kol, askhalt, P) och utvärdera vilka typer av biokol som kan uppfylla kraven, samt mängden skogsbiomassa som finns i förhållande till dessa krav, och hur tillämpningskraven för jordförbättring skiljer sig åt.

Resultaten från denna studie visar att biokol har den tekniska potentialen att ersätta fossilt kol i vissa metallurgiska tillämpningar, men variationer i råvaror och produktionsmetoder påverkar kvaliteten på den producerade biokolen. Dessutom kräver jordförbättrings- och metallurgiska tillämpningar vanligtvis motsatta egenskaper.

En slutsats som kan dras från intervjuerna med metallproducenter är att användningen av biokol till stor del uppfyller de metallurgiska processkraven. Förbättrad sortering av biomassa kan bidra till att generera mer lämpliga råvaror för metallurgisk biomassa. Dessutom konkurrerar för metallurgi och för jordförbättring inte om samma biokols material, förutom potentiellt i samband med kolbindning i marken. Dessa slutsatser kan bidra till att fungera som drivkrafter för fossilfri utveckling inom den svenska metallindustrin.

Table of contents

Acknowledgement	i
Abstract	ii
Sammanfattning	iii
1. Introduction	1
1.1 Background	1
1.2 Transition	2
1.2.1 Emission in transition	2
1.3 Sustainability	3
1.4 Problem description	3
1.5 Aim, objective and research guidelines	3
2. Method	5
2.1 Data collection	5
2.1.1 Literature review	5
2.1.2 Interviews	5
2.1.3 Seminars	7
2.1.4 Analysis method	7
2.1.5 Uncertainty	7
3. Literature review	9
3.1 Biomass	9
3.1.1 Sweden's biomass resource, mainly from the forest industry	9
3.2 Conversion processes of biomass to biocarbon	11
3.2.1 Pyrolysis	12
3.2.2 Gasification	14
3.3 Interviews	15
3.4 Biocarbon carbon dioxide neutral material	15
3.5 Previous research	16
4. Results and Discussion	18
4.1 Robust industry	18
4.2 Forest, sawmill and tree management	18
4.3 Biocarbon from different biomasses	21

4.4 Metal industry description and quality description	24
4.4.1 Carbon in the processes	24
4.4.2 Metal productions requirements.....	27
4.4.3 Fossil coal consumption	29
4.5 Biocarbon production and quality	31
4.6 Comparison requirements	33
4.7 Biocarbon for soil improvement and application.....	34
4.8 Concluding discussions.....	35
5. Conclusion.....	38
6. Future work	39
7. References	40
8. Appendix.....	48

1. Introduction

The Swedish metal industry is facing a crucial shift towards fossil-free production to meet both national climate goals and international demands for reduced carbon emissions. As fossil coal is still used in several important metallurgical processes, the need for sustainable, bio-based alternatives such as biocarbon is both urgent and necessary. By mapping the technical requirements and opportunities for the use of biocarbon in metallurgy and comparing these with available biomass and existing use in soil improvement, this work contributes knowledge that can accelerate the transition to more climate-friendly metal manufacturing. It is a piece of the puzzle in the work towards a sustainable industry, where the raw material comes from Swedish resources from forests to metal.

1.1 Background

The world and society are in great need of metals, as it stands now and the trend does not seem to be slowing down, on the contrary, society's need for metals is increasing, both for advanced applications and as well as machinery and infrastructures.[1, 2, 3, 4] Metals play a major role in the high-tech modern society that the world and Sweden find themselves in, at a time when the fossil-free transition is extremely topical and challenges to cover the demand for sustainable materials are relevant.[5] The number of mines where ore is mined has dropped from 240 in 1900 to 12 in 2012, while ore mining and ore production have increased at roughly the same rate.[6] Where domestic extraction of iron ore is the most.[7] In the production of metals at the present time, coal in form of fossil coal is used in the vast majority of cases in the various metallurgical processes, which contributes to large amounts of carbon dioxide emissions. For Sweden to reach its climate goals, a comprehensive transition of industrial processes towards fossil-free alternatives is required.[8, 9] Companies in the industry have long and actively worked to reduce the use of fossil coal in production through efficiency improvements.[8] Despite this, metal production is one of the most carbon-intensive processes in industry. The Swedish metal industry was responsible for approximately 5.5 million tons of CO₂ emissions in 2023, which corresponds to almost a third of the industry's total climate impact.[10, 11] One of the most promising pathways is to replace fossil coal with bio-based alternatives such as biocarbon, a carbon-rich material produced from the conversion of biomass by pyrolysis or gasification, has slightly different properties, metallurgical coal must be developed to achieve the conditions for a greater recovery of the resource.[12, 13] Biocarbon is currently used primarily in soil improvement, carbon capture and environmental engineering, but its potential in metallurgical processes has not yet been fully exploited. However, unlike soil applications, the metallurgical industry has specific requirements for ash content, reactivity, P and S content properties that vary depending on the raw material and the manufacturing process.[12, 14]

In Sweden, there is a large supply of residual streams from the forest and agricultural industries that can potentially be processed into metallurgical biocarbon. At the same time, there is a lack of standardization and technical guidance on which type of biomass is suitable for which metallurgical processes for example, electric arc furnaces (EAF), tunnel furnaces (TF) or submerged arc furnace (SAF) processes and how these requirements differ from other areas of

use.[14] According to the forest industry, the forest industry's climate benefit should increase by 30 % by 2040.[15]

1.2 Transition

The metal industry stands in front of and in a transition towards changing and developing production towards more environmentally friendly production. Sweden has a national goal of being at the forefront of the green transition towards climate neutrality and net-zero-emissions by 2045. The metal industry's goal is therefore to be able to manufacture fossil-free metals by then.[2, 9, 16] Being a country that wants to be at the forefront of the green transition brings both challenges and opportunities. The challenge is to develop new (in today's production processes, applying the carbon atom from a new carbon source, charcoal has previously been applied in metal production), disruptive technologies which are not yet implemented in other parts of the world. At the same time, this comes with great opportunities for Sweden to develop and lead the market to meet customers' demands for sustainability, climate health and climate neutrality. Climate neutrality and sustainability are expected to be advanced to drive development forward in the European Union (EU). The Swedish industry's ambition to be at the forefront comes from the green commitment that exists among the EU's member states, in addition to achieving climate neutrality by 2050.[16] The European Green Deal was launched in 2019 and is a climate package to achieve the ultimate goal of climate neutrality by 2050. It is a strategy that supports green-transition measures in various sectors, including the industrial sector. The Green Deal is the EU's contribution from the Paris Agreement in 2015.[17] Agenda 2030, also called the Paris Agreement, is an action plan that Sweden is involved in working for and working forward in sustainable development within 17 set goals.[18]

1.2.1 Emission in transition

Despite the shift to a more sustainable society, metal production still relies on large amounts of coal in several stages of metallurgical processes. Carbon is used, among other things, for slag foaming, as a reducing agent, for alloying, and is the material making up graphite electrodes (used in electric arc furnaces). The use of fossil coal contributes significantly to carbon dioxide emissions, making it the single largest source of global greenhouse gas emissions.[19] The metallurgical processes that account for the largest share of carbon dioxide emissions (85 %) is the blast-furnace-basic-oxygen-furnace process where iron ores are reduced to metallic iron and then melted to form hot metal.[2, 20] The remaining emissions in production come from fuels for heating and heat treatments but also from the processing of raw materials along the process chain.[2] HYBRIT is a corporate initiative and research project that aims to use sustainably renewable hydrogen as a reducing agent and then create water vapor instead of carbon dioxide during the reduction to reduce the largest emissions from metal production to produce fossil free steel.[20, 21] Green hydrogen is said to be changing the steel industry.[22] Despite the HYBRIT initiative, the problem with emissions remains. To make environmental carbon dioxide fossil-free metal, it is not enough to use renewable hydrogen and green electricity alone as a metal producer, they cannot avoid the fact that carbon as a substance or atom is also needed for further processing steps in metal making (e.g. melting, secondary refining). To reduce fossil carbon dioxide emissions in metal production from fossil coal, biocarbon produced from

sustainability harvested biomass has emerged as an attractive alternative to replace fossil carbon. Depending on the raw material and production technology, biocarbon can exhibit similar technical properties to fossil coal and thus be an enabling step towards fossil-free metal production. At the same time, fossil coal is still an attractive material in industry, due to its low cost, availability and manageability.[14, 23] Fossil-free carbon is applied to in this report as biocarbon and metallurgical biocarbon and is defined as biological residues from Swedish forest waste. There has been much previous research on biocarbon in metallurgical processes, not least for application in blast furnaces, but this is no longer as relevant as Sweden is to close down its blast furnaces.[20, 24] As large emissions come from steel production, this has been chosen as a material to investigate.[25] As well as ferrochrome production was also included as it is an important alloy in the production of stainless steel, and a large part of Swedish steel production is of the stainless grade.[26]

1.3 Sustainability

This work relates to several of the UN's global goals for sustainable development, in particular Goal 9 – Sustainable industry, innovation and infrastructure, Goal 11 – Sustainable cities and communities, Goal 12 – Sustainable consumption and production and Goal 13 – Combating climate change.[18] By investigating the possibilities for biocarbon in metallurgical processes, Swedish industry can take steps towards more sustainable material production while reducing its climate footprint.

1.4 Problem description

To reduce dependence on fossil coal in the metal industry, bio-based alternatives are being investigated, including biocarbon. Despite increased interest, there is currently a lack of a clear technical overview of how well biocarbon meets the specific requirements set in various metallurgical processes, such as in EAF, TF and SAF. Biocarbon is also produced for other purposes, such as soil improvement, but these areas of use place completely different demands on the properties of biocarbon. There is therefore a knowledge gap regarding the qualities required for metallurgical applications, how these can be achieved through the choice of biomass and production technology, and how biocarbon can be distinguished between different applications. This study aims to map and compare these requirements, with a particular focus on the availability of Swedish biomass and the potential to create biocarbon adapted for metallurgy.

1.5 Aim, objective and research guidelines

The aim of this study is to explore the technical feasibility of using biocarbon as a fossil-free alternative in Swedish metallurgical processes by evaluating the compatibility between the metal industry's carbon requirements and the biocarbon qualities available from Swedish forest-based biomass.

To achieve this aim, the study focuses on the following objectives. Identify and characterize the technical requirements for biocarbon in the selected Swedish metallurgical processes, including: i) Höganäs sponge iron process, ii) electric arc furnace (EAF), iii) submerged arc

furnace (SAF) for ferroalloys. Assess how well Swedish forest-based biomass and industrial residues can serve as raw material for producing biocarbon suitable for metallurgical applications. Compare the technical requirements for biocarbon in metallurgical applications with those used for soil improvement, to understand differences in specifications and potential resource competition. Evaluate practical challenges and opportunities for the implementation of biocarbon in the metal industry, including availability, quality variation, and process adaptation needs.

To support this investigation, the following research questions are addressed:

RQ1: Can Swedish wood-based biomass meet the requirements for biocarbon in metallurgical applications?

RQ2: What technical requirements do Swedish metal companies have on biocarbon, and how well do they match with the properties of biocarbon produced in Sweden?

RQ3: How do the biocarbon requirements for metallurgy differ from those for soil improvement?

2. Method

The main goal of this theses project is to create a technical summary of requirements for biocarbon in Swedish metallurgical processes, which includes the production, refining and manufacturing of various metals. The method is designed to describe: (1) the areas of use and functions of the carbon in the various metal production processes investigated; (2) analyzing the properties of fossil carbon, Swedish-produced biocarbon or biocarbon available in Sweden and compare with requirements from metallurgical processes; (3) identify any disadvantages and competitors with biocarbon use and what quality requirements the soil improvement has for biocarbon. This is therefore a preliminary study to probe the terrain for metallurgical biocarbon in Sweden - to check where we are, what opportunities there are and what quality metallurgy requires, further transition and improved climate work in the metal industry.

In order to achieve the aim of this project, several different project activities will be included during the course of the project. As the report is an information gathering literature study, material collection will be done through literature, interviews and seminars. Most of the information comes from interviews with respondents with knowledge in the areas and processes investigated, for the compilation of requirements specifications, knowledge and opportunities. The research design is described as a mixed method, which means a mixture of both qualitative and quantitative information collection to provide a more comprehensive picture and understanding of the research problem. When mixed methods can work for a complementary purpose and therefore explain and fill in the information for one of the different methods.[27] The qualitative information comes from literature reding. Meanwhile, quantitative information comes from interviews and seminars.

Direct contact with the companies concerned and the different industries to compile the report's essential work areas. Interviews provide most of this report's information and the opportunity to ask follow-up questions that are directly linked to the interview occasion, as well as a sense of attitudes and commitment.

2.1 Data collection

Data collection was carried out through the following methods.

2.1.1 Literature review

In order to gain broader knowledge in the researched area, studies are made within published facts on the internet. Articles are retrieved from various scientific publication sites such as Diva publishing portal, Science direkt, Google scholar, Multidisciplinary digital publishing institute, etc., as well as other relevant websites with articles. Websites are found on common social internet search engines.

2.1.2 Interviews

Held in three different stages to collect information from knowledgeable people from each area investigated. First, 5 exploratory interviews were held with metal and biocarbon producers from

the consortium, as well as participants from Jernkontoret who had participated in the first seminar. In order to create a picture of the technical application of biocarbon with more broad open questions. This served as a basis for the next rounds of interview steps and for building the larger interview guide for the second interview steps. The exploratory interviews were held with two other thesis colleagues in the HåBiMet group. Interview phases two and three consisted of semi-structured interviews, where more concrete questions were asked and discussed, and in total 21 semi-structured interviews were conducted. The first part of the semi-structured interviews was held with metal producers to collect their requirements for biocarbon. Then continued with the final interview part where interviews were conducted with biocarbon producers, forest companies, and other relevant actors, to collect information about available biocarbon quality, possible resources from Swedish forests and requirements for biocarbon for soil application. After the interviews were completed, the interviews are transcribed in Microsoft Teams' own transcription service and post-processed separately and then applied in the report. Table 1 shows the people interviewed using the semi-structured approach (phase two and three). In Appendix A the interview questions are listed.

Table 1: Compilation of semi-structured interviews, company and role

Respondent ID	Role	Company	Country	Date	Time (min:sec)	Transcribed words
R1	Consultant	GRu konsult	Sweden	5-3-2025	62.15	8104
R2	Project Management Office – Group Technology	SSAB	Sweden	6-3-2025	33.06	3495
R3	Manager Process Development	Alleima	Sweden	7-3-2025	63.04	8220
R4	Process developer	Ovako	Sweden	10-3-2025	40.29	4142
R5	Project Manager - Mainly with all biochar projects	Carbomax	Sweden	13-3-2025	52.29	8982
R6	Process developer Electric arc furnace	Outokumpu	Sweden	17-3-2025	39.48	5721
R7	Senior Sustainability Engineer	Outokumpu	Sweden			
R8	Energy engineer	Outokumpu	Sweden			
R9	Director Global	Höganäs AB	Sweden	21-3-2025	58.12	8964
R10	Process Development Engineer	Höganäs AB	Sweden			
R11	Project Manager	Future Eco	Sweden	24-3-2025	66.57	7327
R12	Metallurgist	Vargön Alloys	Sweden	24-3-2025	48.08	7794
R13	Professor of energy engineering	Luleå University of Technology	Sweden	2-4-2025	31.36	4939
R14	Technical business specialist	Envigas	Sweden	3-4-2025	49.25	4717

R15	Business development	Envigas	Sweden	3-4-2025	59.08	6663
R16	Business development new markets	Svea Skog	Sweden	7-4-2025	55.30	8681
R17	Product manager	Meva Energy	Sweden	7-4-2025	45.29	5280
R18	Chief Technology Officer	Cortus	Sweden	8-4-2025	57.20	7394
R19	Production Manager	VOW green metals	Norway	9-4-2025	39.42	6103
R20	Scientists biocarbon/biomass	Linnaeus University	Sweden	11-4-2025 2-5-2025	100.60	5632
R21	Associate Professor in Energy Systems	Sveriges Lantbruksuniversitet	Sweden	14-4-2025	27.58	3498
R22	Program manager	Skogforsk	Sweden	17-4-2025	32.43	5425
R23	Founder/Vice CEO	Biokolsprodukter and Ecotopic	Sweden	5-5-2025	-	283
R24	CEO and Constructor	Harads arctic heat AB	Sweden	7-5-2025	-	398

2.1.3 Seminars

The project included participation in the consortium's seminars. Where information, knowledge, discussions and workshops were shared and worked on around the topics of crash course in metallurgy and metal production (as the project participants had different backgrounds), current situation seminar, conflicts of interest and social acceptance of metallurgical biocarbon, and competence development. The discussions were then compiled and shared within the consortium.

2.1.4 Analysis method

When all the information from the literature study and interviews was collected, the information was structured at the same time as the data analysis was done. This analysis is found under section 4 Results and discussions, where the results and discussions are presented in both table and text format. The comparative analysis was done by visually comparing the values in the collected data based on the project's research questions and read information. Included comparisons between fossil carbon and biocarbon for the Swedish metal production processes, as well as with soil improvement carbon. Based on the discussed analysis and compilation, the project's conclusions and further research directions are presented.

2.1.5 Uncertainty

Uncertainty may arise during data collection, but efforts have been made to minimize it by validating information from multiple sources, including both interviews and literature. Where possible, multiple interviews were conducted within similar processes to strengthen reliability. However, limitations remain, such as unavailable respondents, withheld values, or qualitative responses such as “high” or “low” that lack precise definitions. Misinterpretations may also occur, but are mitigated through supervision, peer review, and fact-checking. As this is a

preliminary study with limited time and scope, some data may be incomplete or missing, contributing to the overall uncertainty. To lower uncertainty in interviewing follow up questions were used.

3. Literature review

In this section of the report, more introduction into the topic and the various practical processes will be explained and described, as well as showing the importance of carbon in the various inputs.

3.1 Biomass

Biomass is an organic material that originates from plants, trees and algae, among others. With a relatively high energy content as the main components of biomass are carbon and hydrogen, biomass can be converted into an ecological fuel or biogas through biological degradation, into green products.[28, 29] An existing definition describes biomass as biodegradable waste or residues of materials of biological origin, such as plant and animal substances related to: agriculture, forestry, fisheries, aquaculture and industry. Resources such as municipal waste and wastewater and sludge from sewage treatment plants are also included.[29, 30] Biomass is generally characterized by a high moisture content, low calorific value, hygroscopic characteristics and large volumes or low bulk densities. These mentioned properties result in difficulties in collection, grinding, storage and transportation and give a low conversion efficiency.[31] Biological resources are considered a 100% renewable, future-proof raw material that is widely available, as the raw material is produced every day and in almost unlimited quantities.[29] The variations among biomass are very large, as the soil consists of a lot of organic materials. An important thing to consider before refining or burning biomass is whether it is classified as a waste raw material or not. For organic biomass that fall under the category of waste, there are special waste incineration rules. The Energy Research Institute has a handbook listing available biomasses for producing renewable biological biofuels in Sweden for district heat purposes and their suitability for different district heating plants.[28]

3.1.1 Sweden's biomass resource, mainly from the forest industry

The availability and renewability of biomass is to a large degree dependent on how quickly the bio-organism is able to bind carbon dioxide using sunlight, water and nutrients through photosynthesis.[32] Three -quarters of Sweden's land area consists of production land of biomass where 68 % are forest land and 7 % are agricultural land. Of the forest land, 84 % are productive forest land and are suitable for forest production. The largest proportion of forest land in hectares is in between and northern parts of the country and the agricultural land more located in between and southern parts of Sweden.[33] Sweden has a large domestic extraction of natural resources every year, which is used both in the country and for exports. Total domestic material consumption has increased since 1998 by 39 % and in 2021 88 % of the total extracted biomass was used for own consumption. In the same year, the extraction of biomass was an amount of 67 billion tonnes, where 60 %, 41 million tonnes consisted of timber.[34]

As society demands more bio-based energy for, among other things, industries, biomass is required to meet the need and keep the robustness reliable.[35] The Swedish forest is an important natural resource for both design material and as fiber raw material.[32] The harvested biomass should be harvested in a resource-efficient way, and with a low environmental impact, which requires that you need to reach a high level of utilization of the biomass. The problems

with the withdrawal of forest raw material differ depending on where in Sweden you are, in southern Sweden, an expansion is needed, while in northern Sweden you need to recreate the delivery system to meet demand.[36] When a tree is harvested, no part of the tree should be wasted. What is made of which part of the tree is controlled by what gives the highest possible value added from the different parts of the tree. In the order of priority from below and up the tree excluded the roots that can be seen in Figure 1, the trunk goes to, among other things, wood and furniture, the more thinner parts go to the manufacture of more pulp-based products such as paper and cardboard and last the tree's branches and tops “grot” with supply from other residual streams from the forest industry or sawmill industry goes to the production of bioenergy, fuels and other chemicals.[35] Figure 2 shows the raw material supply from forest to industry in Sweden 2022 in units of million cubic meters.[37] Today's driving force of logging is driven by demand for timber and pulp industry's need for raw material, and this results in an annual harvest of 1 % of the Swedish forest growth. Residual streams that the timber industry does not want or can use are sawdust, bark, branches and tops as well as rot-damaged, storm-damaged and bark drilling in wood.[32, 38]



Figure 1: Sketch of value-added priority order for trees [35]

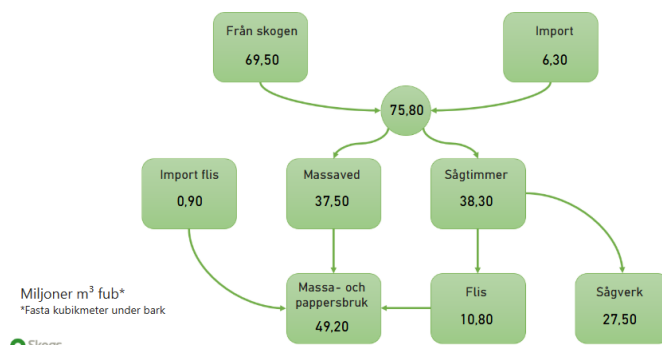


Figure 2: Schematic picture of the forest industry's timber supply 2022 [37]

Much of the Swedish biomass has the potential of coming from the Swedish forest. The forest market has been a very interesting raw material to cover society's increasing demand for domestic fuels. In order to switch up the forest industry's potential and utilize the forest to max, there is a biomass resource that is not fully utilized, this is the categorization of branches and tops also called “grot” in Swedish. In 2020, Skogforsk conducted a survey based on the Forest Agency's impact assessments from 2015 on final harvests for forests and considered whether the withdrawal of “grot” was possible in different areas based on the recommendations of the Forest Agency. The compilation of Skogforsk's analysis with slightly included percentage deductions for possible withdrawals does not amount to 100 percent, but at 70 percent and that half of the bars remain in the forest. The compilation becomes as in Figure 3 (a), where darker green stands for counted at a higher total “grot” amount in GWh. To further see how much “grot” potential was in Sweden in 2020, transport data was counted on actually withdrawn “grot” from Biometria (a forest contractor in Uppsala) which can be seen in Figure 3 (b) and then Figure 3 (c) was created with compilation on the “grot” surplus.[39]

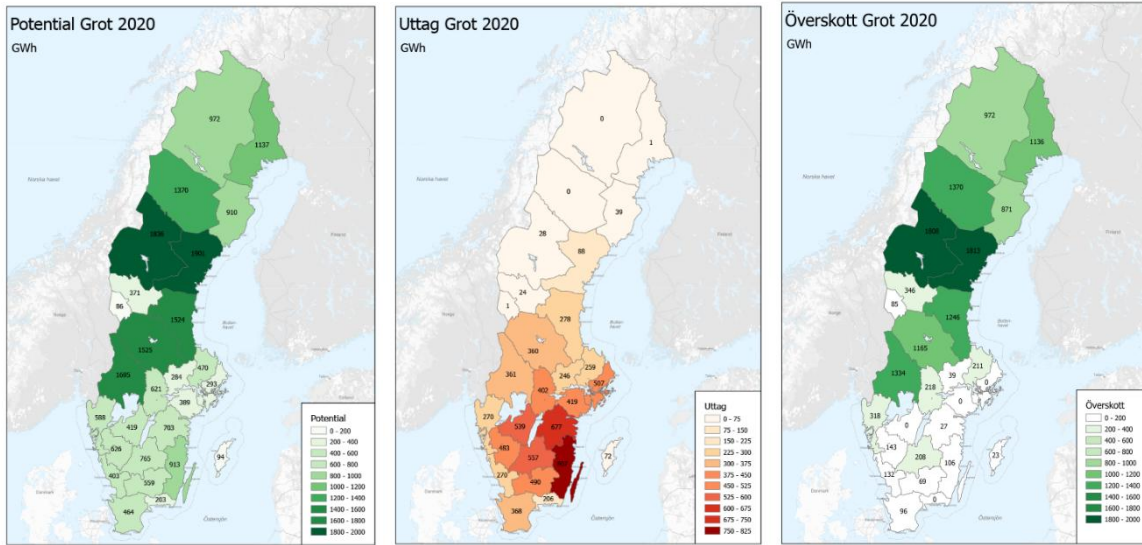


Figure 3 (a): Total GROT Potential in Sweden 2020 [39]

Figure 3 (b): Estimated withdrawal of cave in Sweden 2020

Figure 3 (c): Potentially GROT surplus in Sweden 2020

3.2 Conversion processes of biomass to biocarbon

Processed biomass has several uses and climate benefits. Biocarbon is used, among other things, for soil improvement, heat source, biofuels and carbon sinks.[40] In order to be able to use biomass as a carbon-containing material in Swedish metal and the steel industry, the biomass needs to undergo a conversion process.[28] Unlike the combustion of fossil carbon, which involves consumption of the earth's stored resources, biomass is usually from a forestry in balance, a renewable resource that is produced continuously.[32] When biomass is affected by heat, the material is chemically transformed, where the bonds change shape from aliphatic to aromatic bonds.[41] The combustion of biomass is part of the natural carbon circuit and is therefore not as harmful to the environment as fossil carbon.[29, 32] Biomasses are a bulky resource, to increase the energy content per unit volume and homogenize the size for easier handling, the biomass is processed through a refining process. Care must already been taken when storing biomass such as pellets, chips and straw since biomasses quickly absorb moisture, and will impair its processing efficiency.[29] Then follows further processing of biomass until it transform into biocarbon as a product. Biocarbon is thus a form of processed carbon, where the bond angles give carbon chains different properties.[42] When biocarbon is produced, it should be done in an oxygen-free environment, also done in an oxygen-poor environment as a 100 % oxygen-free environment can be difficult to achieve, where thermal conversion, heating or combustion, breaks down organic biomass into biocarbon as a solid and stable carbon material. Parameters such as choice of organic feedstock, a temperature, heating rate, residence time and oxygen concentration are typically well-controlled during biomass conversion process. The carbon content of biocarbon is usually between 40-90 wt%.[30, 41, 43] The properties of biocarbon varies significantly depending on the biomass feedstock and processing conditions used-such as total carbon content, volatile carbon content, ash content, H, O, P and

S concentrations.[44] Today, there are two international certification systems for biocarbon, The European Biochar Certificate (EBC) and the International Biochar Initiative (IBI) Standard, where EBC certification is adapted to European Regulations.[44] EBC has developed a definition of Biochar that is:

“Biochar is a porous, carbonaceous material that is produced by pyrolysis of plant biomasses and is applied in such a way that the contained carbon remains stored as a long-term carbon sink or replaces fossil carbon in industrial manufacturing. It is not made to be burnt for energy generation.”[45]

Biocarbon differs in structure and function compared to activated carbon and black carbon. Biocarbon has a higher ash content and is therefore generally a lower-purity carbon source compared to activated carbon and can then contain more oxygen-containing, carbon- and hydroxyl groups and phenolic groups and other inorganic minerals.[41] Biocarbon is often used today and has traditionally been used extensively for soil improvement, as biochar due to its porosity is good at holding water and enriching the soil with nutrients.[44] Historically, biocarbon in the form of charcoal has been a very important discovery and is used for a variety of applications, including metal producing, energy sources, gunpowder production, medical applications, soil improvement, water purification and against suspected poisoning.[44, 45, 46, 47]

There are different processes by which biocarbon can be produced. Processes available worldwide include pyrolysis (fast and slow), torrefaction, gasification, hydrothermal carbonization (HTC) and microwave pyrolysis. Below is a presentation of the processes that interviewed biocarbon producers in Sweden have used as production methods.

3.2.1 Pyrolysis

The most common process for producing biocarbon is called pyrolysis and it is usually divided into four different steps.[43, 48] The first step is for organic material to dry to absorb heat and release water at up to 100 °C. Then follows a temperature increase to 250 °C for pre-pyrolysis where the chemical conversion of the material begins and some CO and CO₂ are formed. The next part of the process is where most of the chemical reactions and decomposition take place, in the pyrolysis reactor here at 250-500 °C. There volatile macromolecules and gases such as CO₂, CO, CH₄ and H₂ are also generated and released. Finally, the slow decomposition takes place where the remaining unconverted material is allowed to be converted completely above 500 °C (like pyrolysis reactor two) but the temperature range of transformation varies greatly depending on the type of biomass.[43] This process sequence can be followed here in the following Figure 6.

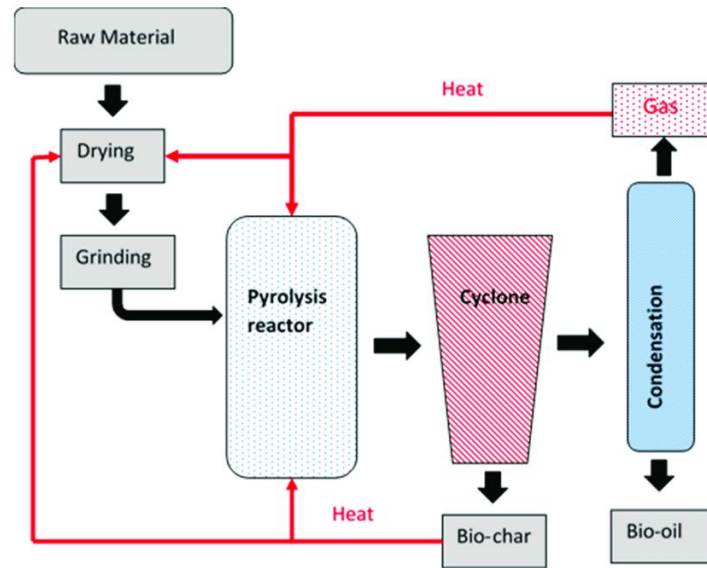


Figure 6: Process flow diagram for pyrolysis[49]

During the pyrolysis of wood fibers, hemicellulose is first decomposed at 200-260 °C, and then at higher temperatures such as 240-350 °C and 280-500 °C, cellulose and lignin are decomposed respectively. The transformation process for the carbon goes from crystalline to amorphous structure in a rapid transformation where bonds and chemical composition change. The surface chemistry of biocarbon is a complex heterogeneous chemical composition, usually dependent on the biomass and pyrolysis conditions. Apart from elements C, H and O which are the main elements of carbohydrates, macronutrients such as N, S, and P are commonly found in biomass while micronutrient elements such as Mg, Na, Ca, Si, K, Al, Cd, As and Pb occur in smaller amounts. Elements such as K and Cl are easily vaporized at low pyrolysis temperatures below 300 °C. While elements such as P, N, Mg, S and Ca are usually more tightly bound through covalent bonds and can only be vaporized at higher pyrolysis temperatures above 500 °C. The release of gases when carbon-rich compounds such as carbon dioxide (CO₂), carbon monoxide (CO) and nitrogen dioxide (NO_x) are decomposed increases with increasing temperatures.[41] Pyrolysis can be further distinguished as slow or fast pyrolysis based on the temperature and residence time. Slow pyrolysis converts biomass in the temperature range of 250-900 °C with residence time from one minute up to several hours while fast pyrolysis requires rapid heating and is typically conducted at 425-700 °C with a residence time of less than 2 seconds.[30, 41] Hydroxyl and carboxyl groups are common in biocarbon and emerge mostly from fast pyrolysis, while in slow pyrolysis C-H groups are produced and become more dominant.[41] When starting a pyrolysis process, an external starting energy such as electricity or gas is needed to start the slowly self-propelled exothermic process.[44] The products that come out of a pyrolysis process are the charred biocarbon followed by a variety of residual products where a large percentage (50-70 %) converted into gas from the incoming biomass, then also pyrolysis oil, soot and water vapor.[41, 43, 44] The waste gas can be transformed and produce hydrogen gas.[48] In a pyrolysis chain, several different pyrolysis methods can be applied one after the other to achieve the desired product, for example if one were to start with a slow

pyrolysis which then transitions to a fast pyrolysis and finally a gasification step is carried out.[30]

3.2.2 Gasification

Gasification is a thermochemical process in which organic material, such as biomass, is converted into a synthesis gas under limited oxygen or air supply. Gasification refers to a method where biomass is partially oxidized in the presence of a limited amount of oxygen to produce a fuel-usable gas mixture. In contrast to complete combustion, which occurs in excess oxygen, gasification aims to create a gas mixture rich in carbon monoxide (CO), hydrogen (H₂), methane (CH₄) and carbon dioxide (CO₂) with a minimal content of tar and particles depending on the operating conditions.[50] The process usually takes place in several distinct stages. First, the biomass is dried at temperatures up to about 200 °C to remove moisture from the biomass. Then the material is pyrolyzed between 200–600 °C, where the biomass is broken down into gaseous components, bio-oil and solid carbon (biocarbon). After that, the pyrolyzed material is burned in an oxidation process. There, in an environment with a controlled amount of oxygen, it reacts with the solid carbon and tar, generating heat that drives the other stages. This is most common at temperatures above 700-800 °C.[30, 50] Finally, carbon dioxide and water vapor are converted to CO and H₂ through the Boudouard reaction ($C + CO_2 \rightleftharpoons 2CO$) and the water-gas-shift reaction ($C + H_2O \rightleftharpoons CO + H_2$). Gasification systems are often classified by the reactor design: fixed bed, fluidized bed and entrained flow. These designs are able to handle different temperatures, residence time, ash amounts, and they differ in efficiencies. Entrained flow reactors operate at the highest temperatures (above 1200 °C) and produce the purest synthesis gas but require pretreatment of the biomass to a powder form.[50] In Figure 7 shows a schematic illustration of the gasification process.

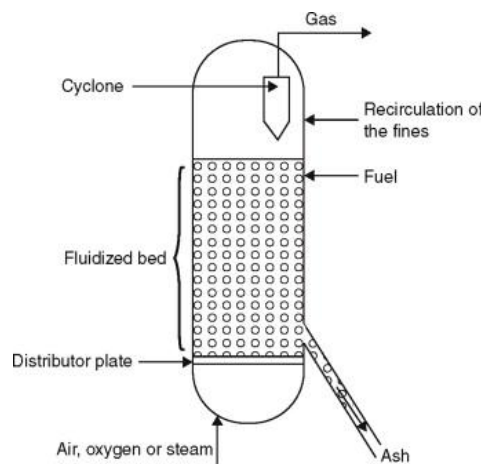


Figure 7: Cross-section of a gasification process[50]

Gasification is a conversion process in which a carbon source is converted into a gaseous product called synthesis gas, using an oxidant (air, oxygen and steam). The final yield of biocarbon in this process is about 10 % of the biomass, which is less than that of pyrolysis. The factors involved in this process are the gas to biomass ratio, reaction temperature, residence time, particle size and pressure. Among them, temperature is the process parameter that affects

the overall yield the most. In the past, syngas from gasification were used for domestic cooking, heating, lighting etc. In gasification, the plants are subjected to two sections. In the first section, gasification takes place, while in the second section, the synthesis gas is cleaned and cooled. The continuous generation of biocarbon uses the screw type of reactor. However, the process can be sensitive to the properties of the feedstock, and the biocarbon produced by gasification may contain a high level of ash.[50]

3.3 Interviews

The interviews have been designed and analyzed with support from an abductive research approach, where theory and empirical evidence are developed in parallel in an iterative process. This method is well suited for studies in complex and interdisciplinary contexts, where prior understanding is combined with insights from reality to generate new understanding.[51]

The abductive approach has enabled initial theoretical assumptions about, for example, the technical properties of biocarbon and the industry's requirements to be gradually adjusted based on information that emerged in interviews. The interviews have mainly been semi-structured, which has provided space for capturing unexpected and context-specific knowledge while at the same time following up certain key issues systematically.

Practical knowledge about interview methodology, structure and interpretation of responses has also been gained from conversations and exchange of experiences with other thesis workers within the larger research project HåBiMet (Sustainable use of biocarbon in metallurgy). This has contributed to an increased awareness of interview ethical considerations and triangulation of data in the analysis.

3.4 Biocarbon carbon dioxide neutral material

Biocarbon is classified as a climate-neutral emission raw material and in the agricultural industry as a carbon sink in the soil as biocarbon has high resistance to degradability and then binds the carbon in the soil over a long stable time.[43, 44] In the case of the use of biocarbon in the metallurgical industry, no carbon sink would be created except for the case when carbon is alloyed into the steel, since carbon is released as gas (CO , CO_2) into the atmosphere in most applications. However, in this case, the carbon emissions would be classified as green and climate-neutral due to the sustainability of the biocarbon itself. As the green carbon dioxide is part of today's cycle of uptake and release of carbon dioxide for plants.[52] Burning biomass does not increase greenhouse gas levels compared to coal and gas-fired power plants. The carbon dioxide produced when burning biofuels does not exceed the amount of gas that would be produced by natural conversion.[53] Biofuels bind carbon dioxide via photosynthesis and are usually considered carbon-neutral fuels.[28] In today's metal industry, carbon sources such as anthracite, coke or graphite are used in production and gives the production chain a safe and consistent production in terms of quality, quantity and price.[54] For metallurgical use of coal, the coal needs to have a high solid carbon content, low volatile content, low CO_2 reactivity and high mechanical strength.[48]

3.5 Previous research

Biocarbon has become a relatively well-studied alternative to fossil coal in metallurgical processes, especially in light of the ongoing transition towards fossil-free production. Several previous projects have focused on the use of biocarbon in metallurgy[8, 55, 56, 57], including extensive work at Swerim, where as many as 31 projects have been carried out since 2012 on the application of biocarbon in metallurgical contexts.[58] A large part of the research has been directed towards the blast furnace process, with studies ranging from identification of technical barriers to laboratory experiments, simulations and modelling.[59–65]

Several studies have investigated the potential for replacing fossil coal with biocarbon in blast furnace processes in the iron and steel industry. A review article identifies key challenges and opportunities, such as the varying quality of biocarbon, the adaptation of existing equipment, and the optimization of process parameters to integrate bio-based materials into conventional blast furnace operations.[59] To reduce fossil carbon emissions, researchers have developed high-strength biocarbon composite briquettes (BCBs), tested for both mechanical integrity and reduction performance under realistic conditions.[60] Further studies have focused on modeling and optimizing biocarbon injection in blast furnaces to improve combustion efficiency and reduce environmental impact. Numerical simulations highlight how variables like particle size and oxygen content affect both combustion and raceway dynamics.[61] A combined experimental and numerical study shows how pretreatment methods such as pyrolysis temperature affect reactivity and carbon yield during charcoal injection.[62] Other works have explored the impact of charging biocarbon briquettes into the top of the blast furnace, demonstrating effects on thermal zoning and reduction efficiency.[63] Energy-saving potential through reduced coke usage and improved process integration has also been emphasized in recent literature.[64] In summary, research indicates that biocarbon is a technically viable alternative for use in blast furnaces, though its widespread application still requires further adaptation in material handling, logistics, and process control.[65]

The use of bio-based carbon in steel and ferrochrome production has also been studied from both technical and environmental perspectives. A key area of interest has been how the production method of biocarbon affects its properties and industrial performance. Pyrolysis, a thermochemical process conducted in the absence of oxygen, is a widely used method for producing biocarbon. The resulting solid carbon-rich material varies in chemical and physical properties depending on temperature and residence time. Reviews indicate that biocarbon produced by both fast and slow pyrolysis has different structures and reactivity levels, influencing its effectiveness as a reducing agent in EAF.[54, 66]

Torrefied biomass, often described as a mild form of pyrolysis, has been identified as a particularly suitable carbon source. This process occurs at lower temperatures (200–320 °C), enhancing energy content and hydrophobicity while reducing volatile content qualities that improve suitability for metallurgical applications.[67] In addition, studies on ferroalloy production emphasize that torrefaction and pyrolysis can produce carbon materials with sufficient strength and low ash content, essential for maintaining process stability.[68, 69] In

EAF operations, where scrap is the primary feedstock, biocarbon has been evaluated both for its role in slag foaming and as a reducing agent. These studies suggest that while biocarbon is a promising alternative, its reactivity and ash composition must be tailored to each specific EAF process.[54, 66, 70]

In ferrochrome production, biocarbon has been evaluated for use in SAF, with promising reactivity compared to fossil coal. However, challenges such as dust generation, handling logistics, and consistent raw material supply remain barriers to large-scale deployment.[68, 69, 71, 72] The broader transition to fossil-free steel production involves not only technical change but also shifts in market structure and competitiveness, where both hydrogen and biomass are expected to play key roles.[73]

Apart from solid carbon products, gasification has also been explored as a complementary strategy in fossil-free metallurgy. In a life-cycle assessment of biosyngas-based direct reduced iron (bio-DRI) production, gasification is described as a way to generate synthesis gas (CO and H₂), which can replace natural gas as a reducing agent.[74] Although gasification is primarily aimed at gas production, it also generates solid residues with potential metallurgical applications, depending on ash content and composition. These gas-based reduction methods are of particular interest in Sweden's electrification strategy for steel production. Life-cycle assessments further highlight how biocarbon affects the energy balance in EAFs and how process optimization can reduce emissions without compromising steel quality.[74, 75, 76] In addition, the presence of impurities in ferroalloys and how these affect steel inclusions is influenced by the choice of carbon source, further underlining the importance of biocarbon quality.[77]

In summary, previous research shows that pyrolysis and torrefaction are the most commonly used methods for producing biocarbon for metallurgical use, while gasification is primarily utilized for generating synthesis gases. The choice of production process has a significant impact on the structure, reactivity, volatile content, and ash properties of the biocarbon, all of which are critical parameters for successful metallurgical integration.

4. Results and Discussion

Further down in this section, results from completed interviews will be presented in summary forms and displayed in visualization tables. Interviews are an essential piece of this report to provide the matching puzzle to compare requirements and quality and to gain new insight into the area and not least for the role of the different industries, technical knowledge, technical possibilities, quality and requirements in this transition.

4.1 Robust industry

This thesis deals with two large Swedish robust industries that have their specialties and where change is complicated and takes a long time. Each sector has extensive experience and plans for strategically managing events that arise in their industry. Two large industries that have a past together from history and are now probably on their way back to each other.[47] In order to optimize the metal manufacturing process, the Swedish metal and steel industry has been tweaking its processes for many years to make them more efficient and reduce the environmental footprint as much as possible. Since the Swedish metal industry would like to change the source of carbon material to more fossil free emissions, this now places great pressure and quality requirements on biocarbon as a raw material for the metal industry.[58] Most of the metal companies concerned a lot about if it will be a smooth transition of switching from using fossil carbon to biocarbon, while some are more open to being a little flexible and ready to adapt the process a little after the change in material resources.(R2, R3, R4, R5) This transition places great demands on the quality of biomass as an raw material resources for biocarbon, as the metal industry does not want an uncertain source of raw materials as a substitute, especially not if the metal producers would have to make changes to the process in order to achieve the application with biocarbon in a correct way. Respondent 5 (R5) told how there were many metal producers in Germany in the early 2000s who invested a lot of resources in changing their production to use a specific plastic raw material in production. The companies ended in a complicated situation since they invested in the development of new technologies, which involved using this plastic raw material that was no longer available at the time. From the presentation that Albaeco hold on the current situation seminar 30-01-2025 at Energiforsk they talked about changing the system you work in or jumping on a new innovation trend, and that it will be tough in a transition period until you have come out on the other side and created stability after all the breakdowns, experimentation and shaking. Changing systems is not always easy or goes positively all the way but can sometimes provide an appropriate solution to a system problem. Now it is the case that in the area of safe operating spaces for people to work in for the well-being of the planet, 6 of the total 9 categories will be outside the safe space framework in 2023. One of these is climate change involving carbon dioxide concentration, which biocarbon is a new old system that the metal industry is now thinking of adopting again.[58]

4.2 Forest, sawmill and tree management

For information on the current state of Swedish forests, forest management, raw material flows from the forest and the competition of its raw materials, two respondents (R16 and R22) provided the most input while several other respondents also touched upon relevant

information. Above ground, the living tree biomass is estimated to be 1.3 to 1.5 billion tons, dry weight.(R22) As could be seen from the literature study, a large part of Sweden's land area is forest land, which is mostly located in the northern part of Sweden such as in the Norrbotten and Västerbotten regions, but also southern Norrland and Bergslagen and down over Götaland.(R16) Where forest research is a research actor driving to describe the chemical properties most relevant to the driving factors of the forest.(R22) The driving factors in today's forest industry are to create raw material for the sawmill industry and paper mills. The driving productive forestry is currently built on getting large amounts of timber, firewood and pulpwood for the paper industry. Today, many more players are keen to use biomass as a greener material of choice, some have already had access to biomass as a raw material and want to continue to have it, while others are also curious about biomass as a raw material. These competing sectors to metallurgical biocarbon include the energy sector, the heating sector, the chemical sector, the fuel industry for fuel and aircraft fuel and gasification processes for the production of, for example, green bio-methanol, etc.(R5, R13, R14, R15, R16) The demands from the competitors experienced by the forest sector are quite uncertain as no player has announced any major production and all operations are so far on a pilot scale. The forest industry, the pulp and paper industry, and the heating sector are the biggest competitors for woody biomass today, partly also because they are more established in the biomass market than other sectors. R16 *"It feels like people are a little more cautious now than they were a year ago"*. Right now there are "competitors" also in exports to other countries, a concrete example of this is that Sweden exports biomass to Finland after Russia's outbreak of war in Ukraine when Finland's resource from Russia disappeared.(R16) R20 today *"no biomass is grown for biocarbon, but it is taken from waste streams to make it"*, there is forest that is grown for energy as energy forest, but as far as R20 knows, no biomass is grown for biocarbon production.(R20)

From the forest side, the trees are divided into different parts. The parts that are more valuable include: (1) rough logs- that typically go to sawmills, (2) thin logs higher up in the trees- that go to the pulp and paper industry as fiber raw material, and there are also sawmills that saw thin timber. Up at the top of the tree there are many branches and tops called "grot", and this part of the tree today typically goes to the heating plants especially when the flow from other by-products in the sawmill chain does not amount to sufficient quantities. Wood is classified as industrial wood and energy wood. Industrial wood is wood fiber raw material that goes to production of pulp and paper. Energy wood to produce energy and heat, and includes instead "grot", logging residues and more unpredictable biomass raw materials such as insect-damaged wood, storm-damaged wood, fire-damaged wood, fungus-infested wood and bark beetle-infested wood.(R16, R22) This unpredictable wood is largely due to natural events or climate change, as the earth's temperature increases the risk of storms and dry periods. Dry periods increase the risk of bark beetle infestation.(R22) Energy wood is not a raw material that is wanted for the pulp and paper industry as they want fresh fibers into their manufacturing process and makes it a good biomass source for biocarbon production. There are also different types of fungal attacks on different types of wood, some hardwoods get diseases, infections or fungal attacks that only affect that specific species. This type of attack is not as common for conifers, where it is more common with a bluish fungus that causes discoloration in the wood parts of the tree and then makes the sawmill industry unwilling to have the trees, as sawn-up

products such as wall panels would have a bluish tint and be more difficult to sell. Sawmills also have difficulty handling wood that is, for example, storm-damaged so that it is crooked. Furthermore, several side-streams are produced by the sawmill industry, such as sawdust, bark and wood chips. The chips usually go to the pulp industry as they are cellulose chips while the sawdust is mostly to other industries, such as the pellet industry. Sawmill residues come from, for example, sawing logs from round to square, when sections are sawn open, and sawing logs.(R16, R22) Bark is a commonly unwanted residue both from the sawmill industry and the paper industry. Neither industry wants to use bark as a product. Based on the requirements of the metallurgical industry, bark is an abundant biomass resource with great potential.(R16) There have been attempts to harvest tree stumps as biomass, as 25-30 % of the tree's volume is buried underground and they carry high energy value. However, up to date today, no stumps are picked up except during exploitation since the tested attempts have not been economically sustainable and stumps also contain a lot of unwanted impurities such as soil and sand compared to other parts of the tree, which creates difficulties for further process handling. Other reasons for not harvesting stumps are: to retain carbon in the soil; to strengthen the soil to provide a solid, stable ground for forest workers to work on for safety concerns.(R22)

The felling in the forest is affected by the demand placed on the forest industry. The felling of timber in Sweden is not only affected by demand from within Sweden but is also affected by the supply and demand balance within the Baltic Sea area. Since the invasion of Russia into Ukraine, a high pressure has been placed on the Swedish timber market which has driven the price of timber upwards and now more forest owners are out felling.(R16) For a very long time, biomass from the forest has cost 200 SEK per megawatt hour and now the biomass has gone up and costs 350 SEK per megawatt hour.(R13) The annual growth of the forest is around 120 cubic meters and the felling rate is around 90 cubic meters, the growth and the removal can vary slightly from different year-to-year.(R22) Today, up to 90-95 % of the grown forest is felled, which is very close to the maximum sustainable felling levels. Right now, the Swedish policy is that more trees should be planted and grow than what is harvested.(R16)[78] However, the policy can shift rapidly to the extremes- there could be a ban on logging in order to collect more carbon dioxide in the short term to reach the climate goal, or it can go in the other direction. Currently, Sweden wants to create a robust platform to stand on as its own self-sufficiency instead of saving the forest and building up a high level of biodiversity.(R16) Out of parts of the tree above ground, the largest fraction is stem wood, which represents 60-70 % of the total weight. In contrary, “grot” represents approximately 15-20 % of the tree (more on younger trees) and the remaining 11 % is bark. To get these parts of the trees, thinning and felling are carried out in stages. Normally, thinning is carried out in Sweden 2-3 times in a forest cycle, to control the growth of the trees. More frequent thinning is carried out in the southern parts of the country due to higher quality and more fertile soils. Sometimes even a small timber felling and finally final felling of fully grown trees after 50-80 years, then there is also the possibility of “grot” removal.(R16, R22) The strategy for forestry determines a little about how many thinning's are done during a growth cycle, if the purpose is to produce volume, it is more common not to go in and thin out as thinning also increases the risk of damage to the remaining forest. While if you want to produce timber, you want to place the growth in fewer trees for thicker tree trunks.(R16) When felling, you cannot take all the felling residues, you

can choose between thinning residues or “grot” and this is only taken out once and the rest is left in the forest land, partly to provide nutrients back to the forest, to provide nests for insects and to stabilize the soil. Guidelines for the removal of residues from the Swedish Forest Agency are to leave 20 % of what you intended to take out above the land level. During felling, wood chips and “grot” are also used as road-strengthening material in the forest to avoid causing damage, including on wet felling days for the forestry machinery to drive on. This is not taken up when it is worn down and earthy and muddy. This can lead to a reduction in possible “grot” removal by 30-50 %, sometimes even up to 100 %.(R22) Felled timber then goes to the sawmill, the logs are collected quickly after felling and are at the sawmill within a few weeks. Much depends on the moisture content and season, felled timber may not be left in a pile on a clearing for too long during spring and summer according to legislation due to the risk of insect nurseries.(R16) At the same time, it is wanted that the wood has time to dry out some of the moisture content, which is around 50 %. If “grot” is taken out, they are piled up at the edges of forest roads with paper cloth over them for 3-15 months to dry.(R16, R22)

4.3 Biocarbon from different biomasses

With Respondent 20 (R20), biomass as a product has been discussed in terms of properties, structure and impact when biomass is converted into biocarbon. There are slightly different types of biomasses, including plant-based materials, algae and sewage sludge. Where biomass that is wood-based can come from the forest, park and garden waste or other woody biomass. The quality of biocarbon is already affected by the quality of the biomass where the carbon content can vary greatly since different biomass have different amounts of ash substances depending on the collection process. Sludge typically yields biocarbon with a low carbon content since the sludge consists of a lot of inorganic compounds and the organic parts have already decomposed. Biocarbon material can have varying pH values from neutral to high alkaline values of 11. This is due to the fact that, chemically speaking, biocarbon from woody biomass contains a lot of hydroxides, including sodium and potassium hydroxides. R20 *“According to the definitions of biocarbon, you can only call it biocarbon that leads to a long-term carbon sink. So if you're talking about many of the applications for the metal industry, you can probably call it charcoal instead. If it's consumed.”* Biocarbon can be called biocarbon because the carbon atoms remain in the material. If they are used for reducing agents, it's a little more sensitive for contamination from other materials. It's about the carbon atom not becoming carbon dioxide, but a protected carbon atom in the metal is protected and then the release of the carbon atom is about the degradability of the metal.(R20)

Trees are made up of different components where the content differs in different parts and where the different components become different parts of the products of biocarbon production. Below in Figure 8 the amount of P and S in different biocarbon from different woody biomasses is shown, which is part of a preliminary study conducted by Ann-Mari Fransson from Linnaeus University. The table was created after one of HåBiMet's discussion seminars where Ann-Mari participated and perceived that P and S contribute to major problems for metal manufacturers.(R20)

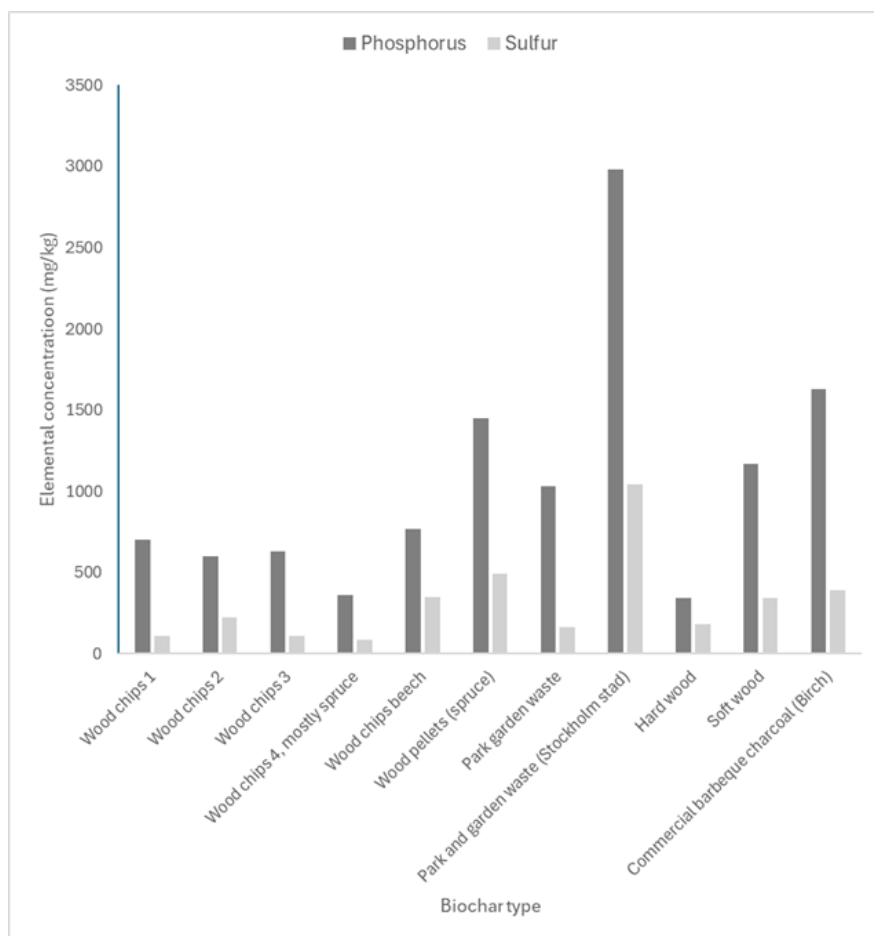


Figure 8: Amount of phosphorus and sulfur in different biocarbon's with different biomass inputs[79]

Nutrients for trees include P and S, which are located slightly differently in the different parts of the tree. Phosphorus is mostly found in the green parts, while S is not as clearly divided as to where it is located, but mostly in the green parts but also in the wood in the tree, so it is not completely removed from the wood. The wood in the tree is almost dead as there are not many cells in that part of the tree. The structure of the wood is the built-up carbon structure. The most variable substance, as can be seen in Figure 8, is the variation in P. Most of the differences come from variations in the amount of green parts or living parts in the different biomasses, as much of the tree's nutrients are in the green parts. Green parts mean bark, leaves and needles, and the smaller the wood parts you use, the different ratio between bark and wood, many twigs have more bark in relation to wood. R20 *"So generally speaking, I think that the more branches and bark and leaves that are included. The higher the phosphorus and sulfur content."* The type of tree differs between the different biomass raw materials, this can also vary during the year depending on what the wood pellet and chip manufacturers receive as biomass to work with. So far, they have not been so picky with incoming material, but have been more happy with what has come in and mostly taken everything they can get their hands on. There has been no demand from customers to know what type of wood the biomass for the biocarbon has been in the past and from a competitive commercial perspective, it has not been so easy to find such information since the companies have not wanted to release that information due to competition.

Noticeably higher concentrations of P are found in park and garden waste Stockholm city (Stockholm stad), woody rice, shrubs due to high bark content in these biomass. Trees and shrubs are structured in the same way, with nutrients in the green parts and a little S in the wood. This category of biomass undergoes large fluctuations in quality during based on what woody waste comes in. An example of variation is that in February there are a lot of Christmas trees and in March a lot of shrubs and hedge clippings. Hardwood is a slower growing biomass and softwood is faster growing, softwood is probably a conifer in this case. In this case, softwood has higher P levels, which is probably logical as the tree grows faster, there are larger amounts of green material in circulation. Finally, commercial barbecue biocarbon is probably birch. The growth rate can also make a difference, there are also fast-growing deciduous trees such as hybrid aspen or poplar.(R20) A comment from HåBiMet's results seminar said that fast-growing trees have lower organic levels.

The quality of the biocarbon comes from the biomass, where lignin, cellulose and structured parts become the solid biocarbon, hemicellulose and unstructured parts become gas. Volatile substances come from the glucose-rich parts when they evaporate and become hydrogen gas and carbon monoxide, when all the building blocks that the plant lives on are not fixed. The ash substances come mostly from the green parts of the tree, from substances that become hydroxides during combustion and substances that the tree absorbs from the ground, which usually contain, among other things, P, S, Na, K and Ca, can also contain Al and more. The biocarbon is linked to the tree species and how much lignin is in the tree and the tree's density. Lignin, cellulose and hemicellulose are the structured molecules, different tree species have different amounts of these. There are also large variations in the bark, there is bark called shoot bark that has a good ability to protect against fires, in other parts of the tree lignin ignites very poorly compared to volatile substances. Among the conifer species in Sweden, pine has shoot bark while spruce is poorly adapted for fires. The density still differs more in the wood than in the bark, below in Table 2 the density of a few slightly different species are listed. Where the density is the ratio between lignin and cellulose and it is based on how the tree needs to be adapted to growing loads such as wind. In a pyrolysis process, the density of the wood is one when it enters the process and another when it comes out when substances have evaporated and the structure has been leached out a little during combustion. R20 is not aware of any numerical connection in the standard how much percent the density changes during pyrolysis. This decrease in density differs greatly depending on the particle size in the process. Despite different bulk densities in the input materials, the true density value after pyrolysis and compaction is quite close to each other at 1.6-1.8 kg/m³, as a maximum value in density that is achievable. Due to how the chemical bond lengths work in relation to each other, its length and how the relation is between other bonds. True density is also published in the biocarbon handbook that respondent 20 has been involved in working with.(R20)[80]

Table 2: Density for different types of wood, (R20) [81]

Wood fiber	Density (kg/m ³)
Lilac	945
Pine	550
Spruce	430
Alder	535
Brich	610

4.4 Metal industry description and quality description

To compile and investigate the requirements that the metal industry has set for biocarbon, respondents R1, R2, R3, R4, R6, R7, R8, R9, R10 and R12 were interviewed. More interviews to compare the fossil carbon that we use in metallurgy today were conducted with respondents R5 and R11. Interviews for Swedish metal production to obtain insights into the metal production processes (e.g. how the process works, what are the functions of carbon in the processes...etc.) and requirements for coal. The goal of the interviews was to obtain results for a compilation and overview of coal in metallurgical processes. The most relevant questions discussed during the interview were the application and goal fulfillment of the coal as well as the requested requirements. There are very different requirement specifications for coal for the different processes, while some requirements have no quantitative description, as they are based on experience of buying the same product at the same quality from the same company over and over again.(R5) Many interviewees referred to the fact that requirements for coal differ from recipe to recipe and according to what is available at home in material quality, which is adjusted in quantities to the recipe to be manufactured. The main discussion was about the requirements for coal in EAF, tunnel furnaces (TF) for direct reduction, and SAF. However, the requirements for coal in later process steps (e.g. ladle) were also mentioned. The later the carbon is added in the process chain, the stricter the requirements for the carbon material but the usage amount are also not as large as in the aforementioned processes (EAF, TF, SAF). The main principle of selecting the suitable carbon material for any process is that, you want to start by using raw materials to get as close as to the final targeted composition as possible to reduce extra purification of steel that consumes more material and energy. Carbon added later in the process such as in the ladle furnace and argon oxygen decarburization (AOD) process has requirements that are up to 100 % purity on carbon, or carbon according to the final recipe. As these steps are closer to the final product and then the companies do not want to have to reprocess the metal to get to the correct final recipe.(R3, R4)

4.4.1 Carbon in the processes

During the interviews, in addition to questions about requirements and the application and fulfillment of the carbon target, the process and carbon application has also been explained.

I. Electric arc furnace (EAF) process

EAF is today the most effective way to melt scrap. This is done via three electrodes made of pure graphite called needle carbon furnace to create an oxidizing environment. A short circuit is created between the tip of the electrodes and the scrap that forms a hot arc that gradually penetrates into the burden and melts the scrap. The electrodes are consumed slowly in the process but are not counted as fuel. Carbon is typically added as an alloying agent in the scrap basket or is injected through a lance to create a foamy slag.(R1, R2, R3, R4) In the basket, you can mix either 100 % scrap or mix in more fresh dry material. Depending on this ratio between scrap and dry material, different amounts of charge coal are needed to be added to the basket from the beginning of the process. There are different scrap qualities used in metal remelting. Scrap is sorted according to different levels of critical and usable metals in remelting. The recipe for processed metal and usable scrap determines how much alloying carbon needs to be added to the scrap bucket at the beginning of the process. The quantity of charged coal therefore depends on how much carbon is already present in the scrap loaded into the furnace. Depending on the raw material filled in the basket and the raw material's carbon content, different amounts of charge coal are needed. The charged coal is dissolved in the molten steel and enters the material as an alloying element from the bottom of the scrap bucket. The first charged carbon therefore needs to have a sufficiently high mechanical strength so that it can withstand high drops when placed and the pressure from the remaining material loaded on top in the scrap bucket. If this charged carbon were to break into smaller pieces or become pulverized, it would combust immediately and the desired carbon content in the melt would not be achieved. Coal is also commonly added by injection via a lance from a silo with gas pressure. This coal is used to get the right effect on the foaming of the process. As the foaming has a major impact on the productivity of the process. The slag creates an energy-saving lid as the heat remains in the melt and increases energy efficiency and protects the arcs and the refractory material on the inside of the basket. The foaming slag also dampens the sound from the process and helps react with certain materials so they go into the slag and you get rid of them. To get the right desired properties of the foam, the foam is desired to be basic, as fossil coal has a fairly acidic character, lime needs to be added to increase the basicity. During stainless steel production, it is more challenging to get a foamy slag since chromium-oxide-rich slag has a high viscosity which makes foaming difficult. Coal can be used as a fuel in the EAF process, but is not something that Swedish plants aim to do as it would contribute negatively to the renewable transition due to increased carbon dioxide as a fuel. After the EAF process, several refining steps are carried out to achieve the desired nominal composition of the steel by using an AOD process (for stainless steel only) and ladle furnace treatment (for all types of steels). The later in the process the carbon is added, the stricter the requirements are.(R1, R2, R3, R4, R6)

II. Tunnel furnace (TF) direct reduction process

Coal is used as a reducing agent to separate the oxygen from the iron oxide to form carbon monoxide and further carbon dioxide. This is a solid process so no melting takes place but rather it is a slow sintering of the iron atoms into a sponge iron tube. The coal acts as both a reducing agent and a fuel as the combustion from carbon monoxide to carbon dioxide provides heat to

the process. Coal has a high heating value for this process, the focus of this process is not to use coal as a fuel but more as a reducing agent. As there are other materials intended to be used as fuel in the process. Magnetite is packed together with the coke in a ceramic tube so that the coal surrounds the magnetite. Here the carbon needs to have a specific particle size range so that the desired degree of compaction can be achieved. Mechanical strength of carbon material is critical as in this process a low reactivity is desired as it is a slow process and all reactions must have time to occur in due time with each other. These ceramic tubes are then placed on a 2 m x 2 m trolley and travel on rails through a long tunnel oven, a slow process. In the kiln, the magnetite is reduced by the coke and sintered together. The rest becomes burnt material such as ash which is vacuumed out at the end of the process and depending on the amount of S, this residual product can be recycled and unreacted carbon may have the opportunity to react. The vacuumed material contains unreacted carbon, ash, quicklime, S and P. The sponge iron is then crushed into a powder. (R9, R10) In Figure 9, the process of a tunnel oven can be seen and its different process steps.

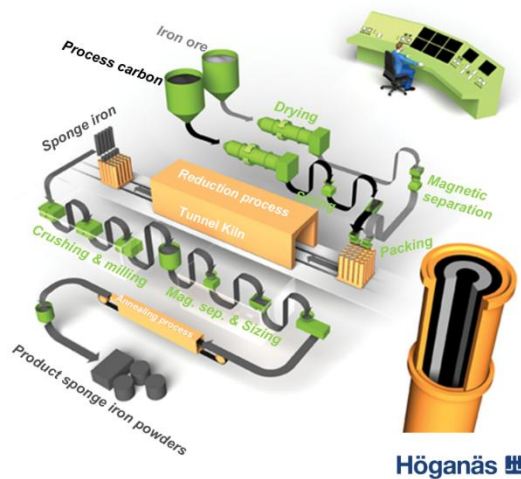


Figure 9: Process flow chart for a tunnel oven (R9, R10)

III. Submerged arc furnace (SAF) process

SAF is a manufacturing process with an reducing environment to reduce chromite ores and to produce ferro chrome. Chromite ore, coke, slag formers and electrodes are fed into the process continuously. The electrodes as fuel and according to Söderberg's electrodes with continuous feed. Tapping then takes place in batches after 2-2.5 hours to get the molten metal out. Tapping takes place with a large proportion of slag, up to 1.8 tons of slag/ton of alloy. The coke in this case for ferrochromium is one of the carbon-bearing substances and is the carbon-bearing substance that is flexible to be replaced. The task of the coke is to be a reducing agent and reduce the oxygen from the iron oxide and chromium oxide and create the formation of ferrochrome. The task of the coal when producing ferrochromium is also to form a coke bed above the molten slag to contribute to an increased flow distribution and a greater spread of heat inside the furnace. The reactivity affects the reduction as 80 % of the reduction takes place in the so-called low zone under the furnace, i.e. the zone under the electrodes. This means that

the reactivity must be relatively low so that the desired reactants have time to get to the desired location in the furnace before the reaction has occurred or the material has already been consumed. Mechanical strength of the carbon is also quite critical in this process as it should remain intact through the entire sintering process. In Figure 10 a picture of what a submerged arc furnace looks like is shown.(R12) Ferrometal manufacturers are sensitive to P as it remains in the final product.(R11, R12)

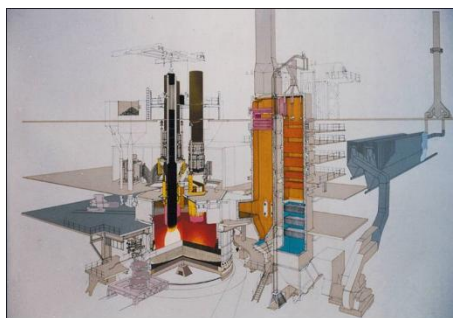


Figure 10: A picture of a submerged arc furnace (R12)

4.4.2 Metal productions requirements

Table 3 shows a compilation of the requirements of biocarbon for different metallurgical process. For confidential reasons, the interviewed metal producers are here presented as A, B, C...etc. in the table.

Table 3: *Quality requirements in metallurgical processes (Interviews)*

Metal producer	Process	Steel type	Application	Particle size (mm)	Fixed carbon content (%)	Ash (wt%)	Volatiles (wt%)	S (wt%)	P (wt%)
A	EAF	Stainless steel	Charged coal	10 - 30	> 90	≤ 8	6 - 9	< 0.7	0.015 - 0.025
			Injection coal	2 - 3	> 95	≤ 8	6 - 9	< 1.2	0.015 - 0.025
B	EAF	Low alloy	Charged coal	10 - 40	> 80	< 8	< 8	< 0.9	< 0.05
			Injection coal	3 - 8	> 85	< 8	< 8	< 0.9	< 0.05
C	EAF	Stainless steel	Injection coal	1mm, 50% must be 0.15 - 0.45mm	97.5 - 100	< 1.1	< 1	≤ 1.8	0.0015 - 0.0045
D	TF	Sponge iron	Reduction	~ 10	> 75	< 10	< 15	< 0.5	0.05 *
E	SAF	Ferrochrome	Reduction	-	> 85	< 2	< 10	< 0.1	<0.03

*Note: This is the historical requirement of the process to be adapted and reviewed.

Where we can see that the quality requirements for biocarbon even differ for the same process operated by the different steel companies, which is to a large extent affected by the steel grades that they produce. Elements such as S and P in biomass are unwanted impurities in metal production process as they deteriorates the mechanical properties of the final steel product. From Table 3 you can see that the requirements on P is stricter than S for all metal producers. Also note that metal producer C has the most strict quality requirements for biocarbon. Early in the interviews and several times in some interviews it has been said that metal companies want coal in the quality that they have right now. That is, coal in the quality of fossil coal.(R2, R3, R4, R6, R9, R10, R12) Some people added the comment that more the more similar today the better, we may have to adapt a little.(R3, R9, R10) Most quality requirements are listed in the table above, but there are a few other requirements that have been ambiguous and are instead presented in text. The switch of the carbon material must allow fundamental reactions of the processes to function normally. This can be done, for example, by ensuring that the biocarbon used to replace fossil carbon have the right chemical composition and reactivity. The reactivity of biocarbon is related to many other parameters, such as fixed carbon content (C-fix), particle size, and density. In Figure 11, the relationship between reactivity and C-fix content of biocarbon can be seen. These are linked to the process, to how long the process takes and how the companies want the coal to react, as well as how they run their furnaces. R3 *“Companies are different in their ability to run their businesses, so subsequent purification steps can vary in effectiveness.”* Reactivity can be adjusted by increasing the density and reducing the free surface area. The reactivity requirement of biocarbon material for different processes are often vaguely described as “low, very low or just enough so that all material will have time to go through the reaction, melt and enter the metal where it should be or carry out the reaction it complete”. Also linked to both reactivity and density is particle size, also mechanical strength. The particle size can also be seen in table 3. But mechanical strength is more difficult to get concrete answers to as this is a requirement that is tested before a purchase agreement is signed, to investigate whether the carbon has mechanical strength for the applied process. The mechanical strength must, from case to case, between the different processes, be able to handle weight, weight pressure, high drops and handling and be crash-resistant example in gas injection. Companies want the density to be high, this from several aspects not only technical but also economic to bring together transport economy, logistics in both transport and possession of the material inside the steel plants and storage efficiency at the company. High densities such as fossil coal today reduce the cost and management of needing to have several different silos and larger biocarbon piles, as coal with a lower density than today would take up more space. When storing at companies outside silos, this should be done in piles and not in big bags, which is currently the standard method of transporting biocarbon. Big bags are considered cumbersome to handle and would be less space-efficient.(R4) Storage usually takes place outside in an open atmosphere without a roof. Despite this, metal companies have expressed their desire for as low moisture content in the biocarbon as possible, preferably 6 – 8 %.(R2, R4, R9, R10) Some companies have also mentioned several requirements for the concentrations of other non-metallic elements in the biocarbon such as N. The quantities of carbon materials that the companies use on regular basis in their processes has been described as sensitive information and the collected responses are not as complete. But as some examples

for EAF charging, the answers have been 0 - 1.8 tons/melt, 0.6 - 1.6 tons/melt, 0.3 tons on an 82 tons melt. Furthermore, for EAF and injection, the answers were 0.2 - 1 ton/melt, 0.8 ton/melt, 0.5 - 1 ton/melt. For TF 45,000 - 47,000 tons of reducing agent per year, of which approximately 8,000 is anthracite and the rest coke for a total internal flow of 130,000 tons. Finally, SAF uses approximately 500 kg coke/ton of alloy and produces 60,000 tons of alloy/year.(R1, R2, R3, R4, R6, R7, R8, R9, R10, R12)

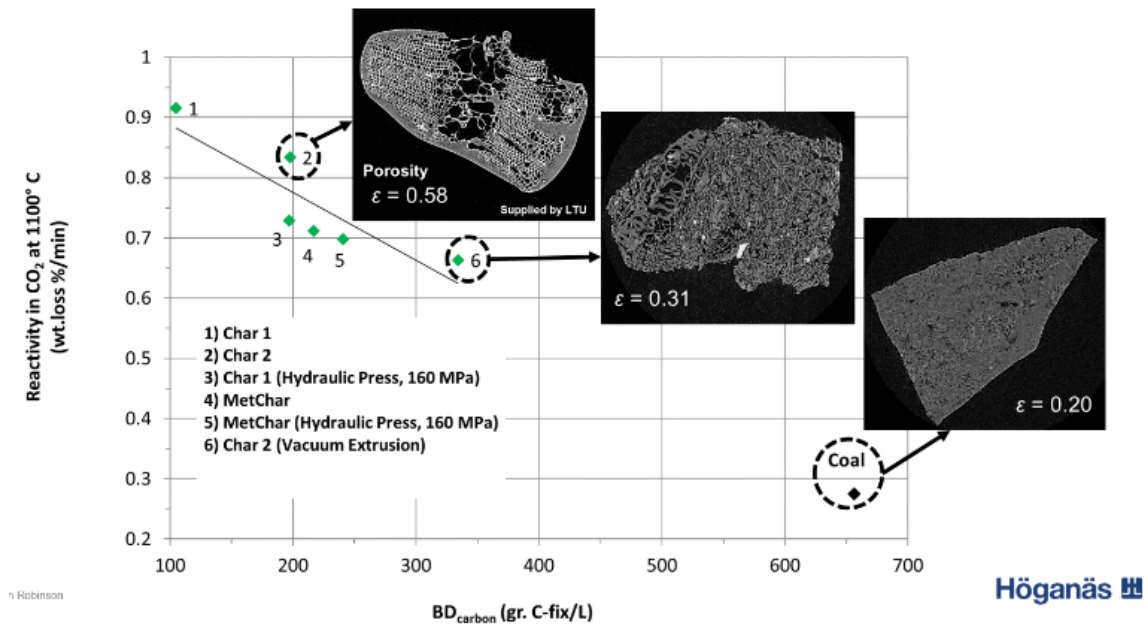


Figure 11: The relationship between reactivity, carbon and porosity (R9, R10)

Tests and development have been paused due to price as biocarbon is not considered to be or be economically viable as they are 4 - 5 times more expensive and 1/3 in energy value and density compared to fossil charge coal. Unsafe handling of biocarbon has also been expressed as a concern as there can be risks of spontaneous combustion. Moreover, the lower than average values of C-fix contents and densities, high P levels, high reactivity, dusting, explosion risk, and recyclability all poses hindrance towards large scale deployment of biocarbon in metal production processes.(R2, R3, R4, R6, R7, R8)

4.4.3 Fossil coal consumption

In today's production, untreated anthracite and petroleum coke are the most often used for large scale production, which is early in the process chain. Fossil coal that has a lower content of bound carbon has treatment steps that are applied to carbonize the coal, with the coking process increasing the reactivity, among other things.(R1, R2, R3, R5, R11) Finer quality such as pet coke and graphite for later process steps closer to the finished product if carbon needs to be added then. In Table 4, a simple overview of the proportion of different coals of bound carbon and where they are located. Furthermore, in Table 5, there is more compiled information on the quality of the most used fossil coal.(R5, R11)

Table 4: Origin of fossil carbon overview (R5)

Type of carbon source	C-fix (%)	Application	Location
Coking coal	60 - 70	Cokemaking	World
Anthracite	< > 80 *		Asia- China, South America- Peru, Africa- South Africa, Europe
Anthracite	> 90, 93 - 94	Directly	Asia- Russia: Siberia, China
Petcoke	89 - 99		Europe- Norway, United Kingdom
Graphite	> 99.5	After EAF	Asia- China, South America- Brazil

*Note: Both above and below 80% in fixed carbon.

Table 5: Quality, today's used fossil carbon (R5, R11)

	Density (kg/m ³)	C-fix (%)	Volatiles (%)	Ash (%)	S (wt%)	P (wt%)	Mechanical strength
Anthracite	900 - 1100	93 - 94	3 - 8, (20) *	10 - 12	0.2 - 1	0.05	High
Charging coal	-	80 - 95	0.1 - 8	0.1 - 8	0.016 - 0.9	0.05 - 0.65	-

*Note: In terms of quality, it is usually said that there are 3-8 % volatile materials, but there is also fossil coal with up to 20 %.

When using fossil coal, the slag in EAF and SAF becomes acidic as the ash of fossil coal contains more acidic slag components. These substances include silicon oxide, aluminum oxide and titanium oxide. Two common basicity indexes (B2, B4) are used as a measure of how acidic or basic the slag is and they calculated by. Equations 1 and 2, with the unit of oxides appearing in the equations in weight percentage.(R2, R3, R9, R11)

$$B2 = \frac{CaO}{SiO_2} \quad (1)$$

$$B4 = \frac{CaO+MgO}{SiO_2+Al_2O_3} \quad (2)$$

Where the B2 value is a simpler estimate, as it only shows the ratio between calcium oxide and silicon oxide. The B4 value includes several oxides that affect the chemical properties of the slag. Means that it is applied in more advanced process controls, as the value provides a more nuanced and realistic measure of basicity.(R2, R3, R12) A value greater than 1 indicates a basic

slag, which is desirable in most metal processes to effectively bind S and P and protect the furnace lining. Values less than 1 mean acidic slag, which is often less desirable in metal manufacturing. The ash composition of a fossil coal typically yields B2 below 1, closer to 0.7 - 0.9, which means that there is more silicon oxide than calcium oxide in the slag. In contrast, the B2 value for a biocarbon gives a basic slag and a B2 value between 1.5 - 4, which indicates more calcium than silicon.(R11) From a B2 value perspective, a basic value of the slag with a value above 2 is desired, but is also product dependent. There are metal types that in some cases want where one would rather have a more acidic slag.(R2, R3) To correct a low basicity index value, more basic substances are added, such as calcium oxide (lime). As a slag former for EAF and SAF, silicon dioxide is used, which is a more acidic oxide. For the SAF process as a complement when the ore used can have aluminum oxide levels of between 7 – 15 % from the charging.(R2, R3, R12)

Fossil coal, such as anthracite, is formed under completely anaerobic conditions. The organic material has been submerged in water and has become trapped in sediments where all the oxygen has gradually been used up. Under these anaerobic conditions, there is no combustion, but the organic material is instead broken down microbially and chemically over a very long time, under pressure and in an often acidic environment. Since oxidation is absent and reductive conditions prevail, the end product is acidic rather than basic. Biocarbon, unlike fossil coal, is produced through thermochemical processes where part of the biomass is oxidized to ash. Since the ash contains basic minerals such as Ca, Mg and K, biocarbon ash tends to have higher basicity. Even superficial annealing of coke contributes to basic ash. Elements such as S and P are oxidized much more easily and also affect the chemistry of the ash. Ash is formed as a residual product from the material that is oxidized during combustion, even when hydrogen is used as a reducing agent. It is primarily the surface layer of the material that is oxidized, where many basic cations are concentrated. In pyrolytic and combustion processes, this means that a certain amount of biomass is completely burned, leading to the formation of ash that often has a high basicity value. In pyrolysis, this occurs despite the fact that the oxygen supply is severely limited, a completely oxygen-free environment is practically impossible to achieve. Therefore, some complete oxidation also occurs during pyrolysis, which contributes to the basic nature of the biocarbon ash.(R20)

4.5 Biocarbon production and quality

In order to investigate and find out the available quality of biocarbon in Sweden, interviews with respondents R11, R14, R15, R17, R18, R19 and R24 have been held during the course of the project. What all of these respondents have in common is that they work with biocarbon and have a position in the company where their knowledge of their processes, products and process flows has been very helpful in compiling their different biocarbon qualities. Below are two tables with compiled technical information on available quality, Table 6 shows different qualities with the same technical properties as compiled for the metal producers' requirements (Table 3) and in Table 7 several quality properties can be seen.

Table 6: Quality of available biocarbon (R11, R14, R15, R17, R18, R19, R24)

Carbon	Production	C-fix (%)	Ash (wt%)	Volatiles (wt%)	S (wt%)	P (wt%)	Particle size (mm)
Biocarbon A	Pyrolysis	90 - 94	< 1.5	< 5	< 0.01	< 0.05	6 - 8
Biocarbon B	Gasification	80	7 - 8	7 - 15	< 0.05	0.14	Fine powder
Biocarbon C	Pyrolysis	> 90	2 - 4	12 - 15	0.018	0.023	60
Biocarbon D	Pyrolysis	70 - 92	< 2	5 - 18	0.055	0.045	0 - 10
Biocarbon E	Pyrolysis	73 - 93	2 - 5	8 - 10	0.02	0.09	-

Table 7: Quality parameters and information of available biocarbon (R11, R14, R15, R17, R18, R19, R24)

Carbon	Density (kg/m ³)	Moisture (%)	Calcium (wt%)	Nitrogen (wt%)	Production (tons/year)	Upscaling (tons/year)
Biocarbon A	-	0.5 - 2	0.4	0.3	5000	30 000 (2027)
Biocarbon B	-	10	2.5	0.6	400	-
Biocarbon C	~ 340	1.8	0.9	0.4	600	-
Biocarbon D	420 - 450	8 - 10	0.9	-	2500	10 000 (in 4 facilities)
Biocarbon E	250 - 350	5 - 18	0.6	0.8	~ 1200	-

To achieve this quality of biocarbon, biocarbon producers have used different types of wood, all types of wood can be used. But the most common is the use of wood from conifers, mainly spruce and pine. Some respondents have said that they used deciduous tree as raw material, but then they were linked to density for economic transport purposes and that it was hardwood that was close at hand at the pyrolysis plant. The wood biomass is fed into the process as wood pellets or wood chips. Most of the companies interviewed have used pyrolysis as a processing process where the main product out of the process is biocarbon. From the incoming biomass, most producers have managed to produce 20-35 % biocarbon, where the remaining products out of the process are gas, oil and heat. In gasification, bio syngas is the main product and instead a much smaller amount of biocarbon is produced, an amount around 5-10 % biocarbon. Of the remaining products in addition to biocarbon, companies can somewhat determine the amount of oil and gas they will extract, not least with production parameters but also with subsequent processes when the company can condense gas into oil if more oil is desired. The areas of use for biocarbon oil are under development from some quarters to find the optimal area of use. One potential application of bio-oil is as a binding agent in agglomeration process,

due to the high carbon content in the oil. During the process, the amounts of certain technical parameters such as solid carbon can be controlled with time and temperature, among other things. The remaining parameters are very dependent on the tree species and quality, as well as the pollutants that the tree has absorbed. When discussing grot as a resource the response was different. They say both that it is very difficult to produce high quality with only grot and that should be manageable, maybe more expensive.(R11, R14, R15, R17, R18, R19, R24) Table 7 provides information on companies' planned upscaling for biocarbon production. Increased production of raw material provides greater opportunities for adjustment and possible reduced competition as more biocarbon is available, but competition still remains.

4.6 Comparison requirements

For comparison between given values in Table 3 and Table 6, the values of requirements and available quality have been compared and compiled in Table 8. In Tables 3 and 6, the values of metal producers A-E have been compared with biocarbon producers A-D, biocarbon E is not included due to late data income. In total, 6 parameters are considered, which are particle size, C-fix content, volatile matter content, ash content, S content, and P content. The number of fulfilled criteria is shown by using a color scheme. In cases where 5-6 requirements are satisfied, cell is highlighted in dark green, whereas in the case of 4, 3, 2 matching criteria the cells are marked in light green, yellow, and red respectively. As can be seen in Table 1, one biocarbon producer interviewed is not Swedish but Norwegian. However, exceptions were made during quality collection to include this Norwegian biocarbon producer, partly because a metal producer tipped them off that they had been in contact with the Norwegian company and to combine several companies' quality requirements. The proximity to Norway was considered when considering the options.

Table 8: The degree of matching between biocarbon requirements from metal producers with qualities of biocarbon that can be found or produced in Sweden

	Biocarbon A	Biocarbon B	Biocarbon C	Biocarbon D
Metal producer A				
Metal producer B				
Metal producer C				
Metal producer D				
Metal producer E				

After this quality matching, the technical properties have been ranked from best match to worst match, is in the order particle size, P (especially for stainless steel producers), solid carbon, volatiles, ash and S were matched best. Particle size is a property that can be modified afterwards after the biocarbon has been manufactured through compaction or agglomeration. A

compaction step is done to modify the density of the biocarbon, and to manage some of the reactivity as biocarbon is otherwise very reactive. Since particle size can be modified afterwards, P is the most difficult property to find biocarbon matches with. Otherwise, the qualities of available biocarbon are relatively good compared to the desired quality, makes P the most difficult to match and S the easiest according to given quality requirements. However, metal company C does not have very great opportunities at the moment, but as can be seen in Table 3, they also have the highest quality requirements for biocarbon.

4.7 Biocarbon for soil improvement and application

Biocarbon used in soil improvement contexts generally has completely different requirements than biocarbon for metallurgical use. In interviews with respondents 21 and 23, it became clear that there are no uniform quality requirements for biocarbon in agriculture instead, the focus is on the function the biocarbon should fulfill in the soil.(R21, R23) The soil contains many different types of organic carbon that have been collected from roots and leaves that have been broken down by organic organisms in the soil and formed humus. There, biocarbon is another type of carbon that is not biologically active in the same way as the carbon that is broken down by microorganisms. Common requirements are that the biocarbon should bind water and moisture, have a high surface activity for micro-life, and be able to bind heavy metals and retain nutrients, especially P and S. These properties are often favored by a biocarbon with low density, high ash content, and a certain content of nutrients, which is therefore kind of the exact opposite of what is required in the metal industry. So when you are going to add biocarbon to the soil, you think about what is the problem in this soil or cultivation that you want to address or achieve. Based on these questions, you look for some biocarbon that has a broad ability and effect to improve the environment in the soil and the possibility of cultivation.

When biocarbon is used as a carbon sink, the goal is that the carbon atoms should be bound in the soil and not converted to carbon dioxide. Biocarbon is very stable and breaks down slowly in the soil environment. For this application, a high amount of stable carbon (solid carbon) is therefore desired, which makes it somewhat more similar to what the metal industry demands. However, competition is reduced because carbon that remains in metal products after reduction is also considered a carbon sink and thus meets a similar climate goal.

The soil environment is complex, and different soils have different needs. Therefore, the properties of the biocarbon are adapted to the effect that is desired, rather than there being a general requirement. At the same time, it appears that surface-active biocarbon's can have unwanted effects such as binding nutrients from the soil instead of adding them, which means that biocarbon is often combined with fertilizers when applied. Density is not a decisive parameter in itself but plays an indirect role: higher density can mean less surface activity and thus less impact on micro-life, while low density means better water retention capacity but increased risk of nutrient leakage.(R21, R23)

Furthermore, there are strict requirements regarding environmental toxins, especially for certification in soil application. According to the European Biochar Certificate, there are clear

limit values for, among other things, PAH (polycyclic aromatic hydrocarbons), which are carcinogenic. These requirements are even stricter if biocarbon is to be used in, for example, animal feed.(R17, [45]) The pH value is also an important parameter. The ash of the biocarbon affects both the nutrient content and the acidity of the soil, where the soil pH is normally around 6–8. Too high or too low a pH can lead to an imbalance in the soil.(R21, R23)

Physically, biocarbon for agriculture is often handled differently than for metallurgy. Here, wetter biocarbon (up to 30 % moisture) is often preferred to reduce dust formation during application, as well as smaller particles, often round below 30 mm which are sometimes mixed with macadam.(R21, R23)

In conclusion, the comparison between the use of biochar in soil improvement and in metallurgy clearly shows that these are two completely different requirement profiles. Agriculture requires a light, moist and ash-rich biocarbon with high surface activity and nutrient content, while metallurgy requires high density, low ash content and low occurrence of elements such as S, P and K. The requirements of the different applications are therefore not directly competitive, but rather complementary to each other in the raw materials market.

4.8 Concluding discussions

This study highlights several key factors that affect the possibility of using biocarbon in metallurgical processes. Although the technical potential has been demonstrated previously and in many previous studies, several practical, logistical and market-related obstacles remain that need to be discussed.

A fundamental challenge lies in the availability of raw materials, competition and biomass. Today, there are a few different sources or resources from which woody biomass can come. However, the raw material for biocarbon production is only seen to be taken from residual streams. The driving force today is the sawmill industry and the paper industry, where they are primarily allowed to take the raw materials that they want and benefit from the most. Partly because they are established in a fully functioning market and the forest sector knows how to get the most value out of the forest from that sector. Since the wood-based biomass market has many stakeholders, there is no possibility of just taking what you want. The availability of raw materials for metallurgical biocarbon is somewhat limited by the established market. From the forestry side, energy wood is recommended as a suitable wood for the production of biocarbon for metallurgical applications, as there is currently no biomass grown dedicated to biocarbon. The potential for extraction and availability of energy wood is perceived as quite large, as there is great potential to increase extraction and that 30 % of a tree is precisely the root and 11 % is bark. But how suitable is this raw material technically for metallurgical biochar, as the levels of S and P are high in the green parts of the trees, which includes bark and they are also seen with higher levels of branches, the amount of bark and also the amount of S and P increases, as we saw in Figure 8. In terms of communication, there is probably a lack of support for this, as biochar producers are not as unanimous that energy wood alone is not an optimal source of raw material. This is most likely a cost issue, but with increased sorting of the bark, I can imagine

that the availability of biomass for metallurgical biocarbon will increase. Much of this transition is price and cost-dependent and the difference already starts with the biomass, where the price has increased, which has also driven up the price of the finished biocarbon. Although an interested metal industry has driven forward, it has slowed down a bit due to caution and braking in test trials due to the high costs.

Today, forests are felled and harvested in a sustainable way, so the forest has time to recover and harvesting is done so that growth is still positive. Which can also be read about in the Forest Impact Assessments 2022 synthesis report.[82] But there is quite a lot that can change, affect and stand in the way of biomass for biocarbon production. The raw material can abruptly disappear like the plastic resource in Germany, here through, among other things, rapid political shifts regarding decisions to abruptly stop harvesting, the synthesis report also states how the European Union wants to influence Swedish forests and harvesting for increased carbon dioxide absorption by the forest in the short term. Although Sweden is leaning towards wanting to build robustness around the forest, politics does not decide everything as external environmental influences also affect availability. Although there is great potential in increased logging, the quantity and volume are uncertain in how much you actually get in the end. Today's forest market is adapted and tailored to today's forest industry as strategies exist for the growth of the trees so that the ratio between wood and bark material quantity should be extremely profitable and to place the growth where you want it. Techniques during felling, post-processing and shipping where the timber is given high priority and quickly arrives at the sawmills, partly because you do not want the material to go to waste and because they want to handle fresh biomaterial with a higher moisture content than biocarbon producers want, which means that the forest side drives the market here too. The fact that material resources have time to dry up before they reach biocarbon producers does not really matter much except that you can have reduced resources due to damage and that the bark is more difficult to get off branches when it has dried out. From an environmental and emissions perspective, in terms of transport and emissions, Swedish biocarbon does not need to be transported as far as today's used fossil coal, as can be seen in Table 4, and still contributes more to reduced carbon dioxide emissions. However, biomass has a lower density than fossil coal, as can be seen in Table 2 and Table 5. Also, the density of the biomass becomes lower after the processing of biocarbon, which can be seen in Table 7. For even more reduced climate impact and technically to increase the density of biocarbon, treatments of the biocarbon are carried out as a compaction step.

As we have seen, there is a lot of ambiguity, lack of clarity and lack of structure for metallurgical biocarbon. Not least that coal has different purposes in different metal applications and that the degree of sustainability varies depending on whether the coal is encapsulated or not. Then for a carbon sink, the carbon atoms should not have the opportunity to be converted into gas. But that there are different opinions and certainty also in what is environmentally friendly and to what degree, for greener emissions with biocarbon or not. An overall picture has also been difficult to gather as there are no measurement values for certain important technical properties found in biocarbon, but the metal companies rely on old qualifications, tests, contacts and contracts for well-proven coal qualities. Despite this, there

are also large variations in recipe application, as different coal, scrap and ore qualities are mixed to achieve the best matching recipe.

If we compare today's anthracite with the available quality of biocarbon Table 6 with Table 5, we can see that there is some biocarbon that in many categories comes up to levels of quality of biocarbon like the quality of anthracite. But that the biggest obstacles found in this project are the P content in the biocarbon and that it is directly linked to the biomass. Where the biomass can be affected by many different factors and that the growth rate of the tree also makes a difference in the amount of green parts of the tree.

5. Conclusion

To summarize and answer the research questions from the beginning: Biocarbon can be produced by heating or vaporizing all organic materials such as wood, straw, fruit peel, sludge... etc. All these materials may or may not suit well for metallurgical application since the metal industry is a large, robust industry and is very picky about their raw materials for a smooth, stable and safe operation. At the same time, big questions follow in which industry will have access to biocarbon from which raw material, which one is best suited, to what from the requirements specifications for different applications. Will the biocarbon market be able to come together? There are some uncertainties that govern and affect forest management and raw material availability for biocarbon production. As we have been able to see, the raw material availability is a bit uncertain, the quality of biocarbon from metallurgical measurements is relatively good and differences between the desired quality of biocarbon between metallurgical application and land use exist for certain properties. There are some limitations with biocarbon for companies that manufacture metal, but there were also certain types of biochar that fairly well reached the required specifications and when the goals are not reached, there are many other possibilities for biochar, such as for soil improvement and more.

So to summarize the content and answer the research questions individually:

RQ1: Can Swedish wood-based biomass meet the requirements for biocarbon in metallurgical applications?

- Residual biomass from the forest and sawmill industry has the potential to be used for biomass for metallurgical biocarbon by improving the sorting of green parts with high phosphorus contents.

RQ2: What technical requirements do Swedish metal companies have on biocarbon, and how well do they match with the properties of biocarbon produced in Sweden?

- The main technical limitations for biocarbon are phosphorus but the ranking will be as follows: Particle size > **P** (especially for stainless steel producers) > C-fix > Volatile matter > Ash > S.
- Of the producers surveyed, 4 out of 5 metal producers have the opportunity to find biocarbon with a relatively good match.

RQ3: How do the biocarbon requirements for metallurgy differ from those for soil improvement?

- One difference in requirements is the content of sulfur and phosphorus in their biocarbon.

6. Future work

With the project, several areas and knowledge have been discovered, and questions have arisen, some of which have not had the opportunity to be addressed in this report. Among other things, how biomass would be most effectively divided between different sectors and whether there is a particular type of wood that would actually be most suitable for biocarbon for metal applications. How important is density versus technical content. How much positive effect could using biocarbon instead of fossil coal have from the perspective of basicity and lime additives?

Further studies would be interesting to do, for example, within the following topics suggestions:

- Maximize the value of biomass use in different sectors (metal, soil improvement, energy, chemistry...etc.).
- Investigate how phosphorus is bound, in biomass and biocarbon.
- Investigate biocarbon production from biomass other than wood-based biomass, such as algae, roadside waste...etc.
- Investigate the impact of biocarbon ash in metal production processes and its potentially positive impact (e.g. replacement of lime and flux).

7. References

- [Picture front] Stockholms Koloniträdgårdar, *Älska jorden med biokol*, 18 july 2022. [Online]. Available: <https://www.sthlmkoloni.se/alska-jorden-med-biokol/>. [Accessed: 26-May-2025]
- [1] Sveriges geologiska undersökning, "Samhällets behov av metaller," [Online]. Available: <https://www.sgu.se/mineralnaring/mineralnaring-och-samhalle/samhallets-behov-av-metaller/>. [Accessed: 03-Feb-2025]
- [2] Fossilfritt Sverige, "Stålintustrin – Färdplan för fossilfri konkurrenskraft," [Online]. Available: <https://fossilfritt Sverige.se/roadmap/stalindustri/>. [Accessed: 03-Feb-2025]
- [3] Metal Supply, "Framtidens metallbehov och Sveriges roll," [Online]. Available: https://www.metal-supply.se/article/view/823965/framtidens_metallbehov_och_sveriges_roll. [Accessed: 24-Feb-2025]
- [4] Jernkontoret, *Metallutredning 2014 – inklusive bilagor*, [Online]. Available: https://www.jernkontoret.se/globalassets/publicerat/forskning/d-rapporter/d_860_metallutredning_2014_inkl_bilagor.pdf. [Accessed: 26-Feb-2025]
- [5] Naturskyddsföreningen, "Ny rapport: Metaller – en ändlig resurs med oändlig potential," [Online]. Available: <https://www.naturskyddsforeningen.se/artiklar/ny-rapport-metaller-en-andlig-resurs-med-oandlig-potential/>. [Accessed: 03-Feb-2025]
- [6] Sveriges geologiska undersökning, "Mineralstatistik," [Online]. Available: <https://www.sgu.se/mineralnaring/mineralstatistik/>. [Accessed: 06-Feb-2025]
- [7] Statistiska centralbyrån (SCB), "Miljöräkenskaper – Materialflöden 2021," [Online]. Available: <https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/miljoekonomi-och-hallbar-utveckling/miljorakenskaper/pong/statistiknyhet/miljorakenskaper---materialfloden-2021/>. [Accessed: 07-Mar-2025]
- [8] Swerim, "Biobaserade material," [Online]. Available: <https://www.swerim.se/kompetensomraden/materialteknik-och-ravaror/biobaserade-material>. [Accessed: 20-Jan-2025]
- [9] Regeringen, "Regeringens klimatpolitik," [Online]. Available: <https://www.regeringen.se/regeringens-politik/regeringens-klimatpolitik/>. [Accessed: 05-Feb-2025]
- [10] Naturvårdsverket, "Sveriges utsläpp och upptag av växthusgaser," [Online]. Available: <https://www.naturvardsverket.se/data-och-statistik/klimat/sveriges-utslapp-och-upptag-av-vaxthusgaser/>. [Accessed: 03-Feb-2025]
- [11] Naturvårdsverket, "Växthusgaser – utsläpp från industrin," [Online]. Available: <https://www.naturvardsverket.se/data-och-statistik/klimat/vaxthusgaser-utslapp-fran-industrin/>. [Accessed: 03-Feb-2025]

- [12] Näringsliv, "Biokol kommer att bidra till att göra metallurgisk industri mer hållbar i Norden," [Online]. Available: <https://naringsliv.se/legacy/biokol-kommer-att-bidra-till-att-gora-metallurgisk-industri-mer-hallbar-i-norden/>. [Accessed: 20-Jan-2025]
- [13] Envigas, "Biocarbon," [Online]. Available: <https://www.envigas.com/products/biocarbon>. [Accessed: 12-Feb-2025]
- [14] Vinnova, "Hållbart biokol för metallurgisk användning (HABIMET) – tekniskt perspektiv," [Online]. Available: <https://www.vinnova.se/p/hallbart-biokol-for-metallurgisk-anvandning-habimet---tekniskt-perspektiv/>. [Accessed: 01-Jan-2025]
- [15] Skogsindustrierna, "Snabba fakta – Den svenska skogsindustrin i korthet," [Online]. Available: <https://www.skogsindustrierna.se/om-skogsindustrin/branschstatistik/snabba-fakta/>. [Accessed: 13-Mar-2025]
- [16] IVL Svenska Miljöinstitutet, *Framväxten av nya fossilfria värdekedjor*, [Online]. Available: <https://www.ivl.se/download/18.5b7c876191e4f6c9a22c1f/1727097737431/Framvaxten-av-nya-fossilfria-vardekedjor.pdf>. [Accessed: 27-Jan-2025]
- [17] Europeiska unionens råd, "Den gröna given," [Online]. Available: <https://www.consilium.europa.eu/sv/policies/green-deal/>. [Accessed: 04-Feb-2025]
- [18] Regeringen, "Globala målen och Agenda 2030," [Online]. Available: <https://www.regeringen.se/regeringens-politik/globala-malen-och-agenda-2030/>. [Accessed: 04-Feb-2025]
- [19] Sveriges Television (SVT), "En koll på kolet," [Online]. Available: <https://www.svt.se/datajournalistik/en-koll-pa-kolet/>. [Accessed: 17-Feb-2025]
- [20] SSAB, "Fossilfri produktion — Produktionsorter i Sverige: Oxelösund," [Online]. Available: <https://www.ssab.com/sv-se/ssab-koncern/om-ssab/produktionsorter-i-sverige/oxelosund/fossilfri-production>. [Accessed: 26-Feb-2025]
- [21] M. Pei, M. Petäjäniemi, A. Regnell, and O. Wijk, "Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland" Multidisciplinary Digital Publishing Institute, *Metallurgiska och materialvetenskapliga tidskrifter*, vol. 10, no. 7, pp. 972, 2020. [Online]. Available: <https://www.mdpi.com/2075-4701/10/7/972>. [Accessed: 03-Feb-2025]
- [22] IEEFA, "Hydrogen Unleashed: Opportunities and Challenges of the Evolving H2 DRI-EAF Pathway Beyond 2024," [Online]. Available: <https://ieefa.org/resources/hydrogen-unleashed-opportunities-and-challenges-evolving-h2-dri-eaf-pathway-beyond-2024>. [Accessed: 29-Jan-2025]
- [23] Projektbeskrivning, Hållbart biokol för metallurgisk användning, Metals & Minerals, Swerim [Accessed: Dec-2024]
- [24] Sveriges natur, "De släppte ut mest koldioxid 2023," [Online]. Available: <https://www.sverigesnatur.org/aktuellt/de-slappte-ut-mest-koldioxid-2023/>. [Accessed: 26-Feb-2025]

- [25] Energi, "Så kan biokol från värmepannor användas i stålindustrin," [Online]. Available: <https://www.energi.se/artiklar/2023/augusti-2023/sa-kan-biokol-fran-varmepannor-anvandas-i-stalindustrin/>. [Accessed: 21-Jan-2025]
- [26] Jernkontoret, "Världsledande järn- och stålföretag," [Online]. Available: <https://www.jernkontoret.se/sv/stalindustrin/stalmarknaden/varldsledande-stalforetag/>. [Accessed: 23-Apr-2025]
- [27] J. W. Creswell and V. L. Plano Clark, *Designing and Conducting Mixed Methods Research*, 3rd ed. Thousand Oaks, CA: SAGE Publications, 2018.
- [28] Jernkontoret, "Biobränslen," [Online]. Available: <https://www.energihandbok.se/biobranslen>. [Accessed: 10-Feb-2025]
- [29] Regeringen, "Globala målen och Agenda 2030," [Online]. Available: <https://www.regeringen.se/regeringens-politik/globala-malen-och-agenda-2030/>. [Accessed: 04-Feb-2025]
- [30] M. Hussain, M. Farooq, A. Nawaz, A. M. Al-Sadi, Z. M. Solaiman, S. S. Alghamdi, U. Ammara, Y. S. Ok and K. H. M. Siddique, "Biochar for crop production: potential benefits and risks," *Journal of Soils and Sediments*, vol. 17, nr 3, s. 685–716, 2017. [Online]. Available: <https://link.springer.com/article/10.1007/s11368-016-1360-2>. [Accessed: 12-Feb-2025]
- [31] S. R. Bhatnagar, R. S. Rattan, and S. S. Rattan, "A state-of-the-art review of biomass torrefaction, densification and applications," *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 1132–1152, 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032114010910>. [Accessed: 05-Mar-2025]
- [32] Söderenergi, *Svenska skogen är en viktig resurs i kampen för klimatet*. [Online]. Available: <https://www.soderenergi.se/svenska-skogen-ar-en-viktig-resurs-i-kampen-for-klimatet/>. [Accessed: 04-mar-2025]
- [33] Statistiska centralbyrån (SCB), *Marken i Sverige*. [Online]. Available: <https://www.scb.se/hitta-statistik/sverige-i-siffror/miljo/marken-i-sverige/>. [Accessed: 07-Mar-2025]
- [34] Statistiska centralbyrån (SCB), *Miljöräkenskaper – materialflöden 2021*. [Online]. Available: <https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/miljoekonomi-och-hallbar-utveckling/miljorakenskaper/pong/statistiknyhet/miljorakenskaper---materialfloden-2021/>. [Accessed: 07-Mar-2025]
- [35] Skogsindustrierna, *Hela trädet tas tillvara*. [Online]. Available: <https://www.skogsindustrierna.se/om-skogsindustrin/en-viktig-bransch/cirkularitet/hela-tradet-tas-tillvara/>. [Accessed: 12-Mar-2025]
- [36] Biochar in Höganäs sponge iron process-techno-economic analysis of integrated production, *DiVA-Portal*. [Online]. Available: <https://www.diva-portal.org/smash/get/diva2:1220500/FULLTEXT01.pdf>. [Accessed: 02-Apr-2025]

- [37] Skogsindustrierna, *Råvaruförsörjning och produktion*. [Online]. Available: <https://www.skogsindustrierna.se/om-skogsindustrin/branschstatistik/ravaruforsorjning-och-produktion/>. [Accessed: 12-Mar-2025]
- [38] Skogsindustrierna, *Skogsbruk*, i *Vad gör skogsindustrin?*, Föreningen Skogsindustrierna. [Online]. Available: <https://www.skogsindustrierna.se/om-skogsindustrin/vad-gor-skogsindustrin/skogsbruk/>. [Accessed: 17-Aug-2025]
- [39] Skogforsk, *Hur mycket grot lämnas kvar i skogen?* [Online]. Available: <https://www.skogforsk.se/kunskapsbanken/kunskapsartiklar/2023/hur-mycket-grot-lamnas-kvar-i-skogen/>. [Accessed: 04-Mar-2025]
- [40] Naturvårdsverket, *Biokol* (under avsnittet "Klimatklivet"). [Online]. Available: <https://www.naturvardsverket.se/amnesomraden/klimatomställningen/klimatklivet/biokol/>. [Accessed: 28-Jan-2025]
- [41] E. F. Zama, B. J. Reid and H. P. H. Arp, *Advances in research on the use of biochar in soil for remediation: a review*, J. Soils Sediments, vol. 18, nr. 7, s. 2433–2450, 2018. [Online]. Available: <https://link.springer.com/article/10.1007/s11368-018-2000-9>. [Accessed: 12-Feb-2025]
- [42] Stockholms universitet, *Kol i olika former*. [Online]. Last updated: 29-Jun-2023. Available: https://www.su.se/polopoly_fs/1.662992.1688415373!/menu/standard/file/Kol%20i%20olika%20former_pdf.pdf. [Accessed: 21-Jan-2025]
- [43] E. Norberg, *”Effekten av olika typer av biokol på metallers löslighet i förorenad urban jord”*, Exjobb, W-programmet, Lunds universitet, 2025. [Online]. Available: http://www.w-program.nu/filer/exjobb/Elin_Norberg.pdf. [Accessed: 20-Jan-2025]
- [44] SLU & EcoTopic AB, *Förstudie biokolproduktion vid SLU 2022*, Sveriges lantbruksuniversitet (SLU), 2022. [Online]. Available: https://internt.slu.se/globalassets/mw/stod-serv/miljo/forstudie_biokolproduktion_vid_slu_2022.pdf. [Accessed: 14-Feb-2025]
- [45] Ithaka Institute for Carbon Strategies, *Guidelines – European Biochar Certificate, version 9.3*, European Biochar Certificate, Schweiz, © 2012. [Online]. Available: https://www.european-biochar.org/media/doc/2/version_en_9_3.pdf. [Accessed: 14-Feb-2025]
- [46] J. Schwarcz, *Charcoal is one of the most important substances ever discovered*, McGill University – Office for Science and Society. [Online]. Available: <https://www.mcgill.ca/oss/article/environment-health/charcoal-one-of-the-most-important-substances-ever-discovered>. [Accessed: 17-Feb-2025]
- [47] M. Westerlund, *Träkolsframställning i kolmila*, Examensarbete, W-programmet, SLU, Umeå, 18 april 1996. [Online]. Available: https://pub.epsilon.slu.se/4277/1/Westerlund_M_1996.pdf. [Accessed: 17-Feb-2025]
- [48] I. N. Zaini, N. Sophonrat, K. Sjöblom and W. Yang, *Creating Values from Biomass Pyrolysis in Sweden: Co-Production of H₂, Biocarbon and Bio-Oil*, Processes, vol. 9, nr. 3, art. nr. 415, 2021. [Online]. Available: <https://www.mdpi.com/2227-9717/9/3/415>. [Accessed: 21-Jan-2025]

- [49] M. Ilić, F.-H. Haegel, A. Lolić, Z. Nedić and H. Hartmann, “General layout of pyrolysis process,” i *PLOS ONE*, nov. 2022. [Online]. Available: https://www.researchgate.net/figure/General-layout-of-pyrolysis-process_fig5_351482640. [Accessed: 13-Mar-2025]
- [50] ScienceDirect Topics, *Gasification – an overview*. [Online]. Available: <https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/gasification>. [Accessed: 05-May-2025]
- [51] A. Alrajeh, *Qualitative Research Process Using Abductive Approach*, SSRN, 2013. [Online]. Available: https://www.researchgate.net/publication/256659750_A_Qualitative_Research_Process_Using_Abductive_Approach. [Accessed: 05-May-2025]
- [52] Skogforsk, *Är biobränslen klimatsmarta?* [Online]. Available: <https://www.skogforsk.se/kunskapsbanken/temasidor/skogsbransle/ar-biobranslen-klimatsmarta/>. [Accessed: 17-Feb-2025]
- [53] PCC Group, *Biomassa – fördelar och nackdelar*, PCC Greenline® blogg. [Online]. Published: 09-Jan-2023. Available: <https://www.products.pcc.eu/sv/blog/biomassa-fordelar-och-nackdelar/>. [Accessed: 03-Mar-2025]
- [54] L. Kieush, J. Schenk, A. Koveria, G. Rantitsch, A. Hrubiaik och H. Hopfinger, *Utilization of Renewable Carbon in Electric Arc Furnace-Based Steel Production: Comparative Evaluation of Properties of Conventional and Non-Conventional Carbon-Bearing Sources*, *Metals*, vol. 13, nr. 4, art. nr. 722, 2023. [Online]. Available: <https://www.mdpi.com/2075-4701/13/4/722>. [Accessed: 28-Jan-2025]
- [55] Swedish Energy Agency, *Project register: 2022-200355*. [Online]. Available: <https://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?registrationnumber=2022-200355>. [Accessed: 21-Jan-2025]
- [56] BioFuel Region, *Bio4Metals – Grönt kol*, BioFuel Region. [Online]. Available: <https://biofuelregion.se/projekt/bio4metals-gront-kol/>. [Accessed: 21-Jan-2025]
- [57] Energimyndigheten, *Energimyndigheten stöttar forskning om biokolproduktion integrerat i befintliga kraft- och fjärrvärmepannor*, Nyhetsarkiv, 01-Jun-2022. [Online]. Available: <https://www.energimyndigheten.se/nyhetsarkiv/2022/energimyndigheten-stottar-forskning-om-biokolproduktion-integrerat-i-befintliga-kraft-och-fjarrvarmepannor/>. [Accessed: 21-Jan-2025]
- [58] Swerim, "HåBiMet – Hållbart Biokol för Metallurgisk användning," [Online]. Available: <https://swerim.se/habimet>. [Accessed: 26-Feb-2025]
- [59] E. Mousa, C. Wang, J. Riesbeck och M. Larsson, *Biomass applications in iron and steel industry: An overview of challenges and opportunities*, *Renewable and Sustainable Energy Reviews*, vol. 65, s. 1247–1266, nov. 2016. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032116303896>. [Accessed: 05-May-2025]

- [60] Z. Yu, Z. Liu, H. Tang och Q. Xue, *Preparation of high-strength biochar composite briquette for blast furnace ironmaking*, Metallurgical Research & Technology, vol. 118, art. nr. 109, 2021. [Online]. Available: <https://www.metallurgical-research.org/articles/metal/abs/2021/01/metal200170/metal200170.html>. [Accessed: 05-May-2025]
- [61] E. Mousa och K. Sjöblom, *Modeling and Optimization of Biochar Injection into Blast Furnace to Mitigate the Fossil CO₂ Emission*, Sustainability, vol. 14, nr. 4, art. nr. 2393, 2022. [Online]. Available: <https://www.mdpi.com/2071-1050/14/4/2393>. [Accessed: 05-May-2025]
- [62] Y. Liu och Y. Shen, *Combined Experimental and Numerical Study of Charcoal Injection in a Blast Furnace: Effect of Biomass Pretreatment*, Energy Fuels, vol. 34, s. 827–835, 2020. [Online]. Available: <https://pubs.acs.org/doi/10.1021/acs.energyfuels.9b02949>. [Accessed: 05-May-2025]
- [63] H. Tang, Z. Liu och Z. Guo, *Numerical Simulation of Charging Biochar Composite Briquette to Blast Furnace*, ISIJ International, vol. 62, nr. 4, s. 642–651, apr. 2022. [Online]. Available: https://www.jstage.jst.go.jp/article/isijinternational/62/4/62_ISIJINT-2021-450/_article. [Accessed: 05-May-2025]
- [64] K. Fan, Z. Yu och H. Tang, *Applying Biochar Composite Briquette for Energy Saving in Blast Furnace Ironmaking*, i *Energy Technologies and CO₂ Management Symposium*, X. Chen, Y. Zhong, L. Zhang, J. Howarter, A. A. Baba, C. Wang, Z. Sun, M. Zhang och E. Olivetti, red., *The Minerals, Metals & Materials Series*, vol. 37, Cham, Schweiz: Springer Nature, 2020, ss. 115–123. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-030-36830-2_12. [Accessed: 05-May-2025]
- [65] S. E. Ibitoye, C. Loha, R. M. Mahamood, T.-C. Jen, M. Alam, I. Sarkar, P. Das, och E. T. Akinlabi, *An overview of biochar production techniques and application in iron and steel industries*, Bioresources and Bioprocessing, vol. 11, nr. 1, art. 65, 2024. [Online]. Available: <https://bioresourcesbioprocessing.springeropen.com/articles/10.1186/s40643-024-00779-z>. [Accessed: 05-May-2025]
- [66] L. Kieush, J. Schenk, A. Koveria, G. Rantitsch, A. Hrubia, och H. Hopfinger, *Utilization of Renewable Carbon in Electric Arc Furnace-Based Steel Production: Comparative Evaluation of Properties of Conventional and Non-Conventional Carbon-Bearing Sources*, Metals, vol. 13, nr. 4, art. nr. 722, 2023. [Online]. Available: <https://www.mdpi.com/2075-4701/13/4/722>. [Accessed: 06-May-2025]
- [67] L. Kieush, J. Rieger, J. Schenk, C. Brondi, D. Rovelli, T. Echterhof, F. Cirilli, C. Thaler, N. Jaeger, D. Snaet, K. Peters och V. Colla, *A Comprehensive Review of Secondary Carbon Bio-Carriers for Application in Metallurgical Processes: Utilization of Torrefied Biomass in Steel Production*, Metals, vol. 12, nr. 12, art. nr. 2005, 2022. [Online]. Available: <https://www.mdpi.com/2075-4701/12/12/2005>. [Accessed: 24-Jan-2025]
- [68] M. Sommerfeld and B. Friedrich, *Replacing Fossil Carbon in the Production of Ferroalloys with a Focus on Bio-Based Carbon: A Review*, Minerals, vol. 11, nr. 11, art. nr. 1286, nov. 2021. [Online]. Available: <https://www.mdpi.com/2075-163X/11/11/1286>. [Accessed: 06-May-2025]

- [69] A. Subin Kaladi Chondath, L. Bansal, D. K. Rath, N. Ahlawat, B. Sahu, S. Tiwari och R. Kumar, *Metallurgical properties of biocarbon in ferroalloy production: A comprehensive study*, ACS Omega, vol. 9, nr. 23, s. 24142–24162, 2024. [Online]. Available: <https://pubs.acs.org/doi/10.1021/acsomega.4c00866>. [Accessed: 06-May-2025]
- [70] T. Echtermhof, *Review on the Use of Alternative Carbon Sources in EAF Steelmaking*, Metals, vol. 11, nr. 2, art. nr. 222, jan. 2021. [Online]. Available: <https://www.mdpi.com/2075-4701/11/2/222>. [Accessed: 24-Jan-2025]
- [71] A. P. Bandyopadhyay, J. G. Yuan, B. R. Shadle och C. T. Crowley, *Biomass as blast furnace injectant – considering availability, quality and impacts*, Fuel, vol. 167, s. 415–431, 2016. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0196890415003556>. [Accessed: 06-May-2025]
- [72] G. Jahrsengene, S. Jayakumari, I. T. Kero and E. Ringdalen, *Sustainable Metal Production – Use of Biocarbon and the Concern of Dusting*, i *Proceedings of the 62nd Conference of Metallurgists (COM 2023)*, Toronto, Kanada, 2023, ss. 1001–1007. [Online]. Available: <https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/3117418/.../Dusting.pdf>. [Accessed: 06-May-2025]
- [73] J. Sandén, M. K. Junginger, B. Peng, A. Bilberg och P. Jones, *On the green transformation of the iron and steel industry: Market impacts and feedstock price effects*, Journal of Cleaner Production, vol. 420, art. nr. 140517, 2024. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0961953424000539>. [Accessed: 06-May-2025]
- [74] P. Thomson, M. J. Nicholls, S. R. de Medeiros, J. M. Swanepoel och A. Z. Amoako, *Towards fossil-free steel: Life cycle assessment of biosyngas-based DRI–EAF production*, Journal of Cleaner Production, vol. 420, art. nr. 140517, 2023. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0959652623004201>. [Accessed: 04-Mar-2025]
- [75] BHP, *Pathways to decarbonisation – Episode seven: the electric smelting furnace*, BHP Insights, 2023. [Online]. Available: <https://www.bhp.com/news/bhp-insights/2023/06/pathways-to-decarbonisation-episode-seven-the-electric-smelting-furnace>. [Accessed: 05-Feb-2025]
- [76] C. Jeuland and S. Summers, *Influence of direct reduced iron on the energy balance of the electric arc furnace*, Applied Energy, vol. 88, nr. 11, s. 3671–3679, nov. 2011. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S036054421100524X>. [Accessed: 06-May-2025]
- [77] Y. Wang, *Characterization of Impurities in Different Ferroalloys and Their Effects on the Inclusion Characteristics of Steels*, Doctoral thesis, School of Industrial Engineering and Management, Materials Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, TRITA-ITM-AVL 2021:26, 2021. [Online]. Available: <https://kth.diva-portal.org/smash/record.jsf?pid=diva2:1553792>. [Accessed: 04-Mar-2025]
- [78] Swedish Forest Industries Federation, “The importance of using the biodiversity of forests,” *Forestindustries.se*. [Online]. Available: <https://www.forestindustries.se/forest-industry/forest-industry-significance/climate/the-importance-of-using-the-biodiversity-of-forests/> [Accessed: 20-Aug-2025]

[79] Ann-Marie Fransson, *Lineuniversitetet*

[80] Klimatkommunerna, *Handbok Biokol 2020 – för användare*, Rest till Bäst-projektet, 2020. [Online]. Available: <https://klimatkommunerna.se/wp-content/uploads/2021/01/handbok-biokol-2020-lacc8agupplocc88st.pdf>. [Accessed: 21-Aug-2025]

[81] E. Meier, *Wood Filter*, The Wood Database. [Online]. Available: <https://www.wood-database.com/wood-filter/>. [Accessed: 05-May-2025]

[82] Skogsstyrelsen, *Skogliga konsekvensanalyser 2022 – syntesrapport* (Rapport 2022/11), Jönköping, Sverige, 2022. [Online]. Available: <https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-20222021202020192018/rapport-2022-11-skogliga-konsekvensanalyser-2022--syntesrapport.pdf>. [Accessed: 28-Jun-2025]

8. Appendix

A. Interview form

1.

Intro

- Introduction of interviewer and project background
- Purpose of the interview
- Confidentiality and permission to record the interview
- Interview subject
 - *Name
 - *Role
 - *Experience in the metallurgical industry, biocarbon and related areas

-What process do you use

Questions EAF

- Where in the electric arc furnace process do you use coal
- What is currently used as a fossil carbon source for the various applications
 - *Is there coal that could be replaced with biocarbon, which
- General requirements for coal in an electric arc furnace
 - What is the function of coal in the various applications:
 - Goal fulfillment for coal in the various applications
 - How much coal is used in the various process steps, how much through top launching and injection**
 - *What is the heat flow in an electric arc furnace, how much does coal affect heat transfer/heating
 - Would the coal in biochar have the same coal properties as fossil coal
 - What is the maximum temperature the coal is exposed to
 - What atmosphere does the coal need to withstand
- What is there for quality requirements for coal/biochar in the various applications of the process
 - Particle size
 - Mechanical strength
 - Density
 - Calculating value
 - Total carbon amount
 - Solid carbon amount
 - Ash
 - Sulfur
 - Phosphorus

-Mechanical Strength

-Do you have any percentages around these values that are also approved

-If the requirements were to be ranked, which are most important in what order?

-Why are there these requirements for coal

-What would happen if these requirements were not met

-How many different qualities of biocarbon do you think would be needed to use biocarbon in an electric arc furnace

-Do you have access to a good process diagram for an electric arc furnace that I could use in my report

-Strategy for layering material in the scrap bin to minimize combustion of biocarbon when loading it

-Have they tested any biochar in their eaf before, where have they encountered problems

-What are the biggest obstacles to (company with biocarbon use

*expensive?

*the properties of biocarbon are not enough good

*storage problems?

-How do you usually char coal

*how much by top loading

*how much by injection

-Strategy for layering material in the scrap bin to minimize combustion of biocarbon when filling the bin

-Tested biocarbon in their eaf previously encountered problems

-What is the biggest obstacle for (company) to use biocarbon

*expensive

*biocarbon properties not good enough

*storage concerns

Conclusion

-Is there anything we haven't covered that you would like me to take with me in my work going forward?

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

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

2.

Intro

- Introduction of interviewer and project background
- Purpose of the interview
- Confidentiality and permission to record the interview
- Okay to quote?
- How do you want to appear in the report? Anonymously by name?
- Interview subject
 - *Name
 - *Role
 - *Experience in the metallurgy industry, biocarbon and related areas

- What is common fossil coal used today in metal production
 - *Where can you usually get it
- What is special about those coal sources
- Why are they only for metal production
- For which applications is that coal used
- How is fossil coal processed
 - *Combustion/purification
 - *Compaction
- How much does the reactivity change after processing
 - *What is a good reactivity
 - *How is it measured
- How reactive is unprocessed/raw fossil biomass
 - *Can raw biomass be used for metal production
 - *Why is raw fossil biomass not used
- Why is fossil coal processed
- Why is fossil coal compacted
- Most commonly used to have the coal in raw form or compacted

What is anthracite for

- Density
- Total carbon content
- Solid carbon
- Volatile carbon
- Ash skin hole
- Durableness, mechanical strength
- How is it measured
- Sulfur content
- Phosphorus content
- Porosity
- Other content

- How much/large is the requirement for ... for fossil coal when used in metal production

- *Density
- *Total carbon amount
- *Solid carbon
- *Ash
- *Sulfur
- *Phosphorus
- *Durableness/mechanical strength

-Disadvantages of fossil coal use

- Do you produce biocarbon
- What process do you use
- What biomass do you have as raw material
- *Why it

- What is included in the different requirement specifications
- What is the quality specification now for produced biocarbon
- Travel products residual flows

3.

- *What process do you use to produce biocarbon?
- How moist can raw biomass be in the process?
- What comes out as raw materials and residual products from the process?
- How much comes out of each product? Ratio?
- How long after the process does the biochar need to lie down to decrease in reactivity?
- *What raw material do you use?
- Why that?
- *What quality do you get from your biocarbon?
- C fix
- Ash
- Fluid
- Moisture
- Sulfur
- Phosphorus
- Calcium
- Nitrogen
- PH
- Particle size
- Density
- *Is there any risk that the biochar will not be reactive enough for metal manufacturing processes?

- *What different biomass resources are there from the forest?
- How much is there?
- Which of these are suitable for producing biochar for metallurgy? Why?
- *How does the quality differ between different biomass?
- *Can you make biocarbon good enough for metallurgical use from GROT?
- What in the world causes more ash and fly ash during pyrolysis?
- *How does bark beetle infested biomass affect the quality of biocarbon?
- *What is the reactivity of the biomass?
- *Does fast-growing forest have more phosphorus in it?

- *What is on the list for the requirement specification for biocarbon from metal manufacturing?
- *Are there more requirements for biocarbon than for fossil coal?

4.

- *Who is competing for the Swedish biomass?/biocarbon?
- What will the competitors use biomass for?
- *What would you say is the available biomass in Sweden?
- *What can the forest industry offer?
- *What are the different types of biomass?
- How much is there?
- Where in the country is it found?
- Which of these types are for metallurgical use? Why?
- What does it look like for GROT?
- *How do you handle the grot?
- *Take care of? South? North?
- *What in the grot makes it more ash during pyrolysis? Only dirt and sand?

- *How much forest do we harvest in Sweden today as a percentage?
- *What does the handling of harvested material look like in Sweden today?
- When is harvested material collected after harvesting?
- *What does the flow look like, where does the raw material go?
- How much goes to what?
- What does biocarbon production look like?
- What drives the harvesting?
- Who harvests?
- *How much is the maximum sustainable extraction in percent for Sweden in order not to contribute to negative CO2 emissions?

- *What threatens biomass?
- Climate
- Bark borers

- How does the biomass/biocarbon become a raw material infested with bark borers?
When the tree is pulverized, does it become any good biocarbon?

*What is the reactivity of biomass?

-How do you handle it?

*What quality of biocarbon can you get?

*What types of biocarbon are there?

Do fast-growing forests have more phosphorus?

*What do different biomasses look like in terms of the amount of:

-Sulfur

-Phosphorus

-Nitrogen

-Calcium

-Moisture

-Particle size

-Ash

-Price

-Calorific value

