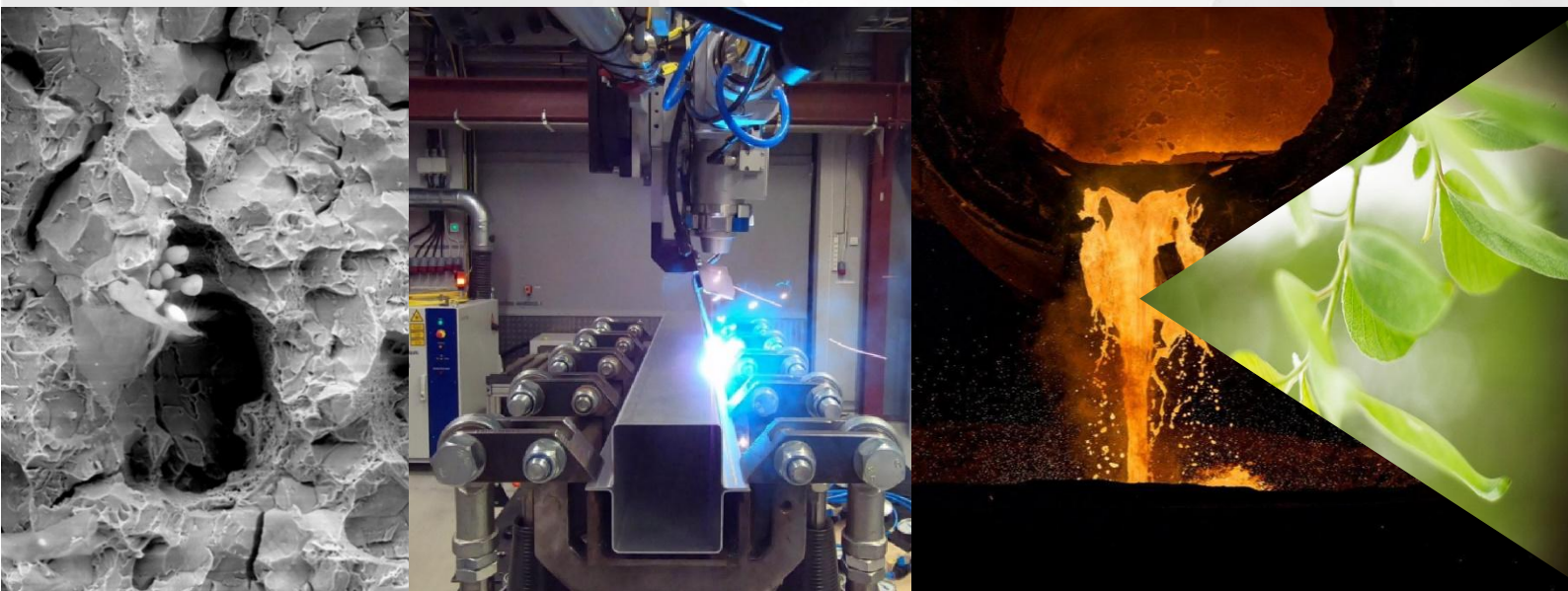




Final report HåBiMet – Technical Perspective

Tova Jarnerud Örell, Erland Nylund

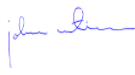
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Research Report

Open report

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Final report HåBiMet – Technical Perspective

Tova Jarnerud Örell, Erland Nylund

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Customer value

The *HåBiMet – Technical perspective* project explored technical feasibility of using biocarbon as a sustainable alternative to fossil coal in Swedish metallurgy. The study identified key technical requirements, assessed biomass availability, and engaged stakeholders across sectors to support the development of a sustainable biocarbon value chain. Key results contributing to customer and societal value:

- Defined biocarbon specifications for key metallurgical processes: Electric Arc Furnace (EAF), Tunnel Kiln (TK), and Submerged Arc Furnace (SAF).
- Demonstrated that Swedish biocarbon can meet many technical needs.
- Identified phosphorus content as a key challenge.
- Mapped biomass supply potential and industry demand.
- Supported new project proposals and cross-sector collaboration.
- Contributed to climate goals and several UN Sustainable Development goals.

Abstract

The *HåBiMet – Technical perspective* project explores the feasibility of replacing fossil coal with biocarbon in Swedish metallurgical processes. As Sweden's steel industry transitions towards fossil-free production, carbon remains essential in several applications, including as reducing agent and alloying element. Biocarbon, derived from sustainably sourced biomass, offers a promising fossil-emission-free alternative.

The feasibility study assessed the technical requirements of the steel industry, evaluated the quality and availability of Swedish biomass, and identified key challenges and opportunities for scaling up biocarbon use. The project involved literature reviews, stakeholder interviews, workshops, and a master's thesis focused on biocarbon applications in metallurgy.

Findings show that biocarbon can meet many technical specifications in the processes included in the study; electric arc furnaces, tunnel kilns, and submerged arc furnaces. However, phosphorus content remains a critical barrier for certain applications. The study also revealed that biocarbon for metallurgy and soil improvement have different requirements, reducing competition and enabling complementary uses.

The project concludes that biocarbon has strong potential to support Sweden's climate goals and industrial innovation. Realizing this potential will require continued research, policy development, and cross-sector collaboration to build a sustainable and scalable biocarbon value chain.

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1 Background

Sweden's steel industry is undergoing a major transformation as it moves toward fossil-free production methods, primarily through the adoption of electricity- and hydrogen-based technologies. Flagship initiatives such as HYBRIT and Stegra are leading the way in replacing coal-based blast furnaces (BF) with electric arc furnaces (EAFs) powered by green hydrogen. However, even in a future where hydrogen replaces fossil fuels for reduction processes, carbon will still be required in several metallurgical applications—particularly as a reducing agent, alloying element, and process aid.

This continued need for carbon presents both a challenge and an opportunity. To meet climate targets and reduce dependence on fossil coal, the industry must find sustainable alternatives. One of the most promising options is biocarbon—solid carbon-rich materials derived from biomass through thermochemical processes such as pyrolysis. When produced from sustainably sourced biomass, biocarbon can significantly reduce the net greenhouse gas emissions associated with metallurgical processes.

Despite its potential, the market for metallurgical grade biocarbon is still in an early stage of development. While the technical feasibility of producing biocarbon is well established, large-scale deployment is limited by several factors: lack of standardization, uncertain supply chains, competition for biomass from other sectors (e.g., energy, agriculture, chemistry), and limited understanding of the specific quality requirements for different metallurgical applications. To address these challenges, the HåBiMet – Technical perspective project was launched as a feasibility study under the *Impact Innovation* program, supported by the Swedish Energy Agency, Formas, and Vinnova. The project brings together a diverse consortium of stakeholders—including research institutes, universities, biocarbon producers, metal producers, and forestry actors—to explore the technical conditions for scaling up biocarbon use in Swedish metallurgy.

The *HåBiMet – Technical perspective* project takes a systems perspective, recognizing that the successful integration of biocarbon into the metallurgical value chain requires coordination across multiple sectors. It aims to map the technical requirements of the steel industry, assess the availability and quality of biomass resources, and identify synergies with other industries such as district heating and agriculture. By doing so, HåBiMet seeks to lay the groundwork for a robust, sustainable, and scalable biocarbon supply chain that supports Sweden's transition to a fossil-free industrial future.

1.1 Overview

Biocarbon - Biocarbon is not a single, uniform product, it encompasses a wide range of carbon-rich materials derived from various biomass sources and production technologies. Depending on the feedstock and process, biocarbon can differ significantly in its properties and applications.

Terminology - There are many terms used to describe biogenic carbon, including: biocarbon, biochar, biocoal, biocoke, biogenic carbon, biographite, carbonized biomass, char, charcoal, circular biocarbon, green carbon, renewable carbon. This diversity in terminology can sometimes create confusion in communication and classification.

Production methods - Biocarbon can be produced through several thermochemical processes, such as torrefaction, hydrothermal carbonization (HTC), pyrolysis, and gasification.

Each method yields biocarbon with distinct physical and chemical characteristics suited to different industrial uses.

Feedstock variety - A wide range of biomass can be used to produce biocarbon, including: wood and forest residues, agricultural waste (e.g., straw, husks), sludge, fruit and vegetable waste (e.g., orange peels), nut shells (e.g., coconut, hazelnut), algae. This flexibility makes biocarbon a promising material for circular economic strategies and low-carbon industrial applications.

Comparative properties and challenges of biocarbon versus fossil coal

Fossil coal and metallurgical coke exhibit significantly higher energy density than biocarbon, a factor that contributes to their widespread industrial use. One of the key distinctions lies in their physical structure: fossil coal has undergone millions of years of geological compression, resulting in the collapse of original plant cell walls and a bulk density typically ranging from 700 to 800 kg/m³. In contrast, biocarbon—such as biocoal—retains a more porous structure, with a considerably lower density of approximately 200 to 250 kg/m³.

Biocarbon is also more chemically reactive than fossil coal. This increased reactivity is primarily attributed to its higher porosity, which exposes a greater surface area to the surrounding environment. While this property can enhance performance in certain metallurgical applications, it also introduces handling and storage challenges. Currently, biocarbon is not produced at industrial scale, and its cost is often several times higher than that of fossil coal. Additionally, the compaction process used to densify biocarbon often involves organic binders. These binders can be susceptible to microbial activity, such as mold growth, which may initiate exothermic reactions and localized heating. Furthermore, moisture heterogeneity within biocarbon particles can lead to internal moisture migration, and in poorly ventilated environments, this can exacerbate the risk of spontaneous heating. These factors must be carefully considered in the design of storage and handling systems for biocarbon in industrial settings¹.

1.2 Literature Review

1.2.1 Global context and drivers

The global metallurgical industry, particularly steelmaking, is under pressure to decarbonize due to its significant contribution to CO₂ emissions – accounting for around 7% of global energy sector emissions². **Sweden and Finland** are at the forefront of integrating biocarbon into green steel initiatives. Companies like SSAB and HYBRIT are exploring hydrogen-based reduction but also testing biocarbon as a traditional or complementary reductant and for carburization. **Norway** has a strong presence in the silicon and ferroalloy industries, which traditionally rely on fossil carbon sources such as coal, metallurgical coke, and petroleum coke for carbothermic reduction in submerged arc furnaces (SAF). These processes are highly carbon-intensive, with direct CO₂ emissions ranging from 0.9 – 1.3 kg CO₂/kg Mn alloy and up to 5 kg CO₂/kg Si. To reduce emissions, Norwegian producers have begun integrating biocarbon, particularly charcoal, into metallurgical processes. Targets were set to 25-40% biocarbon substitution by 2023 in silicon and ferroalloy production. Norway's metallurgical sector is well-positioned to lead in low-carbon metal production, thanks to abundant biomass resources, strong environmental policies, and advanced research infrastructure³. **Germany** is advancing the use of biocarbon to reduce emissions in BF's, sintering, and EAF's. Biomass sources include forestry and agricultural residues, processed via pyrolysis or torrefaction.

Canada has abundant forestry residues and is actively researching biocarbon as a metallurgical reductant. The country is also exploring biocarbon electrodes for use in EAFs and aluminum smelting, although challenges remain in matching the performance of fossil-based materials. **Australia's** metallurgical sector is exploring biocarbon from native hardwoods and agricultural residues. The country is also investigating co-firing of biocarbon in rotary kilns and BFs. **China and India** are major steel producers and are beginning to explore biocarbon options. Projects in India have tested sugarcane bagasse-derived biocarbon in sponge iron production, while China is evaluating bamboo and rice husk biocarbon for sintering and coke replacement⁴.

1.2.2 Towards Carbon Neutral Metals (TOCANEM) – Finland's Industrial Decarbonization Initiative.

The program *Towards Carbon Neutral Metals (TOCANEM)* is a national Finnish initiative aimed at decarbonizing the metals industry, one of the country's most emission-intensive sectors. A central research focus within TOCANEM is the development and integration of biocarbon as a sustainable alternative to fossil-based carbon in metallurgical processes. TOCANEM explores the use of biomass-derived carbon through pyrolysis and other thermo-chemical processes. Research led by VTT Technical Research Centre of Finland investigates the pyrolysis behavior of various biomaterials to produce high-quality biocarbon suitable for industrial applications⁵. The aim is to replace fossil reductants in smelting and reduction processes while utilizing pyrolysis gases for energy recovery or further processing. Biocarbon is considered a key enabler for reducing process emissions in the metals sector. Its integration supports Finland's national carbon neutrality target (2035) and aligns with EU climate policy. The program also emphasizes digital modeling of material behavior and process integration, enhancing the feasibility of biocarbon use in existing industrial systems⁶. Despite its potential, biocarbon faces challenges related to i) Process scalability, ii) Economic competitiveness, and iii) Consistency in feedstock supply and quality. These issues are being addressed through pilot-scale testing and cross-sector collaboration within the TOCANEM consortium. Biocarbon research within TOCANEM contributes to the broader goal of fossil-free metallurgy by combining material innovation, circular economy principles, and industrial piloting. Continued development is essential to overcome technical and economic barriers and to enable large-scale deployment.

1.2.3 Metallurgical Biocarbon in Brazil: Research, Applications, and Challenges

Brazil is one of the world's largest producers of biomass, generating over 597 million tons of agricultural and forestry residues annually. Key sources include sugarcane bagasse and straw, eucalyptus wood residues, coconut shells, rice husk and corn stover⁷. Brazil has a long-standing tradition of using biomass-based carbon in metallurgy, particularly in the production of pig iron. Unlike most industrialized nations that rely on fossil-based coke, Brazil utilizes charcoal derived from planted eucalyptus forests, making it a global leader in low-carbon iron production. This practice aligns with Brazil's broader climate goals and commitment to sustainable industrial development.

Recent research has focused on improving the mechanical strength, reactivity, and carbon content of biocarbon to meet the stringent requirements of metallurgical applications. The conversion process and feedstock selection are critical to achieving consistent quality and performance.

Brazil's metallurgical sector uses biocarbon in i) BF for pig iron production, ii) EAF as reducing agent or carburizer, and iii) Ferroalloy production. The use of charcoal in these processes has shown to significantly reduce CO₂ emissions with some estimates suggesting a 70 – 90% reduction compared to fossil-based alternatives⁸.

The country already uses charcoal (a form of biocarbon) in its pig iron industry, making it a global leader in biomass-based metallurgy. However, the sustainability of charcoal production is under scrutiny, and there is a push toward more efficient and environmentally friendly biocarbon technologies. The transition to biocarbon supports Brazil's climate goals and offers economic benefits by creating value from agricultural waste. It also reduces dependency on imported fossil fuels. However, large-scale adoption must consider land use, biodiversity, and food security. Sustainable sourcing and certification systems are essential to ensure that biocarbon production does not lead to deforestation or other negative environmental impacts⁹.

2 Project Overview

The project *Hållbart Biokol för Metallurgisk användning (HåBiMet) – Technical perspective* explored the feasibility of using sustainable biocarbon as a substitute for fossil coal in metallurgical processes, particularly in the steel industry. It was conducted as part of the Impact Innovation research program Swedish Metals and Minerals – a joint initiative by the Swedish Energy Agency, Formas, and Vinnova. Funding was obtained through the call “Impact Innovation: Feasibility studies within Technological Action Area in the program Metals and Minerals” and received additional financial support from Swerim's Metallurgy Program Council. The project consortium consisted of:

- Swerim AB (coordinator)
- Energiforsk AB
- Envigas AB
- Höganäs AB
- Luleå University of Technology (LTU)
- Swedish University of Agricultural Sciences (SLU)
- Vargön Alloys AB

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

2.1 Motivation

Even with the transition to electricity- and hydrogen-based steel production, carbon remains essential in metallurgy, for example, as an alloying element. Biocarbon from sustainably sourced biomass is a promising alternative to fossil coal, offering a way to reduce net greenhouse gas emissions. Although the technology to produce biocarbon exists, the market for metallurgical grade biocarbon is still in its early stages. A deeper understanding of the current state, technical maturity, and barriers is needed to support Sweden's metal industry with sustainable biocarbon.

2.2 Challenges Addressed and Objectives

The overall objective of the feasibility study was to define and characterize the steel industry requirements for biocarbon, assess the potential contributions from the forestry sector, and to examine the technical specifications and needs for various applications within steel production. Specific objectives of the study were:

- Map the technical requirements of the steel industry for biocarbon.
- Identify what the forestry and biocarbon production sectors can offer.
- Investigate technical needs for various metal industry applications.
- Identify barriers and opportunities for scaling up biocarbon use.
- Understand the broader system, including other industries interested in biomass and biocoal (e.g., energy, chemicals, agriculture).
- Build a cross-sector consortium involving forestry, energy, agriculture, and metallurgy.

The overarching goal was to accelerate the green transition in industry by supporting the shift from fossil coal to sustainable biocarbon.

Sustainability goals

The project aligns with several UN Sustainable Development Goals (SDGs) including:

- Gender equality (Goal 5)
- Affordable and clean energy (Goal 7)
- Resource efficiency (Goal 8.4)
- Industrial innovation (Goal 9.4)
- Sustainable consumption and production (Goal 12)
- Climate action (Goal 13)

2.3 Work Plan and Execution

The project was structured as a feasibility study running from November 1, 2024, to June 30, 2025. This section presents how the project plan was divided into work packages, linked activities, and when they were completed. Communication and dissemination efforts related to the project are also discussed.

2.3.1 Work Packages

The feasibility study was divided into five work packages, presented in Table 1. *HåBiMet – Technical perspective* was conducted as one out of three concurrent HåBiMet-projects, and there were considerable synergies in workshop and seminar activities. Seminars and workshops were coordinated by Erland Nylund from Swerim, and Anna Steorn from Albaeco.

An MSc thesis worker (Saga Grevarp, KTH) was recruited to form part of the project, conducting a master thesis project “*Sustainable biocarbon for metallurgical application. Investigation of the enablers and barriers to sustainable biocarbon – A case study for the Swedish metal industry*” (Appendix 3) covering several of the research aims of the overall project. Interviews outlined in Table 1 were conducted by Saga Grevarp.

Table 1- Description of work packages.

Work Package	Description	Start Date	End Date	Completed activities
1. Project Management	Swerim coordinated and documented all project activities, organized meetings, wrote minutes, monitored the budget, and reported to the Impact Innovation program office. All partners participated in meetings, tracked financial status, and contributed to the final report.	2024-11-01	2025-06-30	• Monthly project consortium meetings • Project plan established in November • Workshop and seminar program established in January • Supervision of MSc thesis student • Creating a project website • Reporting to Vinnova and Impact Innovation
2. Literature Review of Previous Work	Literature review to identify existing work in Sweden and internationally. Partners summarized relevant literature and present findings in a workshop.	2024-12-01	2025-05-31	• Section 1.2, MSc thesis • Orientation seminar, 27 participants, 30/1
3. Workshops and Dialogue	Webinars and workshops, including internal and external sessions, to raise awareness and evaluate biocarbon societal value. A final seminar summarizing project results.	2024-12-01	2025-06-30	• Crash course in metallurgy, 25 participants – 21/1 & 23/1 • Webinar for the energy sector, 39 participants – 19/2 • Sustainability Compass workshop, 16 participants – 9/4 • Concluding seminar with open discussions, 38 participants – 13/5
4. Mapping Supply and Demand	Mapping of available biomass/biocarbon in Sweden and the steel industry needs. Compare specifications with other uses and assess competition and drawbacks.	2025-01-01	2025-04-30	• MSc thesis work • Orientation seminar • Literature review • 5 Explorative interviews • 21 Semi-structured interviews
5. Developing a Full-Scale Project Proposal and Consortium	Form at least one consortium and develop a project plan for continued research.	2025-02-01	2025-06-30	“HåBiMet - Safe management” (submitted 30/4) ”HåBiMet – District heating”, work in progress

2.3.2 Communication and Dissemination

Bringing together a wide range of perspectives and experiences was a key goal throughout the project’s workshops and interviews. To support this, a shared communication strategy was used across all three HåBiMet projects. A dedicated webpage (www.swerim.se/habimet) served as the central hub for sharing results and promoting upcoming events. Visitors could

sign up for the HåBiMet newsletter and register for seminars and workshops directly through the site. Moreover, Swerim's official website announced some of the activities.

LinkedIn played a central role in outreach, with regular updates about project milestones – like the initial orientation seminar, a webinar aimed at the energy sector hosted by Energiforsk, and the concluding seminar. This mix of public-facing communication, established channels, and personal invitations helped attract a diverse group of participants.

In spring 2025, more than 60 individuals took part in project activities. These included representatives from universities, research institutes, steel and alloy producers, energy companies, biocarbon producers, technology developers, raw material suppliers, foresters and forest industries, and industry organizations.

Toward the end of the project, early findings and insights was presented as an academic poster at the European Biomass Conference and Exhibit (EUBCE) in Valencia. In addition, the MSc thesis was presented in a public defense at KTH – Royal Institute of Technology on June 19th.

2.4 Deliverables

In the project application, several key deliverables were outlined. In addition to the planned outputs, an MSc thesis; *Sustainable biocarbon for metallurgical application. Investigation of the enablers and barriers to sustainable biocarbon – A case study for the Swedish metal industry* and a project report; *Comparing methods for estimating biocarbon demand in EAF processes* was produced. Altogether, seven deliverables are included in this report, as summarized in Table 2.

Table 2 - The deliverables of the prestudy.

Deliverables	Can be found in
<i>A report summarizing the work done.</i>	Swerim-2025-222
<i>A webinar targeted at the energy sector</i>	Section 3.1.3
<i>At least one project consortium and project plan for further application</i>	Section 6
<i>Compendium from the orientation seminar</i>	Appendix 1
<i>Compendium from the concluding seminar</i>	Appendix 2
<i>MSc thesis report: Sustainable biocarbon for metallurgical application. Investigation of the enablers and barriers to sustainable biocarbon – A case study for the Swedish metal industry</i>	Appendix 3
<i>Comparing methods for estimating biocarbon demand</i>	Appendix 4 Swerim-2025-229

3 Results

This section outlines the results derived from the project's seminar and workshop sessions.

3.1 Workshops and Seminars

On January 21st and 23rd, a crash-course in metallurgy was held to provide basic knowledge for those without a background in the field. The aim was to facilitate future work and ensure that everyone speaks the same language. On January 30th, an orientation seminar was held to share experiences within the project group. On April 9, a workshop employing the sustainability compass method was conducted to explore the potential social impacts and benefits of proposed follow-up projects. Subsequently, on May 13, a concluding seminar was held to present and discuss preliminary findings. This seminar was open to the public and promoted via the HåBiMet project website, Swerim's website, LinkedIn, and through direct invitations to members of Swerim's metallurgy program council.

The key outcomes from these activities are summarized in the following section.

3.1.1 Crash-Course

The HåBiMet consortium brings together a broad group of stakeholders, not all of whom have a background in the metal industry. Among the participants are engineers, economists, agronomists, and biologists, to name a few. Ahead of the orientation seminar, a crash course was therefore held on the role of carbon in metal production, both historically and in the future. This provided a shared foundation for understanding the function and challenges of metallurgical biocarbon. The crash course was held once digitally (January 21) and once physically at Swerim in Kista (January 23). In total, about 25 project participants took part.

3.1.2 Orientation Seminar

At the orientation seminar, held on January 30, project participants and invited speakers shared their experiences related to biocarbon, aiming to create a comprehensive overview and map out where we currently stand and where future research efforts should be focused. The seminar began with a presentation on planetary boundaries and system transformation, followed by insights into the use of biogenic carbon in various parts of the metal industry, as a soil enhancer, as well as perspectives from biocarbon producers and the bioenergy sector, and the conditions for large-scale production of biogenic carbon from an economist's point of view. The seminar was divided into three blocks, and the presentations are summarized below. The presentation slides can be found at: <https://www.swerim.se/habimet/publikationer>, as well as in Appendix 1 in this report.

Block 1 – Overview, Biomass and Metallurgy

The first block of the HåBiMet seminar focused on the current state of knowledge regarding biomass resources and biocarbon production for metallurgical applications. The session provided a multidisciplinary overview, integrating environmental systems thinking, biomass supply chains, and technical performance in metallurgical processes.

1. Planetary Boundaries and System Transformation

Presenters: Anna Steorn & Louise Hård af Segerstad (Albaeco)

Introduced the planetary boundaries framework and the concept of a “safe and just operating space” for humanity.

Emphasized the need for systemic transformation in industrial sectors to align with ecological limits.

2. Production Processes for Biocarbon & Producing Areas for Biomass / Supplying Biocarbons to the Steel Industry from Agricultural Residues

Presenters: Elisabeth Wetterlund (LTU), Erland Nylund (Swerim)

Compared torrefaction, pyrolysis, and hydrothermal carbonization (HTC) for biocarbon production.

Pyrolysis at >500 °C was identified as the only method capable of producing biocarbon with >80–90% carbon content, suitable for metallurgical use.

Feedstock options include forestry residues, sawdust, bark, lignin, and agricultural residues.

Quantified biomass requirements for the Swedish steel industry and assessed land use implications for branches and tops.

Identified technical and economic constraints, including low yields in slow pyrolysis and the need for integrated supply chain development.

3. Outlook Biomass in the Energy Sector

Presenter: Johnny Kjellström (Svebio)

Bioenergy accounted for 40% of Sweden's final energy use in 2023.

Discussed sectoral distribution of bioenergy use and the role of biopower and biothermal systems.

Highlighted rising biomass prices due to geopolitical factors and increased demand.

Reviewed EU policy developments (e.g., RED II, CBAM, ETS) and their implications for biomass markets.

4. Technical Trials of Biocarbon in Metallurgy

Presenter: Chuan Wang (Swerim)

Summarized pilot and industrial-scale trials of biocarbon in BF, EAF, and cupola furnaces (CF).

Demonstrated successful substitution of fossil carbon with biocarbon (e.g., charcoal, hydrochar, torrefied biomass) without adverse effects on process performance.

Identified key material properties for metallurgical applications: high fixed carbon, low ash, appropriate reactivity, and mechanical strength.

Ongoing projects (e.g., Bio4BF, BioReSteel) are scaling up biocarbon use and testing new feedstocks and briquetting technologies.

Block 2 – Use of Biocarbon and Technical Experiences

1. Position, Requirements and Wishes for Metal Industry's use of Carbonaceous Materials

Presenter: Gunnar Ruist (GRu Konsult)

Applications: Carbon is used in steelmaking for alloying, slag foaming, and reduction of oxides (e.g., in EAF and ferrochrome production). Key Requirements:

- Reactivity: Must be balanced—not too fast.
- Density & Grain Size: Affects handling and process efficiency.
- Composition: Low levels of P, S, alkalis, and ash are critical.
- Standardization: Needed for consistent quality and safe handling.

2. Biocarbon in the Ground – an Introduction

Presenter: Cecilia Sundberg (SLU)

- Biochar is the term commonly used for biocarbon used in soil.
- Carbon Dioxide Removal Potential: 1 kg biochar ~ 3 kg CO₂ sequestered.
- Soil Benefits: Improved water retention, potential yield increases (especially in tropical soil), and pollutant filtration.

- Uncertainties and variability: Effects on N₂O/CH₄ emissions, crop yield, and long-term stability vary by soil type and biochar quality.
- Certification: European Biochar Certificate (EBC) sets standards for feedstock, production, and application.
- Key quality criteria for soil application: heavy metals.
- Key indicator for carbon storage potential: low H/Corg ratio = high persistence.
- Plant nutrients such as S and P are normally seen as beneficial, as they support plant growth.
- Urban greening is the main biochar market in Sweden.

3. HTC Upgrading

Presenter: Yu-Chiao Lu (KTH, BioReSteel project)

Main roles of carbonaceous materials in metallurgical processes: fuel, reduction, carburization

Hydrochar Production: HTC at 180–250 °C, 2–10 MPa; suitable for wet biomass.

Advantages:

- High mass yield (~50%)
- Easier densification than charcoal
- Nutrient recycling (NPK)

Challenges:

- Some feedstock yields low fixed C and high ash, S, P

Performance in EAF:

- Carburization: Fixed carbon content is key; hydrocarbon has lower fixed C than charcoal but can be improved via pyrolysis.
- Addition method: Top-charging yields better carbon utilization than injection due to lower combustion and addition losses.
- Slag foaming: Self-reducing briquettes (hydrochar + metal oxides) show promising foaming behavior.

4. Utilizing Biocarbon in the Metallurgical Industry and its Technical Specifications

Presenter: Konstantinos Rigas (Envigas AB)

The production of biocarbon is commonly achieved through pyrolysis. For metallurgical applications, key requirements such as low ash content and minimal sulfur levels strongly influence the choice of raw material. Among the available options, stem wood from pine and spruce has been proven to be the preferred feedstock, as it consistently meets these quality standards.

Envigas' biocarbon properties:

- Fixed carbon: 85–95% (typically 90-95%)
- Ash: <1-10 % (typically <1.5%)
- Volatile matter: 2–10%
- Sulfur: 0.1–1%, P: 0.015–0.05%
- Bulk density: >500 kg/m³

Applications: Biocarbon can be used in a range of metallurgical applications and can potentially substitute metallurgical and other grade coke in the respective metalmaking and steelmaking processes. Typically, biocarbon can be used in charging, injection, recarburization in EAF, charging in SAF, in TiO₂ production, in induction furnaces, in casting, in production of biographite etc.

Customization: Briquettes, pellets, and agglomerates tailored to customer needs.

Projects: Bio4SAF, BioChargeEAF, R-Carbon4EAF, M-Graphite.

5. Höganäs' Experiences with Biocarbon

Presenter: Ryan Robinson (Höganäs AB)

Processes:

- Sponge Iron: 45,000 t/year fossil carbon; 50% replaceable with biocarbon.
- EAF (Halmstad): 4,000 t/year fossil carbon; 80–100% replaceable.

Pilot Trials:

- 20% biocarbon replacement in sponge iron plant.
- EAF trials showed comparable slag foaming and alloying performance.

Biocarbon specifications for Höganäs processes:

- Fixed C: $\geq 75\text{--}85\%$
- Volatile matter: $\leq 15\%$ (sponge iron), $\leq 5\%$ (EAF)
- Ash: $\leq 10\%$, P: $\leq 0.05\text{--}0.02\%$, S: $\leq 0.5\text{--}0.4\%$
- Bulk density: $\geq 400\text{--}500\text{ kg/m}^3$

Höganäs needs 15 000 tonnes/year

6. Biocarbon for Ferrochrome

Presenter: Ludvig Ånnhagen (Vargön Alloys AB)

Process: Semi-closed SAF with high-temperature reduction of chromite.

Biocarbon Requirements:

- Low Reactivity: To reach lower reduction zone.
- High Fixed C: $>85\%$
- Low Impurities: Especially phosphorus (P) and sulfur (S)
- Low Ash and Volatiles

Challenges:

- High cost (up to $4\times$ fossil coke)
- Limited supply capacity
- High P content in some feedstocks

Block 3 – Opportunities and Policy

1. Co-Production of Biocarbon and District Heating

Presenter: Mikael Karlsson (Energiforsk)

Synergies Identified: Existing district heating infrastructure can be leveraged for biocarbon production.

Challenges:

- Matching biocarbon quality to metallurgical industry needs.
- Adapting industry requirements to current technical capabilities.
Example: E.ON's district heating model shows potential for integration.

Solutions proposed:

- Reduce emissions and fuel price risks.
- Increase flexibility and diversify production units.
- Explore carbon sink potential.

Next Steps:

- Longer test runs.
- Full-year operation trials.
- Collaboration with companies like SolörBioenergi (already producing biochar at 4 plants).

2. How Policies and Market Effects Affect Prices

Presenter: Robert Lundmark (Luleå University of Technology)

Market Fundamentals

- Markets allocate scarce resources to maximize welfare.
- Interconnected markets require a systemic perspective to understand cascading effects.

Criteria for Market Establishment

- Clear demand and differentiation from alternatives.
- Economic viability and supportive regulation.
- Scalable technology and robust infrastructure.
- Risk mitigation and competitive awareness.

Challenges for Biocarbon Market

- Economic: High costs, slow adoption, capital intensity, and competition from other decarbonization technologies.
- Technological: Process optimization and quality assurance.
- Regulatory: Need for adaptive and supportive frameworks.
- Supply Chain: Biomass availability, competition, and import pressures.

Market Modeling Insights

- A 10% demand increase from mining/metals could raise biomass by-product prices by 17–24%.
- Efficient forestry can reduce price impacts by up to 25%.
- Market structure (competition level) significantly affects price dynamics.
- Regional policy decisions can influence local price structures.

Uncertainty Considerations

- Includes parametric and structural uncertainties.
- Importance of stochastic modeling and market completeness (e.g., futures, insurance).

3.1.3 Webinar: Metallurgical Biocarbon – a Business Opportunity for District Heating?

The webinar¹⁰ was held on February 19 and explored whether metallurgical biocarbon could become a viable business for district heating systems. Biocarbon, produced via pyrolysis, generates energy-rich byproducts such as heat, gases and oils. If the excess heat from biocarbon production can be used in local district heating networks it could improve the economic viability of both biocarbon production and district heating, create new markets for byproducts, and enhance system flexibility and resource efficiency. The webinar was primarily targeted at the energy sector and was promoted through the channels of Energiforsk's innovation cluster "Gröna kolatomer" (Green Carbon Atoms) which focuses on advancing sustainable carbon solutions across industries. 39 people participated in the seminar.

3.1.4 Sustainability Compass Workshop

Jernkontoret's (the Swedish steel producers' association) *Technical area 86 – The sustainability compass* is a strategic tool developed by Sweden's steel industry to align with the UN's 17 Sustainable Development Goals (SDGs). The purpose is to help identify synergies and conflicts between sustainability goals. It supports decision-making in projects, investments and policies, and it is used in workshops and by companies to evaluate sustainability impacts systematically.

The workshop held on April 9 explored the potential social impacts and benefits of proposed follow-up projects. The session addressed topics relevant to the technical, social, and policy areas of intervention, fostering a holistic understanding of how future initiatives could contribute to sustainable development across multiple dimensions. 18 participants were invited from different sectors to cover as many perspectives as possible.

The goal was to assess how the biocarbon value chain would impact on the SDGs. The analysis focused on three key areas: occupational health and safety, regional collaboration, and techno-economic feasibility. The biocarbon value chain showed potential to contribute significantly to several SDGs:

- SDG 13 – Climate Action: Reduces greenhouse gas emissions by replacing fossil carbon.
- SDG 9 – Industry, Innovation, and Infrastructure: Supports sustainable industrial development.
- SDG 1 & 8 – Poverty Reduction and Economic Growth: Creates new income opportunities in rural areas.
- SDG 4 – Quality Education: Drives demand for new skills and specialized training.
- SDG 12 – Responsible Consumption and Production: Encourages circular use of biomass and waste.
- SDG 17 – Partnerships: Fosters cross-sector collaboration and innovation.

Despite the benefits, several risks were identified:

- SDG 15 – Life on Land: Unsustainable biomass harvesting could harm biodiversity and ecosystems.
- SDG 3 – Good Health: Dust and fire hazards in production require safety measures.
- SDG 6 & 14 – Water and Oceans: Risk of pollution if by-products are not properly managed.
- SDG 7 – Energy: Biocarbon production may reduce energy efficiency if not optimized.

The sustainability compass revealed several indirect effects:

- Positive feedback loops between education, gender equality, employment, and sustainable communities.
- Negative feedback loops could arise from overexploitation of natural resources, especially biomass, which could undermine environmental goals.

To maximize benefits and minimize risks, the following actions are recommended:

- Sustainable forestry with certification and traceability.

- Industrial symbiosis to utilize by-products efficiently.
- Regional collaboration between agriculture, forestry, and industry.
- Educational initiatives to meet emerging skill demands.

Concluding remarks from the seminar is that a well-designed biocarbon value chain can support all 17 SDGs – provided that ecological, social, and economic risks are proactively managed. Biocarbon has the potential to become a key component in Sweden’s climate transition and regional development strategy.

3.1.5 Concluding Seminar

At the concluding seminar, the lessons learned so far within the HåBiMet projects were shared. The focus was on the technical and social projects that concluded in June 2025, but the seminar also included an update from the policy perspective project, and proposals for follow-up projects were presented along with information on how new partners can join. Invitation to the seminar was published on Swerim’s website, on the HåBiMet project website, and sent to everyone who expressed interest in the project as well as to Swerim’s program council for metallurgy. 18 people participated on-site at Swerim’s premises in Kista, and an equal number followed the broadcast online.

Key findings presented at the seminar:

- Sweden’s steel industry may require 230–300 kton/year of carbon, equivalent to 400–515 kton/year biocarbon.
- Biocarbon quality varies significantly depending on feedstock and production method.
- Matching biocarbon properties (e.g., fixed carbon, ash, sulfur) to metallurgical requirements is critical.

The biocarbon market is at an early stage, characterized by:

- Small-scale production
- Limited investment
- Lack of formal standards

Stakeholders recognize the need for cross-sector collaboration and competence development.

Numerous EU and national policies influence biocarbon development, including:

- EU Bioeconomy Strategy
- RED II/III
- EU Taxonomy
- Carbon Border Adjustment Mechanism

Policy gaps and regulatory uncertainty hinder market formation and investment.

Concluding remarks from the seminar concludes are that:

- Biocarbon from forest residues has potential but improved selection and characterization to meet metallurgical specifications
- Soil improvement and metallurgical applications have distinct biocarbon requirements, reducing direct competition.
- A sustainable biocarbon value chain demands coordinated efforts across sectors, supportive policies, and targeted investments.

Recommendations:

- Develop technical standards and certification schemes.
- Support pilot projects and scale-up initiatives.
- Foster regional collaboration and knowledge sharing.
- Aligning academic programs with emerging industry needs.

3.2 Executive Summary of MSc Thesis

The Master thesis work by Saga Grevarp is summarized below.

3.2.1 Purpose

The purpose of this thesis is to explore the technical feasibility of using biocarbon as a sustainable, fossil-free alternative to fossil coal in Swedish metallurgical processes. The study aims to identify and evaluate the compatibility between the carbon quality requirements of the Swedish metal industry – specifically in EAF, TK, and SAF – and the properties of biocarbon produced from Swedish forest-based biomass. By comparing technical specifications for metallurgical biocarbon with those used in soil improvement, the thesis also investigates whether these applications compete for the same biomass resources. The work contributes to a broader understanding of the enablers and barriers to implementing biocarbon in industrial scale metallurgy and supports the transition toward a fossil-free metal industry in Sweden.

3.2.2 Method

This master thesis employed a mixed-methods approach, combining qualitative and quantitative data collection and analysis to investigate the feasibility of using biocarbon in Swedish metallurgical processes.

Research design: This study is a preliminary technological investigation aimed at mapping the requirements for biocarbon in metallurgy and comparing them with available Swedish biocarbon qualities. It includes literature review, interviews, and comparative analysis.

Data collection: Scientific articles, reports, and databases (e.g. ScienceDirect, Google Scholar, Diva) were used to gather background information on biomass, biocarbon production, and metallurgical applications in a literature review. Five exploratory interviews with stakeholders to shape the research direction, and 21 semi-structured interviews with metal producers, biocarbon producers, forestry experts, and researchers were performed. The interviews focused on technical requirements, biomass availability, and application-specific challenges. Transcripts were analyzed and used to build requirement profiles and compare them with biocarbon properties.

Analysis: Comparisons were made between fossil carbon and biocarbon, biocarbon for metallurgy vs. soil improvement, requirements vs. available biocarbon qualities (e.g. C-fix, ash content, P and S levels, particle size).

Limitations: Focused on solid biocarbon by early-stage metallurgical processes (EAF; TK; SAF). Limited to Swedish biocarbon and industrial scale applications. Only a few biomass types were evaluated due to time and resource constraints.

3.2.3 Findings and Conclusions

A summary of the findings and conclusions from the thesis *Sustainable biocarbon for metallurgical application. Investigation of the enablers and barriers to sustainable biocarbon – A case study for the Swedish metal industry* by Saga Grevarp:

Technical feasibility

- Biocarbon has the technical potential to replace fossil coal in several metallurgical processes (EAF, TK, SAF).
- Particle size, fixed carbon (C-fix), and low sulfur content are generally achievable with Swedish biocarbon.
- Phosphorus content is the most critical challenge, especially for stainless steel production.

Biocarbon vs. Fossil carbon

- Some biocarbon types match or nearly match the quality of fossil anthracite in key parameters.
- However, biocarbon is 4–5 times more expensive, has lower density and energy value, and poses handling risks (e.g., spontaneous combustion).

Biomass availability

- Sweden has significant biomass resources, especially from forest residues (e.g., branches and tops).
- Sorting out green parts (bark, leaves, needles) is essential to reduce phosphorus and sulfur levels in biocarbon.
- No biomass is currently grown specifically for biocarbon; it is sourced from residual streams.
- With improved sorting and selection, Swedish biomass can meet the many technical requirements. Residual biomass (e.g. sawdust, tops and branches) is promising but phosphorous content remains a limiting factor.

Industry readiness

- 4 out of 5 metal producers in the study found biocarbon qualities that matched their requirements.
- The most stringent requirements came from stainless steel producers.
- Some companies are open to process adaptation, while others demand fossil coal-equivalent quality.

Soil improvement vs. Metallurgy

- Biocarbon for soil improvement requires opposite properties: high ash, low density, high nutrient content, while metallurgical biocarbon should have low ash content, low phosphorus and sulphur content, high C-fix level.
- These two applications do not compete for the same biocarbon types, except in the context of carbon sequestration. The two uses are complementary, not competitive.

3.3 Biocarbon demand and supply

3.3.1 Biomass availability

There are a number of residues and side-streams from forestry and forest industries. One of the most interesting ones is the branches and tops (“grot” in Swedish) that is removed from the tree stems during harvesting. In some parts of Sweden these are collected and turned into fuel or products. There is, however, an underutilised potential for increasing the grot harvest within sustainable limits¹¹. The underutilisation is largest in northern Sweden, where there was an effort to begin harvesting grot at a large scale, which led to many foresters losing

money as fuel prices decreased and made their products uneconomical. Skogforsk notes that if these actors are to resume grot harvests, some trust needs to be rebuilt.

The agricultural sector in Sweden also produces large volumes of biomass residues, such as straw and manure. However, these do not produce biocarbon of a sufficient quality for use in most metallurgical applications, but they may satisfy demand from other use cases, such as biobased feedstocks for the chemical industry, or fuel gases.

When it comes to woody biomass, that can be suitable for metallurgical biocarbon production, Fossil Free Sweden¹² estimates that there is some potential to increase biomass harvest by 2030 and 2050. Most of this potential is the previously mentioned increase in grot harvesting, but shrubs and damaged lumber fractions are also included. The district heating sector does not anticipate a large decrease in their need for biomass. Fossil Free Sweden estimates a potential increase in grot extraction of 18–21 TWh by 2045. In that timeframe, the total bioenergy demand is expected to increase by up to around 80 TWh, but not all of this requires woody biomass.

There are woody byproduct streams large enough to supply the metal industry with biocarbon, but they are currently either left unharvested in the forest or used for heating. Heat use is mainly either smaller scale heating in the industries where they are produced (e.g. drying of lumber in sawmills) or larger scale district heating. Here, coproduction of energy and biocarbon could be one way to create a supply chain, another would be replacing the local heating needs with for instance industrial waste heat, freeing up the biomass.

3.3.2 Estimating carbon demand

A number of estimations of carbon demand on a national level, or as a per tonne of steel basis, are present in literature. Closer scrutiny showed that the difference in total Swedish demand varied greatly depending on which estimation was used. Consequently, a limited literature survey was conducted to investigate what methods could be applied, and how to construct a best estimate for total Swedish metallurgical biocarbon demand. The literature survey focused on demand in EAFs, as the new large furnaces currently under construction are the major uncertainty in these estimations.

Altogether, 62 publications were investigated more thoroughly, out of which only 26 were both accessible and contained values for carbon consumption of EAFs. The differences in estimated carbon consumption varied considerably, and there were no clear experimental determinations of upper or lower limits of carbon use for efficient steel production. However, some general principles were established. First, biocarbon demand estimations should be related to the function of the material in the furnace. The main functions are:

- a) Carburising the steel
- b) Reducing metal oxides such as FeO
- c) Generating a foaming slag which improves furnace lining longevity, and electric arc efficiency
- d) Protecting scrap from oxidation during initial smelting by producing a reducing atmosphere
- e) Heat through combustion

These functions are connected. Reduction of oxides (b) primarily occurs as carbon is dissolved in the steel (a), and subsequently reacts with the oxides, producing CO and H₂ bubbles that contribute to producing the foaming slag (c). Combustion of carbon during melting (e) produces the reducing gases that protect metal from oxidation (d).

Some of these functions can also be fulfilled by hydrogen or hydrocarbons, which make up a larger fraction of biocarbon materials. However, as hydrocarbons are more volatile, a larger share of the biocarbon materials will combust or evaporate early on in the process, preventing them from contributing to (a) – (c).

Thus, volatile contents will contribute less to the functions that cannot be easily replaced, and the fixed carbon should be used as the basis of comparison when determining how much of a biocarbon material is needed in an EAF process. This total fixed carbon should be related to the total contents of oxides to be reduced (a), as a larger oxide content will necessitate more reduction work.

It seems that in most cases, if the reduction demand is met, carburisation and foaming are also fulfilled. However, if input materials contain less carbon, more will need to be added, and of course a higher-carbon melting composition will also require more carbon with all other factors unchanged. Additionally, all factors being the same, a larger amount of slag will require more gas bubbles to achieve foaming, and thus more carbon and hydrocarbons that penetrate into the slag to form bubbles.

DRI contains both unreduced oxides and gangue oxides and thus increase both total slag amounts and the need for reductants. Additionally, H-DRI typically contains very little carbon, further increasing the carbon demand when compared to scrap based production.

Based on these insights, there are a few factors that should be taken into account when considering how much carbon is needed in an EAF:

1. Carbon content upon tapping and carbon content of charged materials
2. Total slag volumes
3. Total oxide contents needing reduction
4. C_{fix} of biocarbon material
5. Share of DRI/Scrap in charge

These five principles were used to create a model to calculate biocarbon demand on a market level based on total steel production volumes, carbon content at tap, scrap and DRI share of feedstock, and DRI reduction degree.

3.3.3 Estimations of Swedish metallurgical biocarbon demand

Some previous estimations of total biocarbon demand for the Swedish metallurgical industry are 350 kton, 1–1.5 TWh¹³ (roughly 130–190 kton), and 2.3–3 TWh¹¹ (including Stegra, 296–380 kton).

Using the model, biocarbon demand for future EAF-based steel production was calculated in a low DRI (30% of iron input) and a higher DRI (70%) scenario. Overview of results and assumptions are presented in Tables 3–4.

Table 3 – Summary of assumptions for estimating Swedish carbon demand by 2030, used for three cases – iron input consisting of 100% DRI, 70% DRI and 30% DRI.

	Case 1	Case 2	Case 3
<i>Total steel prod [kton/a]</i>	9500	9500	9500
<i>% DRI</i>	30%	70%	100%
<i>% Scrap</i>	70%	30%	0%
<i>Assumed C in scrap</i>	0.40%	0.40%	0.40%
<i>SiO₂-level in scrap</i>	2%	2%	2%
<i>Gangue in DRI</i>	5.0%	5.0%	5.0%

<i>DRI Metallization</i>	95.0%	95.0%	95.0%
<i>DRI iron oxide content</i>	4.8%	4.8%	4.8%
<i>Base slag per t steel</i>	100	100	100
<i>Tapping C content</i>	1.00%	1.00%	1.00%
<i>Biocarbon C_{fix}</i>	80%	80%	80%

As can be seen, the calculated demand is in the same range as previous estimations but varies considerably if feedstock assumptions change. An important insight is that the large steel producers (Stegra, SSAB) represent ca 80% of total demand, and so their supply of DRI and feedstock mix has great impact on biocarbon markets if they rely solely on biocarbon.

The underlying biomass needed to meet this demand can be calculated in many ways and will depend on the specific feedstock and conversion efficiencies. A rough estimate is that ca 20% of raw biomass by weight is converted into biocarbon, thus requiring between 1.25 Mton and 2.1 Mton of woody biomass.

The biocarbon demand from metal industry in Sweden 2030 in two cases calculated based on Table 3 are shown in Table 4. Carbon demand is broken down according to the contribution from different functions. Stoichiometric carbon is that needed for reduction work, related to FeO contents. Gangue-related demand relates to increased total slag volumes. Losses are the increased demand due to volatile components in biocarbon that are evaporated or combusted. Höganäs and Vargön are the estimated demand from non-EAF processes, based on current carbon consumption and assumed replacement share. Mining industry is not included.

Table 4– Calculated biocarbon demand from metal industry in Sweden 2030 in three cases.

		Case 1	Case 2	Case 3
	Biocarbon demand [kton]			
<i>EAF</i>	Stoichiometric	28	66	94
	Alloying	86	105	119
	Gangue-related	77	84	89
	Losses	48	64	76
<i>Tunnel kiln</i>	Höganäs	33	33	33
<i>SAF</i>	Vargön	10	10	10
	Tot [kton]	281	361	421
	Tot [TWh]	2.3	3.0	3.5

Using energy units, 2.3–3.5 TWh of biocarbon is required, representing about 15% of the unused sustainable potential of grot harvesting in Sweden. As pyrolysis processes can achieve a yield of carbon of ca 50% on an energy basis, there seems to be woody biomass enough to meet this demand in the foreseeable future. This does not, however, take into account the demand from other industries as they transition away from fossil hydrocarbons.

4 Discussion

The *HåBiMet – Technical perspective* project has highlighted both the promise and complexity of integrating biocarbon into Swedish metallurgical processes. From a technical standpoint, the study confirms that biocarbon can fulfill many functional requirements in electric arc furnaces, tunnel kilns, and submerged arc furnaces. However, the variability in biocarbon quality— particularly with respect to phosphorus and sulfur content— poses a

significant challenge. While fixed carbon levels and particle size can be optimized through feedstock selection and processing, phosphorous remains a limiting factor, especially for high-grade steel applications. This calls for further research into feedstock sorting, pretreatment, and possible new production technologies.

Economically, the high cost of biocarbon – currently around 4 times that of fossil coal – remains a major barrier to adaption. The lack of industrial scale production, standardization, and long-term supply agreements further complicates market development. Moreover, competition for biomass from other sectors such as energy and agriculture adds pressure to supply chains and may influence pricing and availability. These factors underscore the need for coordinated investment, policy support, and cross-sector collaboration to scale up production and reduce costs.

The project also revealed the importance of a systems perspective. Biocarbon is not just a technical material but part of a broader value chain that intersects with forestry, energy, agriculture, and climate policy. Synergies with district heating and soil improvement offer opportunities for cascading use and resource energy efficiency, but they also require careful coordination to avoid trade-off, such as biodiversity loss or reduced energy efficiency. The project's workshops and stakeholder engagement activities demonstrated the value of cross-disciplinary dialogue in identifying the opportunities and risks.

Finally, the regulatory landscape plays a pivotal role. While EU and national policies provide a framework for sustainable carbon use, gaps remain in certification, standardization, and market incentives. A clearer and more supportive policy environment is essential to unlock investment and accelerate the transition to fossil-free metallurgy.

5 Conclusions

The *HåBiMet – Technical perspective* project concludes that biocarbon has strong potential as a sustainable alternative to fossil coal in Swedish metallurgy. The feasibility study has mapped the technical requirements of the Swedish steel industry, assessed the availability and quality of biomass resources, and identified challenges and opportunities for scaling up biocarbon use. Key conclusions include:

Technical viability – Biocarbon can meet many of the metallurgical requirements for the furnaces included in the study; electric arc furnaces, tunnel kilns, and submerged arc furnaces. Fixed carbon content, particle size, and low sulfur levels are generally achievable with Swedish biomass. However, phosphorus content remains a critical barrier, especially for stainless steel production.

Biomass potential – Sweden has substantial biomass resources, particularly from forest residues. Improved selection and characterization can help meet metallurgical specifications.

Industry readiness – Most of the metal producers in the study have found biocarbon qualities that match their needs. While some are open to adapting processes, others require biocarbon to match fossil coal performance. However, the higher price of biocarbon remains a challenge.

Market maturity – The biocarbon market is still at an early stage, characterized by small-scale production, limited investment, and a lack of formal standards. Cross-sector collaboration and competence development are essential to accelerate market formation.

Complimentary applications – Biocarbon for soil improvement and metallurgy have different requirements and only partially compete for the same biomass types. This opens opportunities for integrated value chains. Woody biomass is valued both for soil improvement and metallurgy, whereas more nutrient-rich biomasses such as agricultural residues and sewage sludge are less suitable for metallurgical applications.

Policy and regulations – Numerous EU and national policies influence biocarbon development and use. However, regulatory uncertainty and policy gaps hinder investment and large-scale deployment.

Sustainability impact – Biocarbon has the potential to contribute to multiple UN Sustainable Development Goals (SDG), including climate action, industrial innovation, and regional development. However, risks related to biodiversity, health, and water management must be proactively addressed.

In conclusion, biocarbon has the potential to play a key role in Sweden's climate transition and industrial innovation. Realizing this potential will require continued research, policy development, and collaboration across sectors to build a robust, sustainable, and scalable biocarbon value chain.

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9 Appendices

Appendix 1: Presentation from orientation seminar

Appendix 2: Presentation from concluding seminar

Appendix 3: Sustainable biocarbon for metallurgical application.
Investigation of the enablers and barriers to
sustainable biocarbon – A case study for the
Swedish metal industry.

MSc thesis by Saga Grevarp

Appendix 4: Comparing methods for estimating biocarbon
demand in EAF processes

Appendix 1:

Presentation from orientation seminar

Compendium from HåBiMet seminar on 31/1 – 2025

HåBiMet consists of three projects within the strategic innovation program Impact Innovation. HåBiMet aims to investigate what prevents a sustainable market for metallurgical biochar from emerging in Sweden, and what kind of initiatives could promote it. The three projects address challenges from different perspectives; technically, socially, and policy-wise. This supports Sweden's transition to fossil-free production methods and promotes collaboration between different industries to reduce climate impact.

HåBiMet is carried out within the Impact Innovation programme Swedish Metals & Minerals, a joint initiative by the Swedish Energy Agency, Formas and Vinnova

This compendium contains presentations from the Current Situation Seminar that was organized in the project on 30/1 – 2025. The seminar aimed to provide an overview of the state of knowledge regarding the use and production of biochar for metallurgical use, as well as for certain other applications. The exchange of knowledge served as a basis for the continued collaboration in the project. The seminar and compendium are divided into three blocks:

Seminar block 1 – Overview, biomass and metallurgy

- I. **Planetary Boundaries and System Transformation** – *Anna Steorn and Louise Hård af Segerstad (Albaeco)*
- II. **Production processes for biocarbon & producing areas for biomass / Supplying biocarbons to the steel industry from agricultural residues** – *Elisabeth Wetterlund (LTU), Erland Nylund (Swerim)*
- III. **Outlook biomass in the energy sector** – *Johnny Kjellström (Svebio)*
- IV. **Technical trials biochar in metallurgy** – *Chuan Wang, (Swerim)*

Seminar block 2 – Use of biochar and technical experiences

- V. **Position, requirements and wishes biochar in the metal industry** – *Gunnar Ruist (GRu consultancy)*
- VI. **Biocarbon in the ground – an introduction** – *Cecilia Sundberg (SLU)*
- VII. **HTC upgrading** – *Yu-Chiao Lu (KTH)*
- VIII. **Utilizing biocarbon in the metallurgical industry and its technical specifications** – *Konstantinos Rigas (Envigas)*
- IX. **Höganäs' experiences with biocarbon** – *Ryan Robinson*
- X. **Biocarbon for ferrochrome** – *Ludvig Ånnhagen*

Seminar block 3 – Opportunities and policy

- XI. **Co-production of biochar-district heating** – *Mikael Karlsson, (Energiforsk)*
- XII. **How policies and market effects affect prices** – *Robert Lundmark (LTU)*

Block 1 – Överblick, biomassa och metallurgi



Planetary boundaries and system transformation



30 January 2025

Louise Hård af Segerstad and Anna Steorn
Albaeco

Albaeco

Independent organization with broad expertise in sustainable development

Co-founder of Stockholm Resilience Centre

Experts in social ecological systems, transformation and resilience thinking

Research communication and strategic advice on environment, climate and sustainability

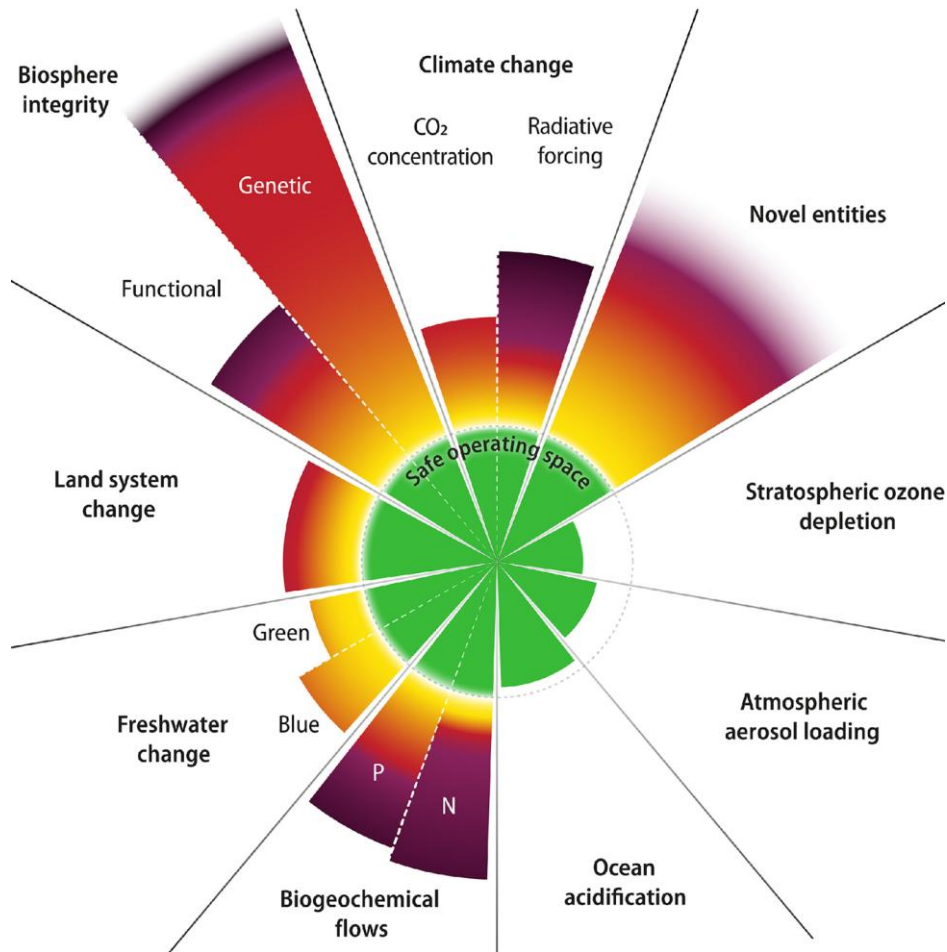




Photo by [NEOM](#) on [Unsplash](#)



Photo by Bernd  Dittrich on Unsplash



A safe operating space for humanity

2023

- All 9 areas quantified
- 6 out of 9 outside safe operating space
- New indicator for functional biodiversity

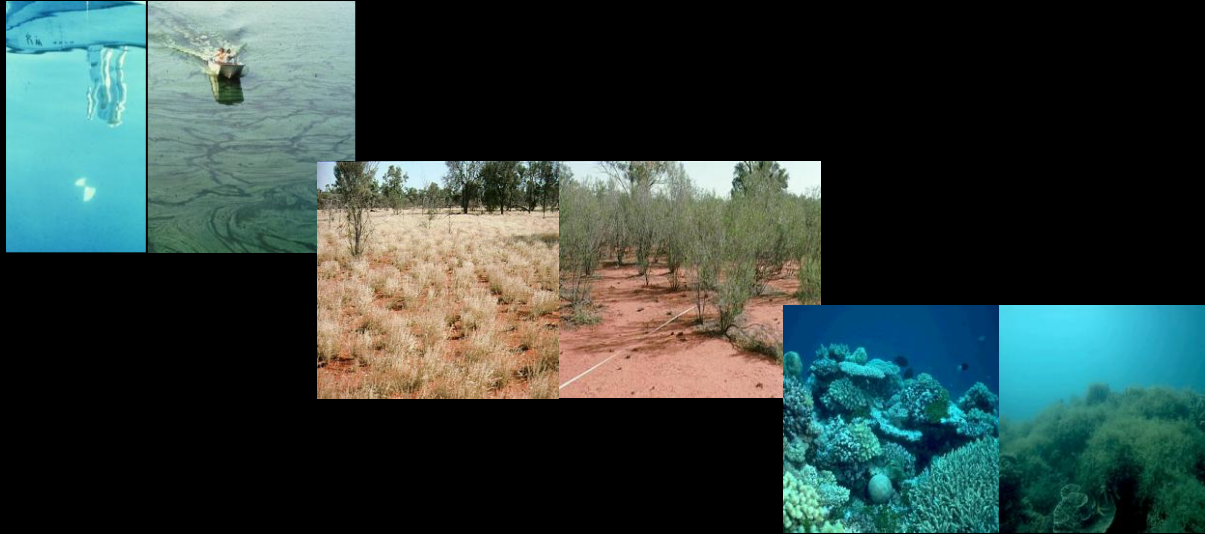
2015

- Biodiversity and climate defined as core boundaries
- 4 out of 9 outside safe operating space

2009

- First article on the PB framework
- 3 out of 9 outside safe operating space

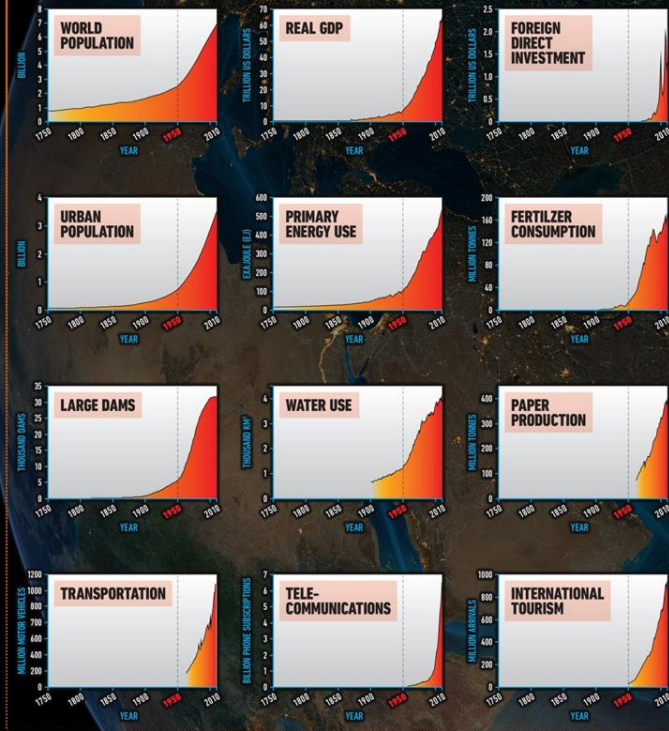
Tipping points



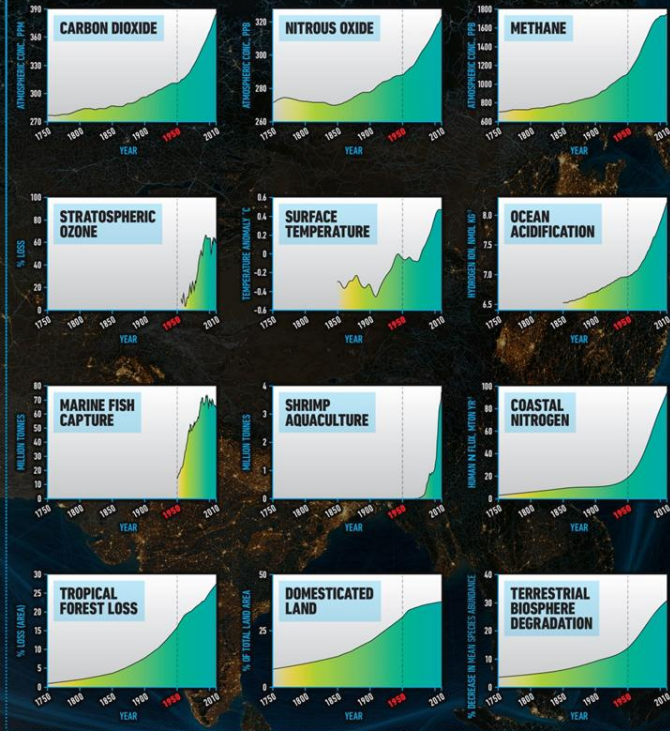
Scheffer et al. 2001. *Nature*; Folke et al. 2004. *AREES*
Threshold database www.resalliance.org

THE GREAT ACCELERATION

SOCIO-ECONOMIC TRENDS



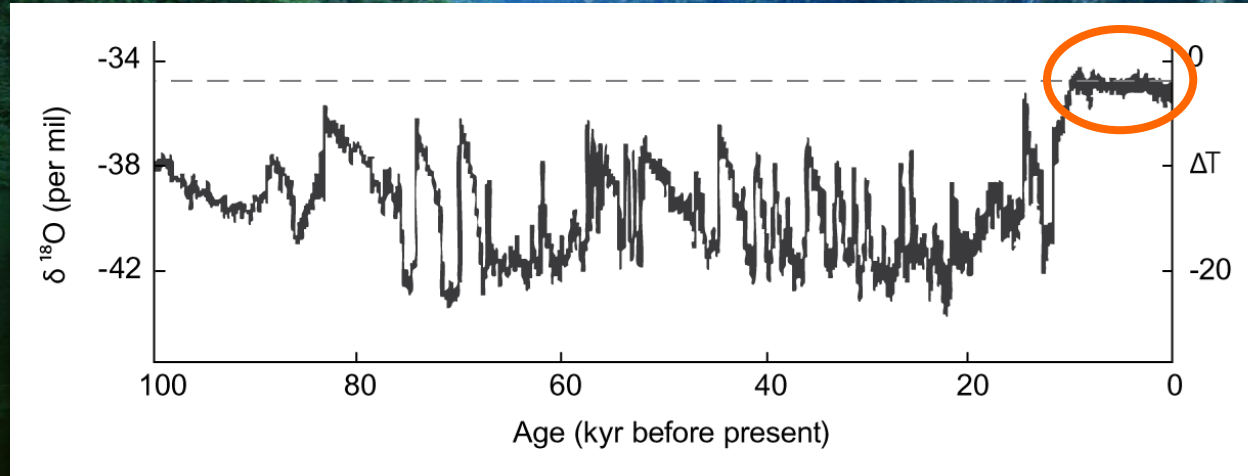
EARTH SYSTEM TRENDS



REFERENCE: Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig (2015), The Trajectory of the Anthropocene: the Great Acceleration, Submitted to *The Anthropocene Review*.
 MAP & DESIGN: Félix Pharand-Deschênes / Globaïa

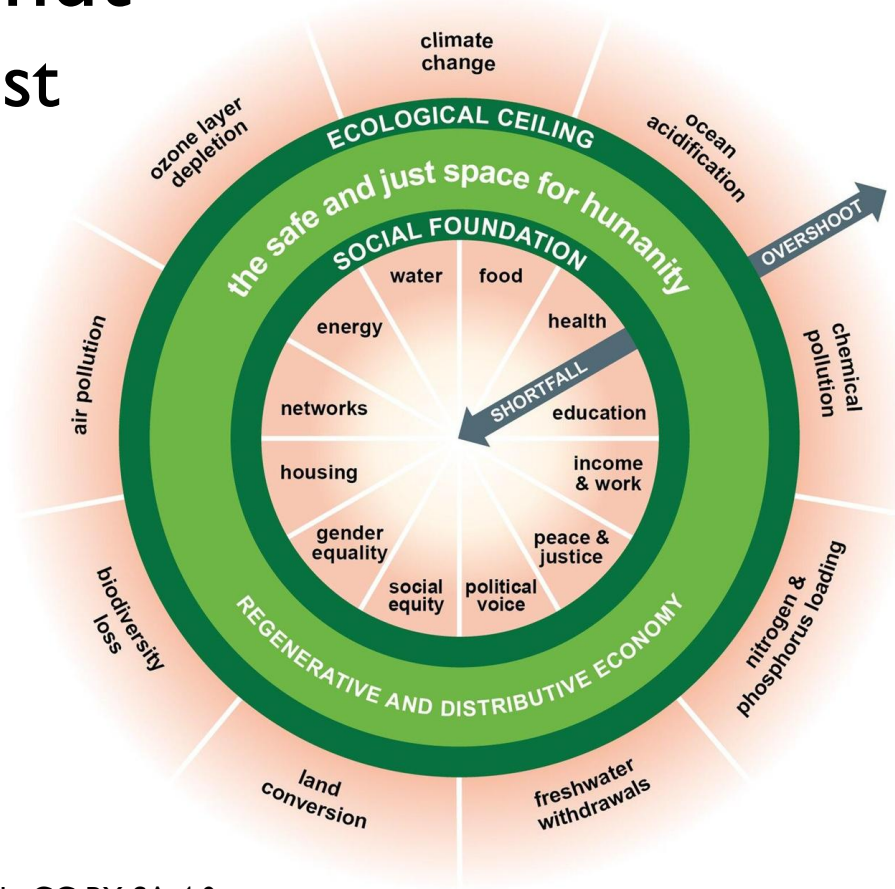


Holocene – 10 000 stabila år



”The Doughnut”

– a safe and just development



Kate Raworth,
Oxford
University



What is a *system*?





Photo by [Guillermo Ferla](#) on [Unsplash](#)

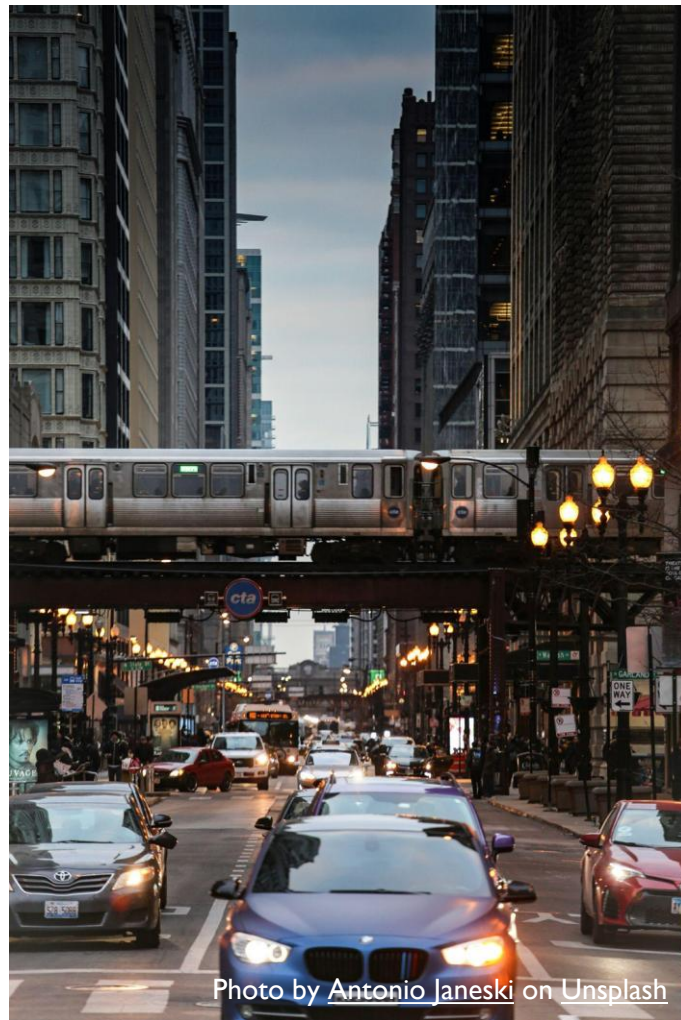


Photo by [Antonio Janeski](#) on [Unsplash](#)



Photo by [Guillermo Ferla](#) on [Unsplash](#)

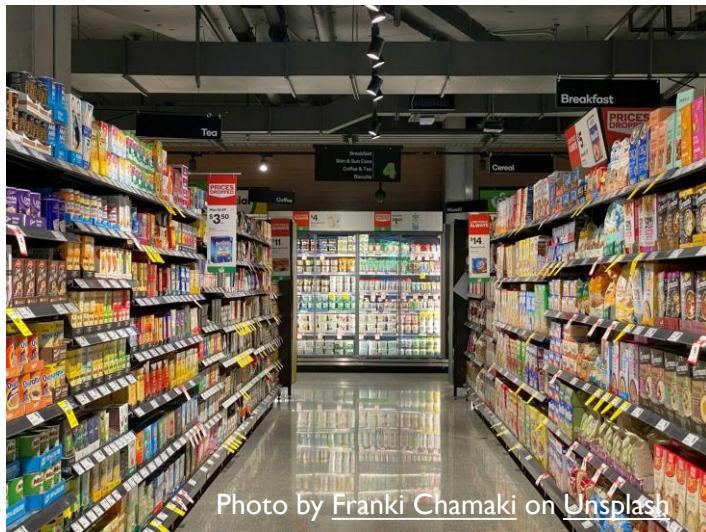


Photo by [Franki Chamaki](#) on [Unsplash](#)

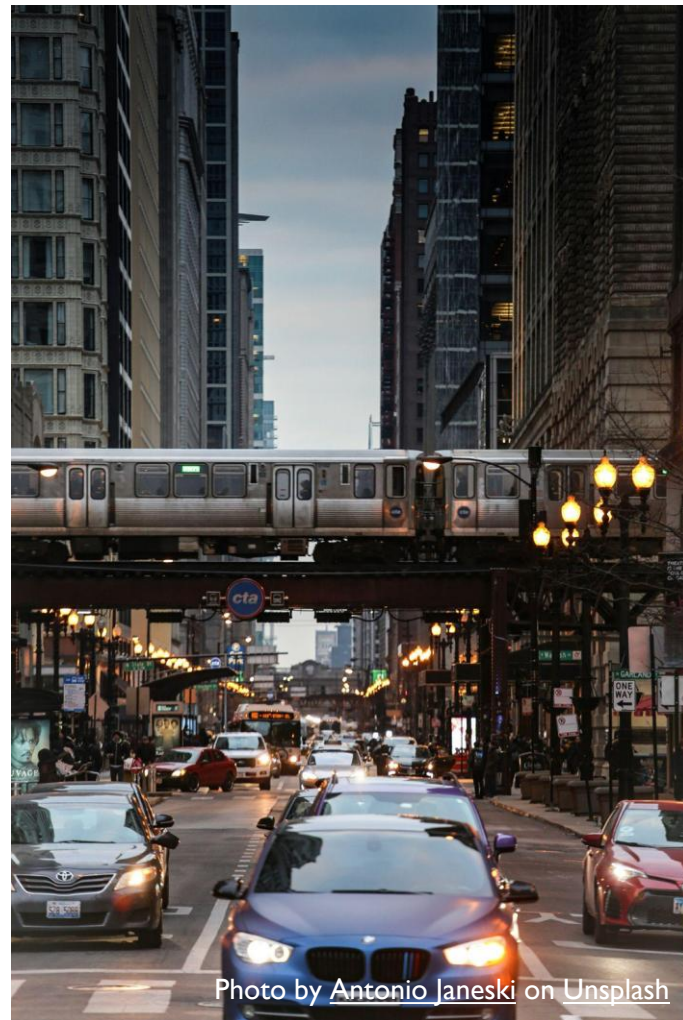


Photo by [Antonio Janeski](#) on [Unsplash](#)



Photo by [Guillermo Ferla](#) on

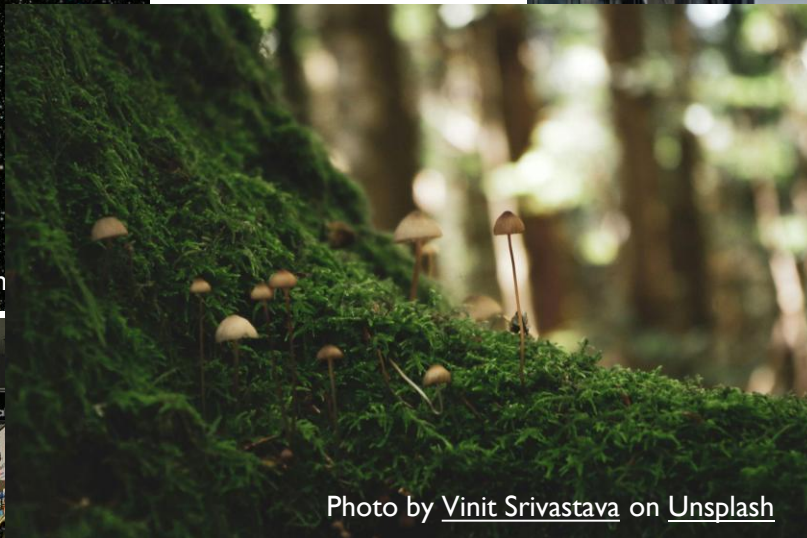


Photo by [Vinit Srivastava](#) on [Unsplash](#)

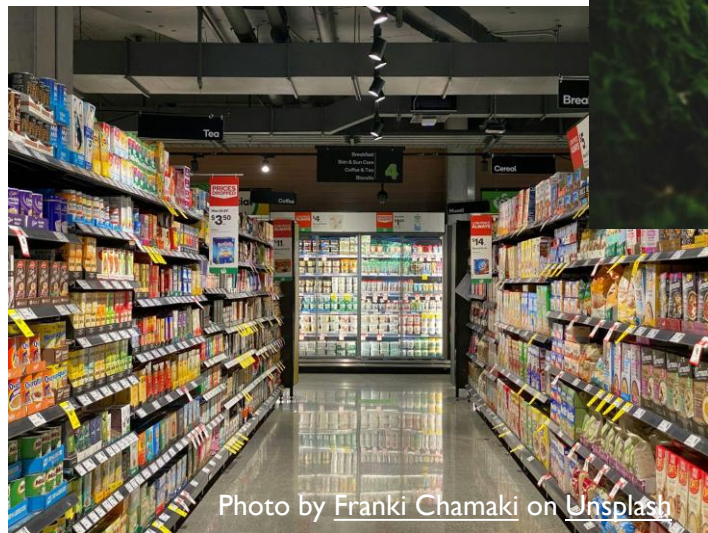


Photo by [Franki Chamaki](#) on [Unsplash](#)

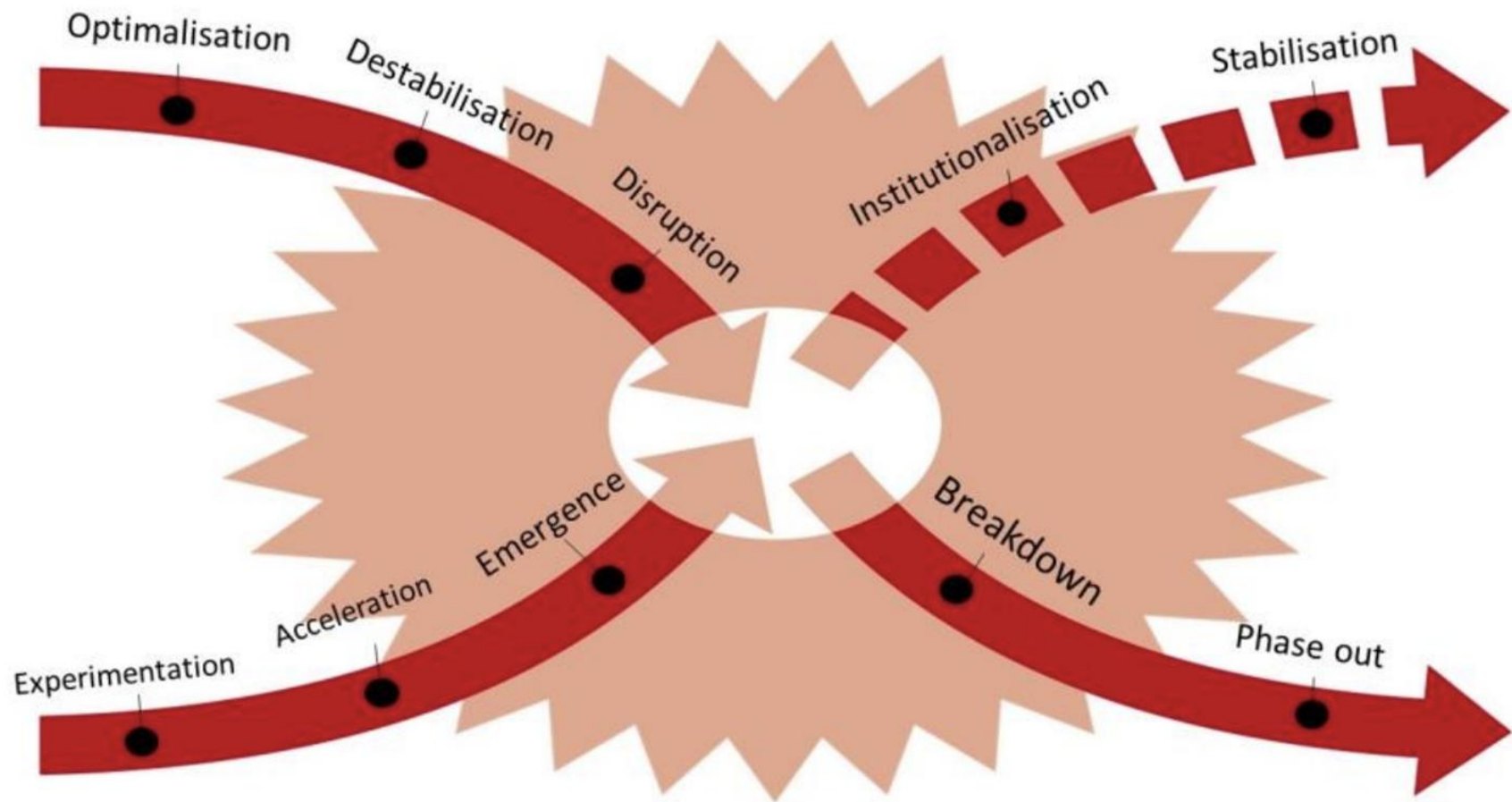


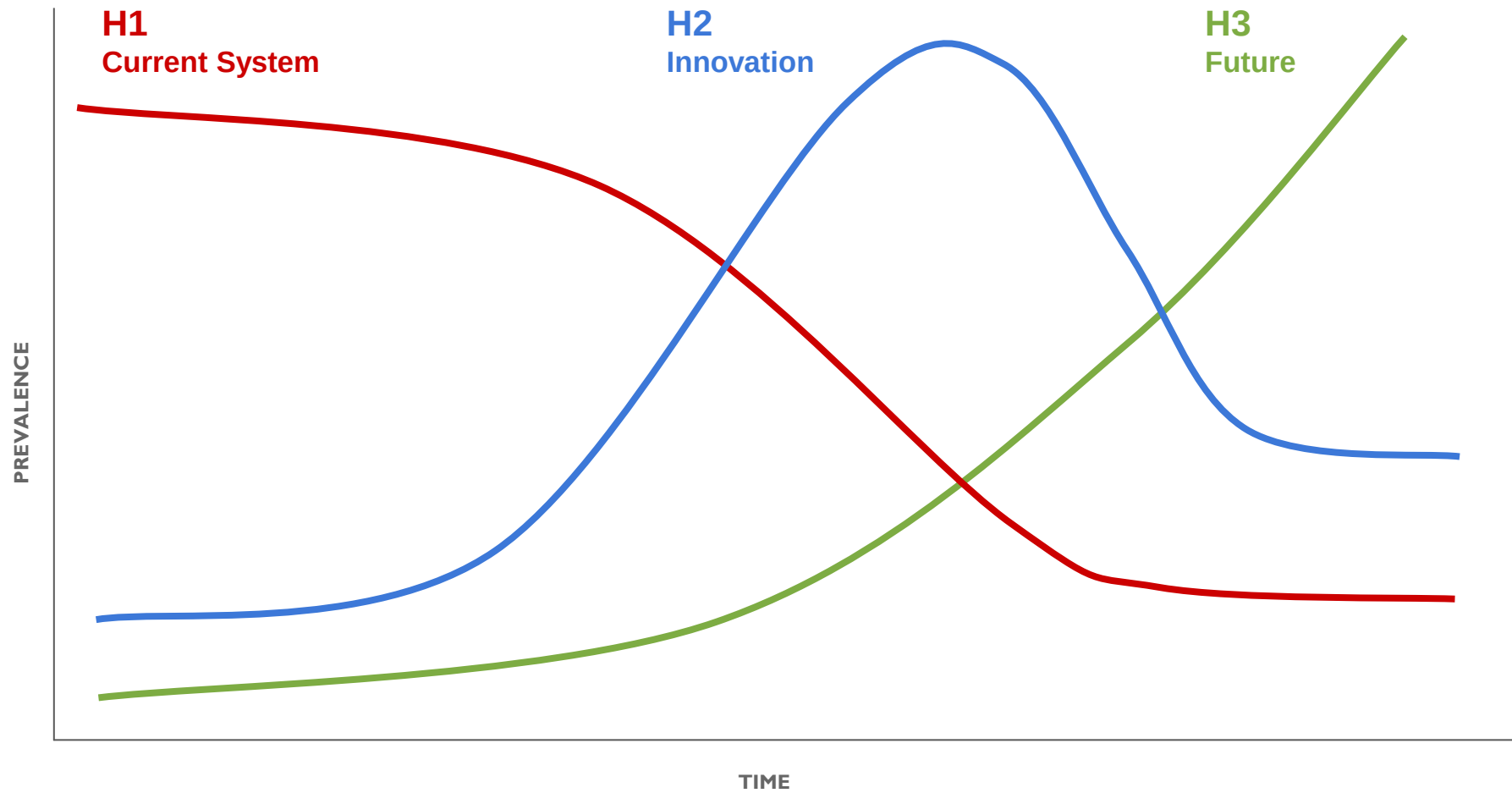
Photo by [Antonio Janeski](#) on [Unsplash](#)

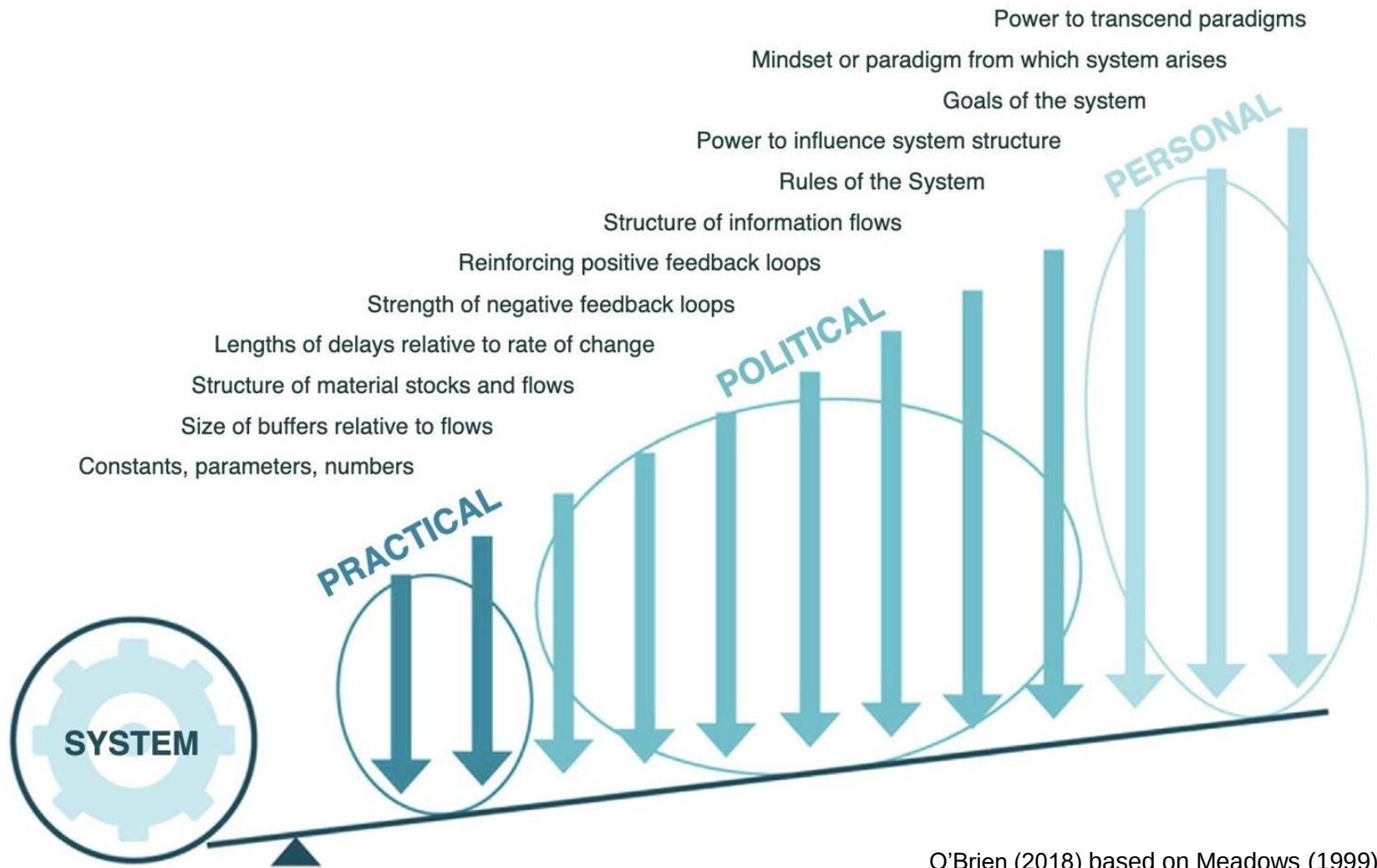
What is transformation?



Photo: [Thomas Bresson Flickr](#)



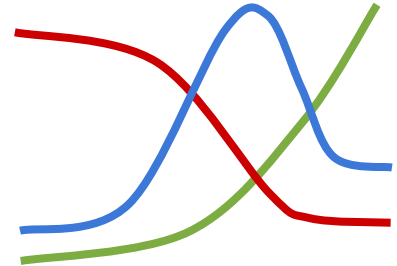




What is the goal of the system?



How do we get there?



How can we achieve this within the safe and just operating space?





TACK

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anna.steorn@albaeco.com

Production processes for biocarbon & producing areas for biomass

Elisabeth Wetterlund & Kentaro Umeki (LTU)
Erland Nylund (Swetim)

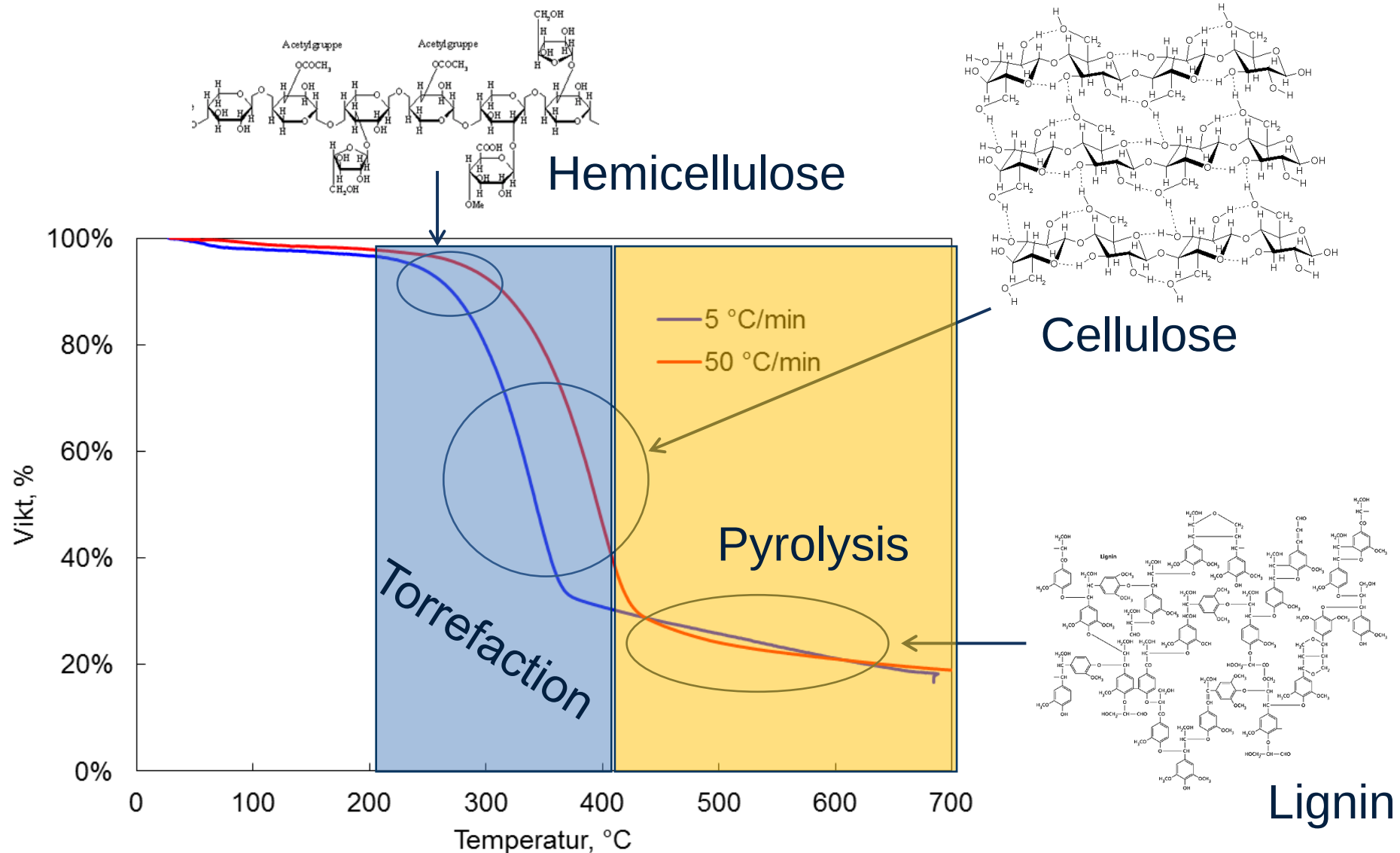


Technology options

	Process	Product
Torrefaction	Heating biomass to 200-350 °C	Torrefied biomass
Pyrolysis	Heating biomass to 400-1200 °C	Biocarbon with almost 100% C
HTC (hydrothermal carbonization)	“Pressure cooking” with water/steam at 150-300 °C	Hydrochar

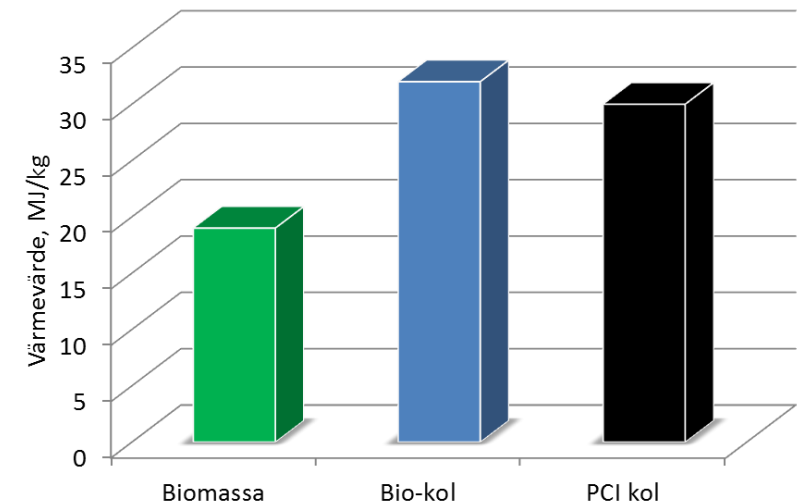
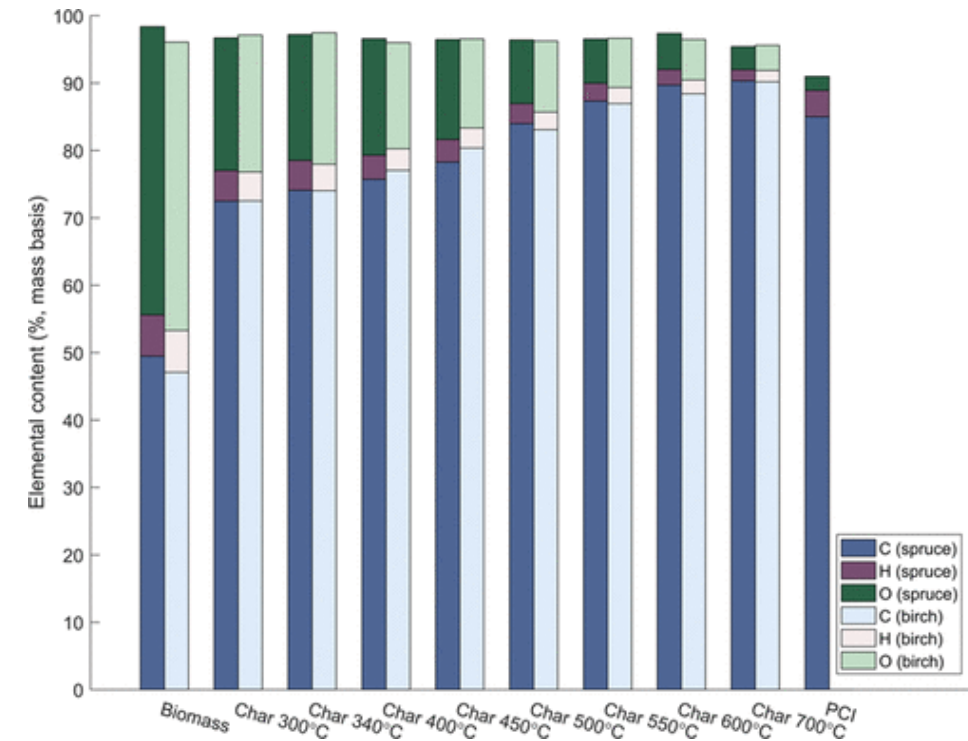


Difference between torrefaction and pyrolysis



Biocarbon properties for metal industry – main requirements

- High C content (low O, H)
- Low volatile content
- High heating value
- Ash content and ash elements

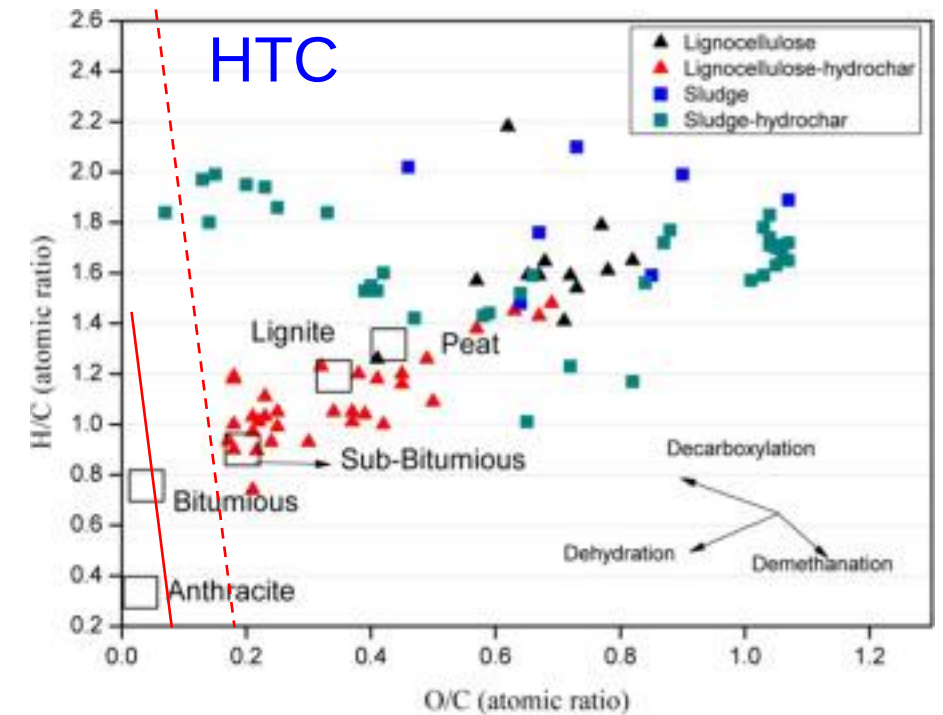
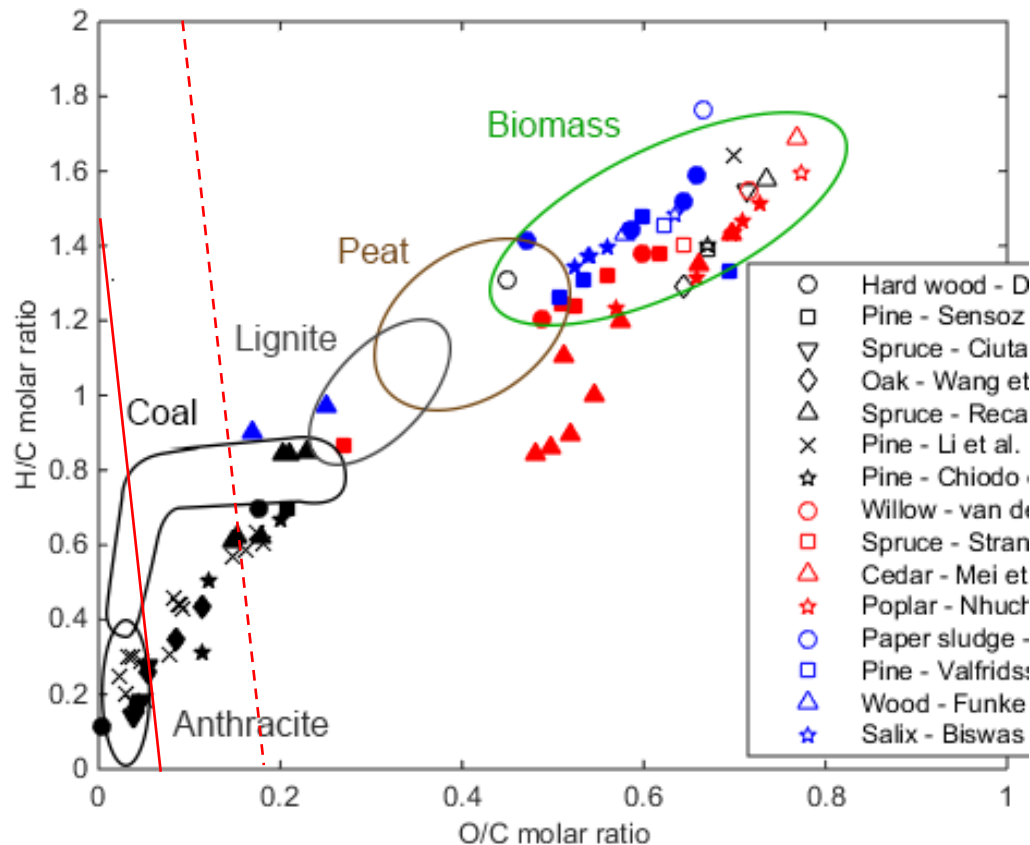


Biocarbon properties for metal industry – carbon content

Black: pyrolysis

Red: torrefaction

Blue: HTC



Requirement: C > 80-90% (red lines)

- Torrefaction and HTC unable to provide biocarbon with high C content
- Pyrolysis with $T > 500\text{ }^{\circ}\text{C}$ only option

Biocarbon properties for metal industry – additional requirements

- Reactivity

- For carburization – low reactivity
- For slag foaming – high reactivity



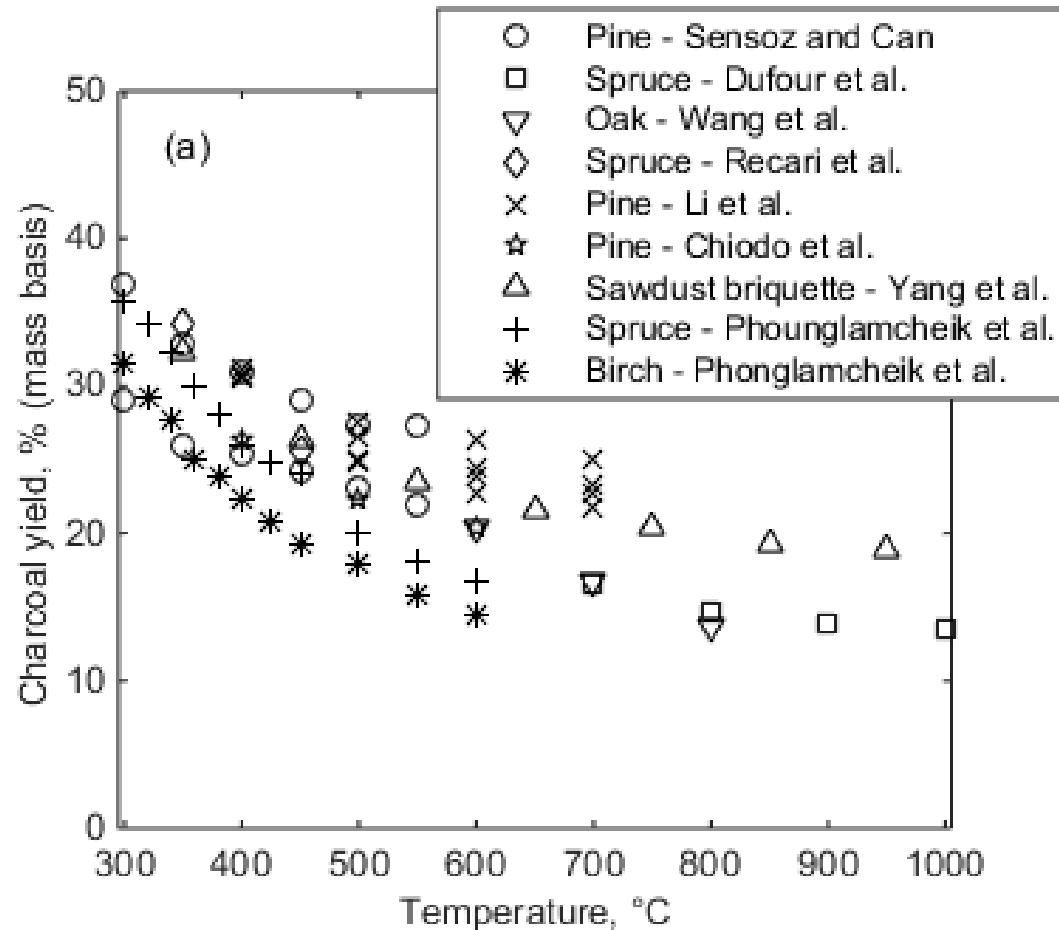
Difficult to control

- High density

- Water absorption capacity

- Particle size (grindability) – important for slag foaming

Drawback – low yields in slow pyrolysis



Process temperature ~700°C

- Biochar yield ~20wt% (50% energy yield)
- Gases ~30% (H₂, CO, CH₄, etc.)
 - Part needed to heat the pyrolysis process
 - Use of excess heat in other industry or in district heating?
- Bio-oil ~40% (phenols etc.)
 - Selling to e.g. refinery?
 - Quality though quite low and important for use in refineries

Summary of biocarbon production processes

- Pyrolysis (high temperature) is always the main process
- HTC and torrefaction can be possible pretreatment processes but that will of course add costs
 - Sawdust needs little to no pretreatment
 - HTC useful at high K/P/S concentrations (sludges, bark, grot etc.)
 - Torrefaction can be useful for compaction (e.g. pelletisation) before pyrolysis

Feedstock candidates – Swedish perspective

Technical suitability

Forestry by-products

- Forestry residues
- Biomass stems from thinning
- (Stumps)

Forest industry by-products

- Sawdust + other
- Sawmill chips
- Pulp mill fibre- and bio-sludges
- Bark
- (Kraft) lignin

Other by-products

- Lignin from lignocellulosic ethanol production
- Other bio-sludges?
- Agricultural residues

Feedstock candidates – Swedish perspective

Economic suitability / availability

Forestry by-products

- Forestry residues
- Biomass stems from thinning
- (Stumps)

Forest industry by-products

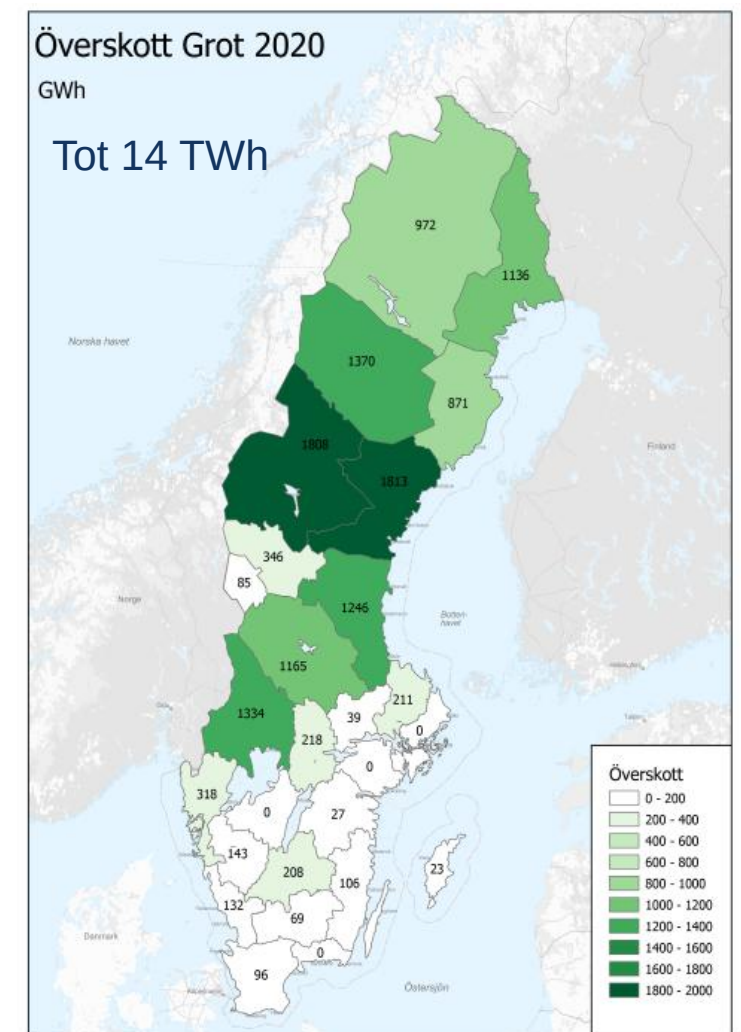
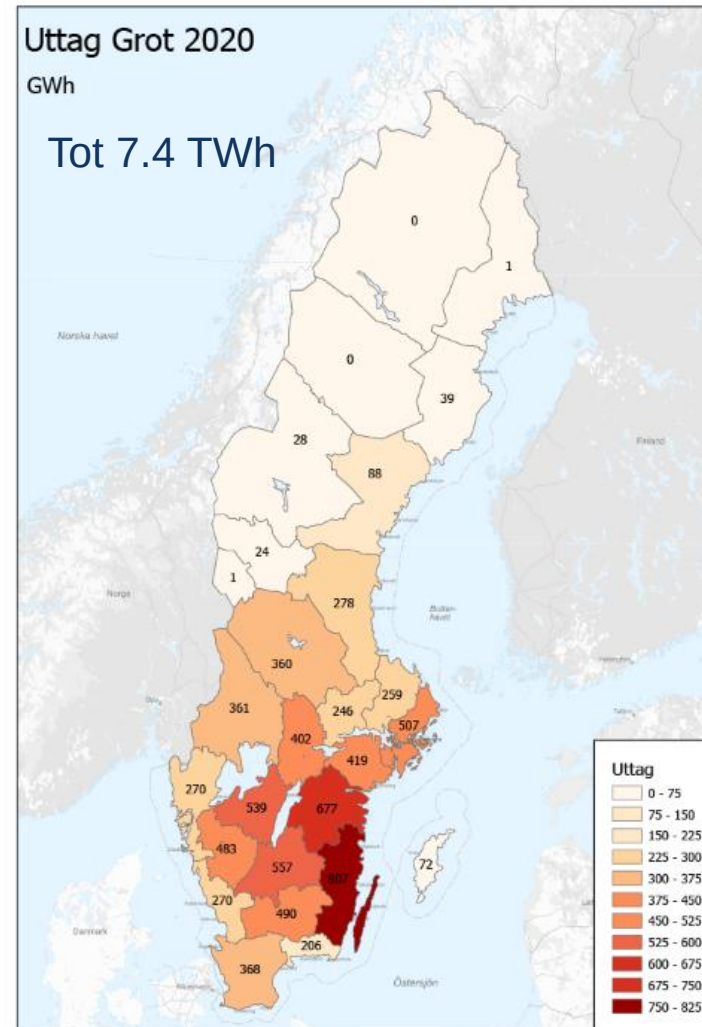
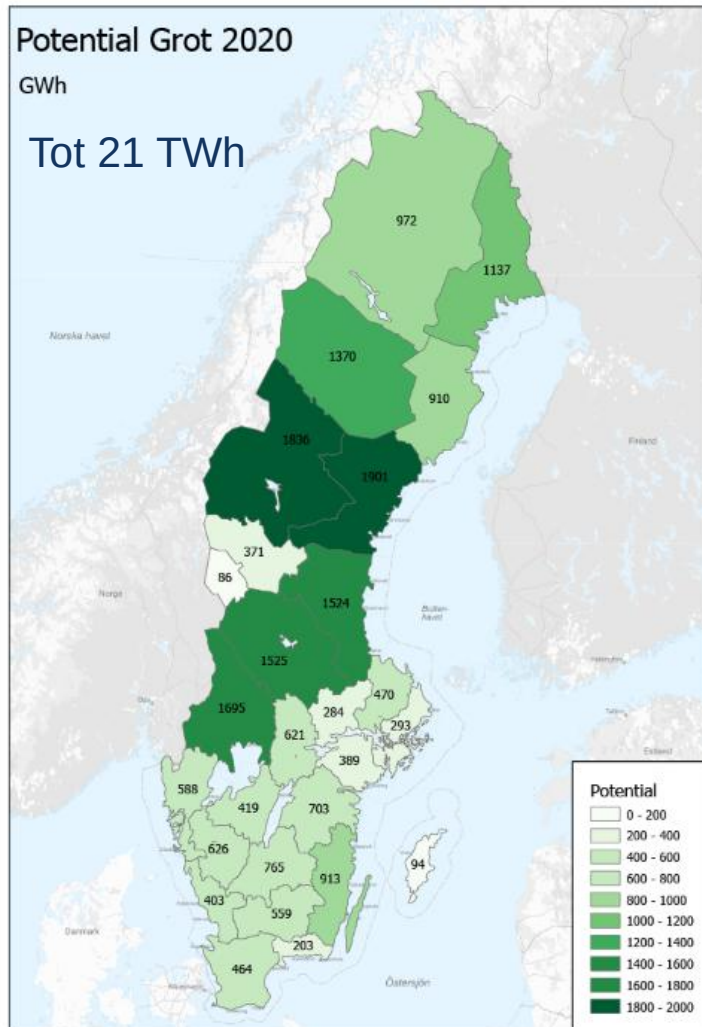
- Sawdust + other
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Other by-products

- Lignin from lignocellulosic ethanol production
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- Agricultural residues

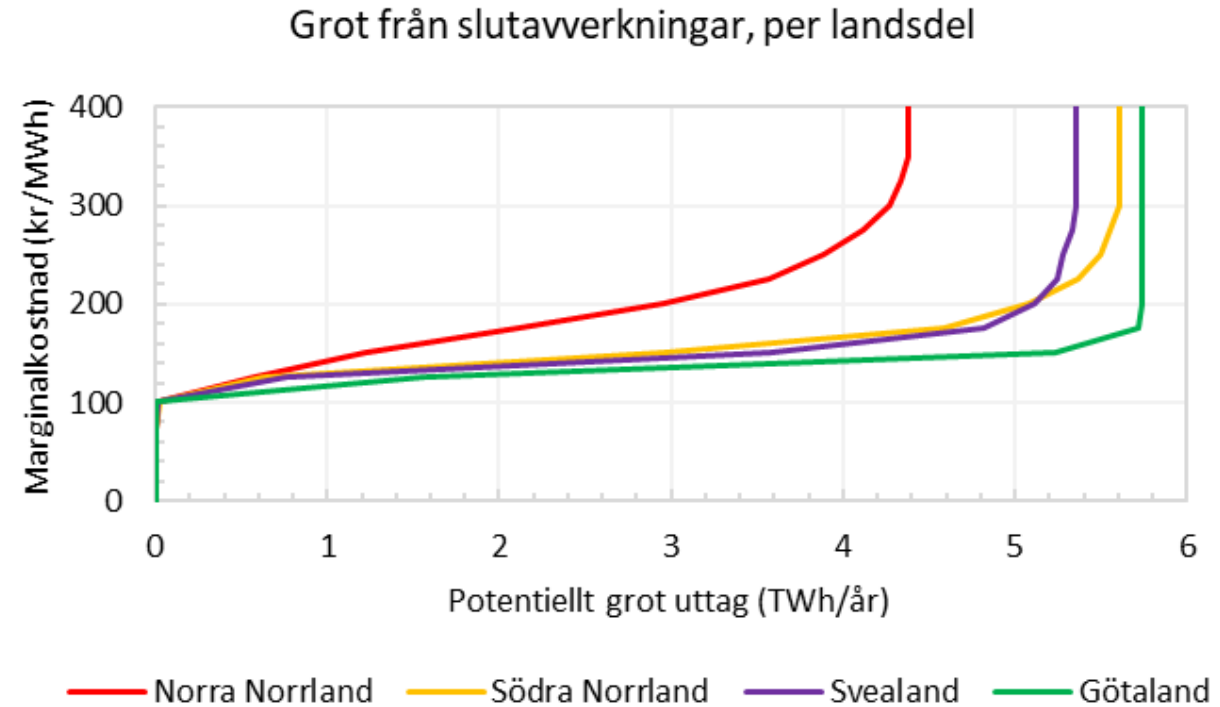
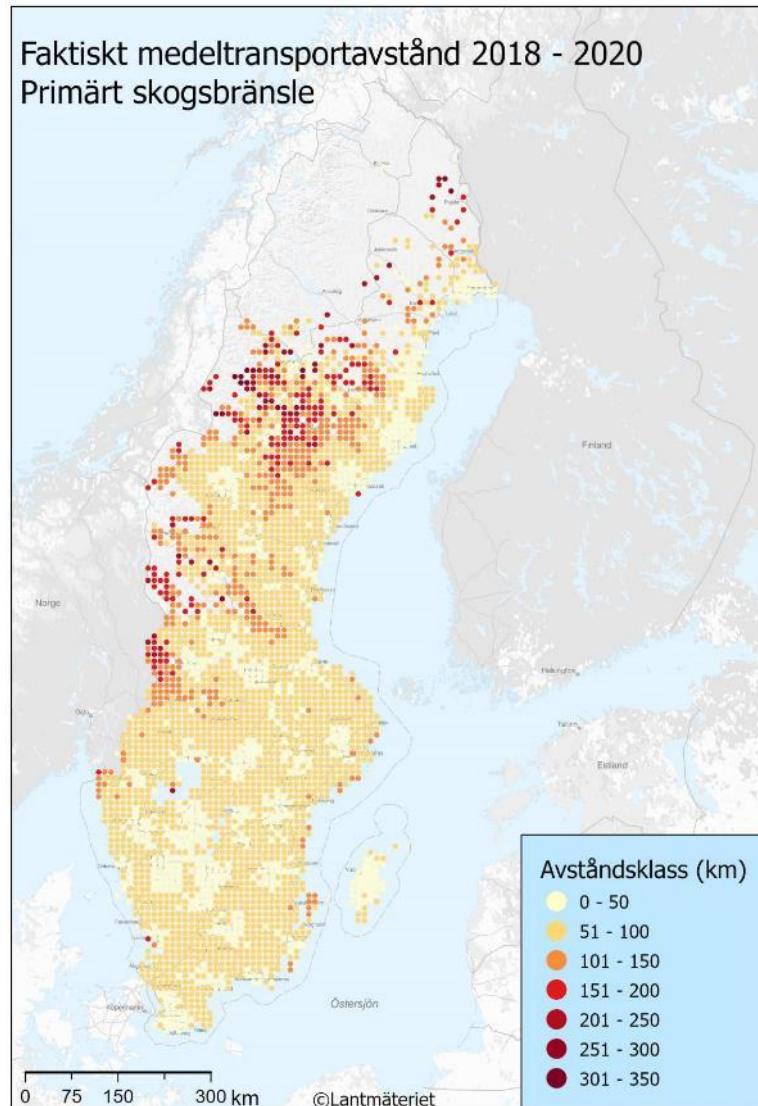
Small squares showing the technical suitability

GROT – potential and outlook



Källa: Skogforsk, Faktablad om grot och dess potential, oktober 2023, <https://www.skogforsk.se/kunskap/temasidor/skogsbransle/faktasammanstallning-grot/>

GROT – production costs



Källa: Skogforsk (2023), Vad kostar det att ta ut mer biobränsle från skogen? <https://www.skogforsk.se/kunskap/kunskapsbanken/2023/vad-kostar-det-att-ta-ut-mer-skogsbiobransle/>

What is needed to increase?

- Trust and long-termism
- Engage the contractors again – and the forest owners
- Investments in machinery
- Coverage for risk
- Time – delivery time on machines
- Time – lead times of 1 year in production of grot!
- Vertical integration – involving customers in the supply chain



Grot samlad i mindre högar på hygge. Högarna hämtas dels av konventionella skotare, dels av skotare specialbyggda för just terrängtransport av grot.



Grotskotning från hygge till bilväg.



Grotvålta som täckts med papp, och lagras vid bilväg.

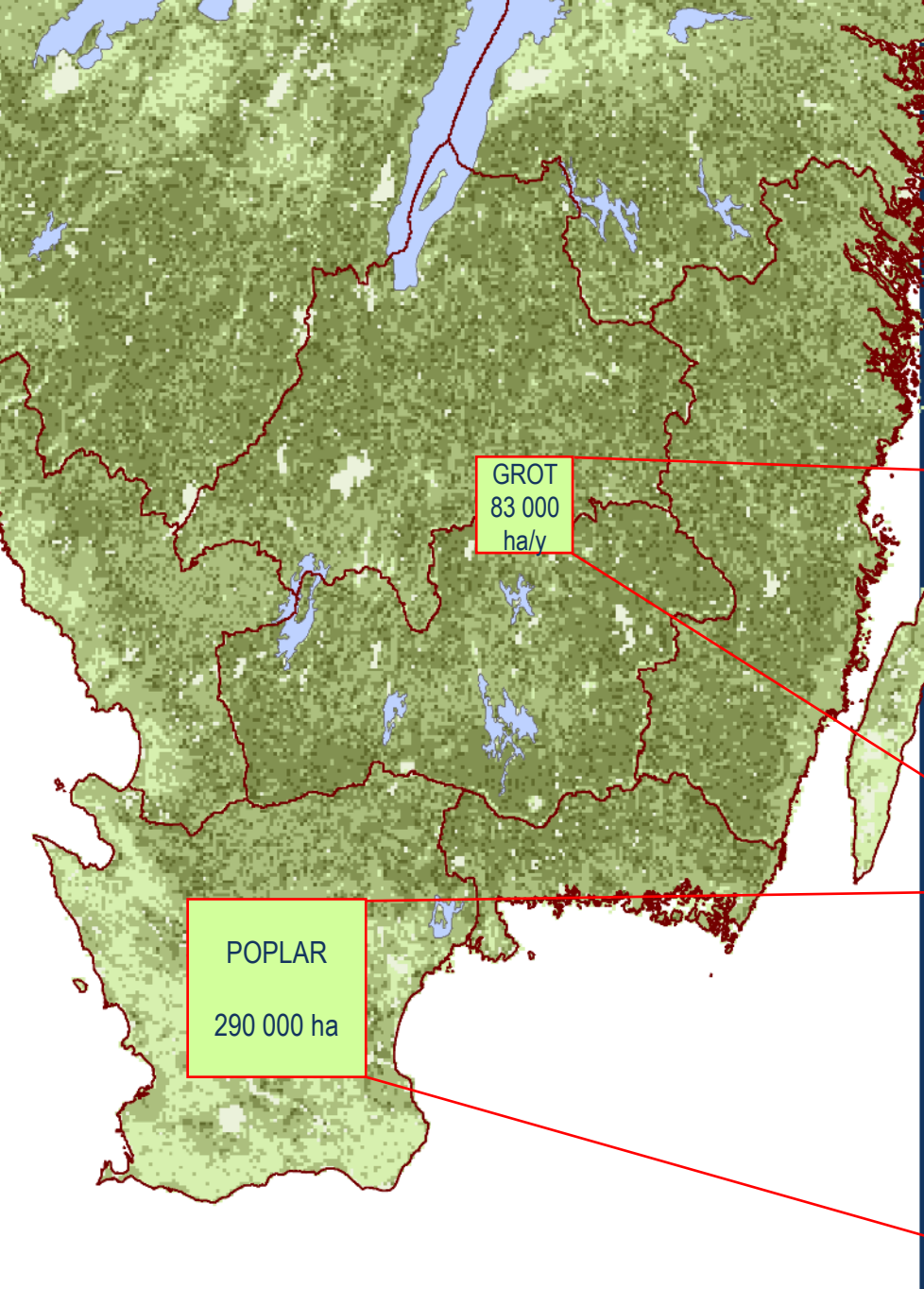


Flisning av grot vid bilväg. Här flisas groten med en så kallad lastbilshugg direkt i ett lastbilssläp.

Källa: Skogforsk, Faktablad om grot och dess potential, oktober 2023,
<https://www.skogforsk.se/kunskap/temasidor/skogsbransle/faktasammanstallning-grot/>

Biomass requirement – Swedish steel industry

Biocarbon requirement	350 000 t DS/y
Feedstock requirement	~1 750 000 t DS/y
volume	~4,2 million m ³ f/y (55% moisture)
energy	~9 TWh/y



Grot as feedstock

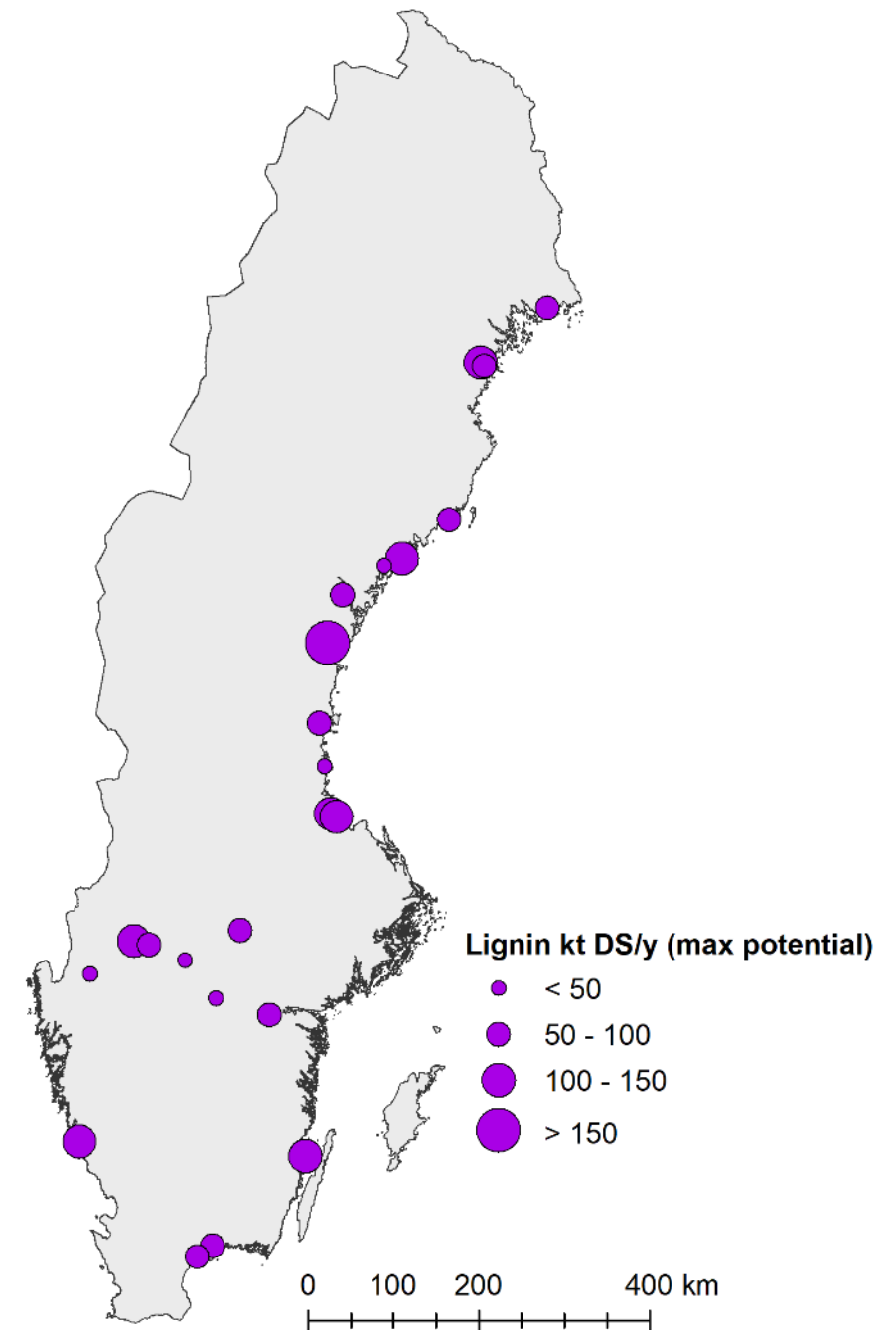
- Final felling area needed:
83 000 ha/y (Götaland) – 100 000 ha/y (Norrrland)
- Corresponds to 60% of entire Sweden's potential for INCREASED grot extraction
- Final felling areas today:
56 000 ha/y (Götaland) – 120 000 ha/y (Norrrland)

Fast growing poplar as feedstock

- Land area needed:
290 000 ha
- Rotation time ~20 y, can be grown on unused or forested agricultural land
- Production ~6-8 t DS/ha,y
- Estimated available land for poplar:
210 000 ha (Skåne) – 930 000 ha (Götaland)

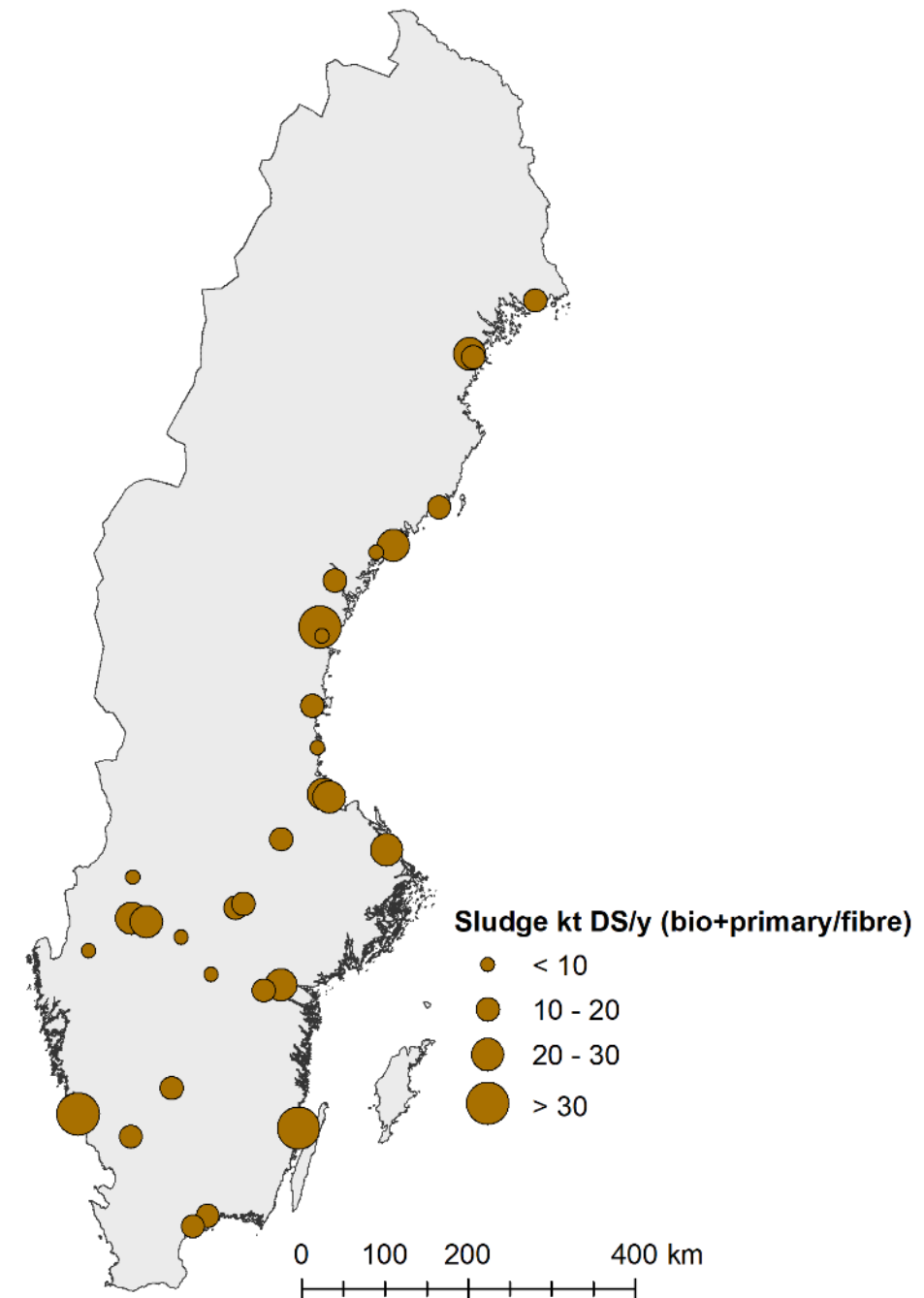
Lignin from pulp industry liquors

- Theoretical max potential ~30% av all black liquor in Swedish chemical pulp mills
 - ~1900 kt lignin per year (dry substance), or 14 TWh/år
 - Corresponds to ~1200 kt C
- Realistic potential limited by the individual recovery boilers
 - ~880 kt lignin per year (dry substance), or 7 TWh/y
 - Corresponds to ~580 kt C



Pulp and paper industry sludges

- ~500 kt sludge per year (dry substance) – bio and fibre sludge combined
 - Corresponds to ~230 kt C
- Hydrochar potential ~320 kt/y
- The hydrochar has low content of both total and fixed C. In EAF ca 4 kg hydrochar is needed to replace 1 kg of anthracite
- Hydrochar can be pyrolysed for a better biochar





Supplying biocarbons to the steel industry from agricultural residues

Erland Nylund

Case study: biohydrogen and biomethane for steel industry

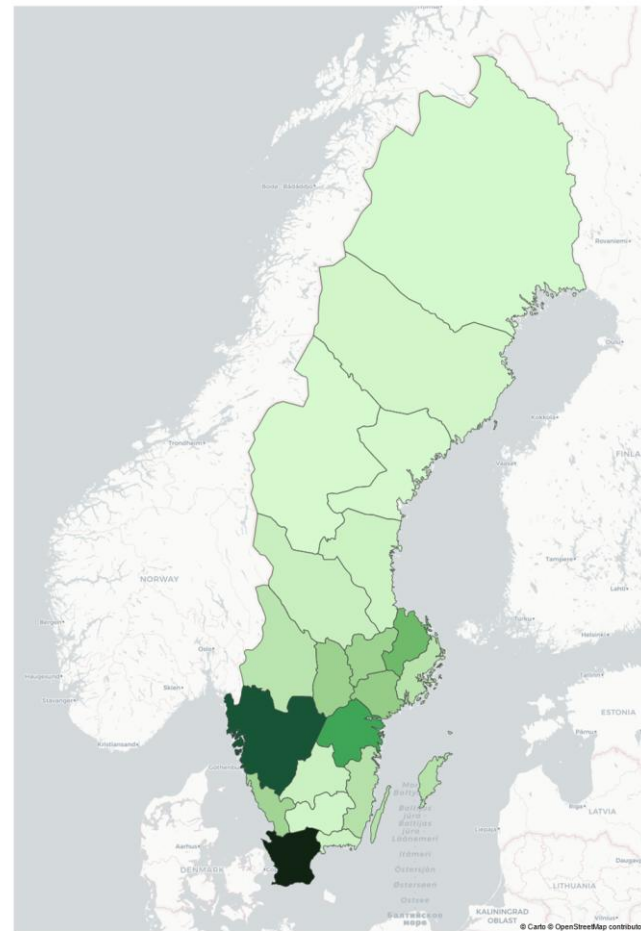
- Short study with Engstam, Falhgren, Tayyebi, 2024
- Three substrate categories: Straw, solid manure, liquid manure
- H₂ or CH₄ production

Potential straw harvest a big enabler

- Cereal production (1)
- Self-sufficiency on straw (2)

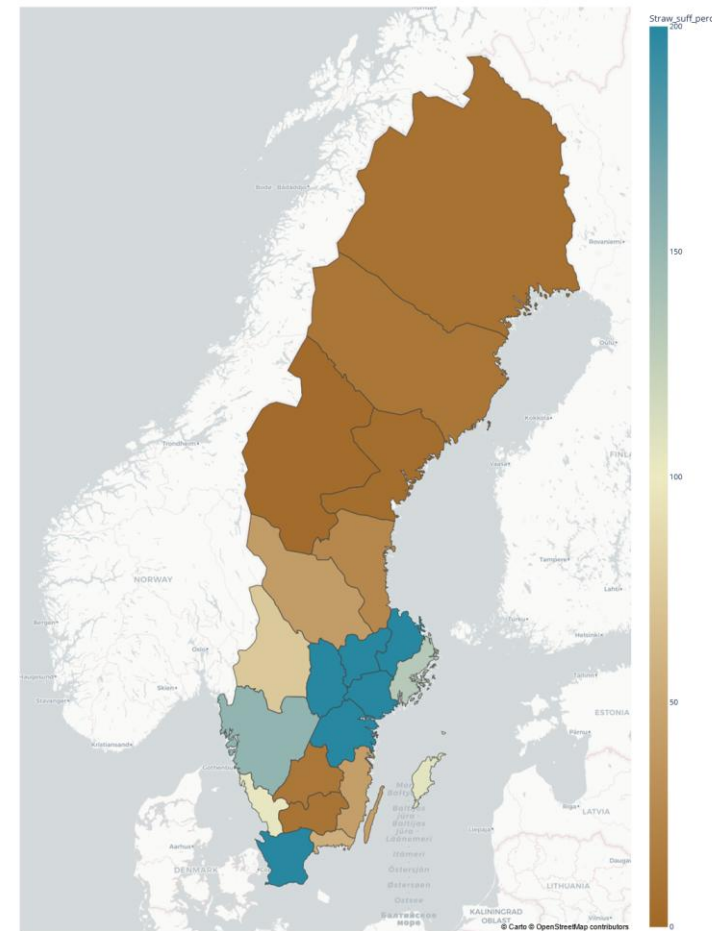
(1)

Total cereal production per region [t/yr]



(2)

Straw self-sufficiency [%]



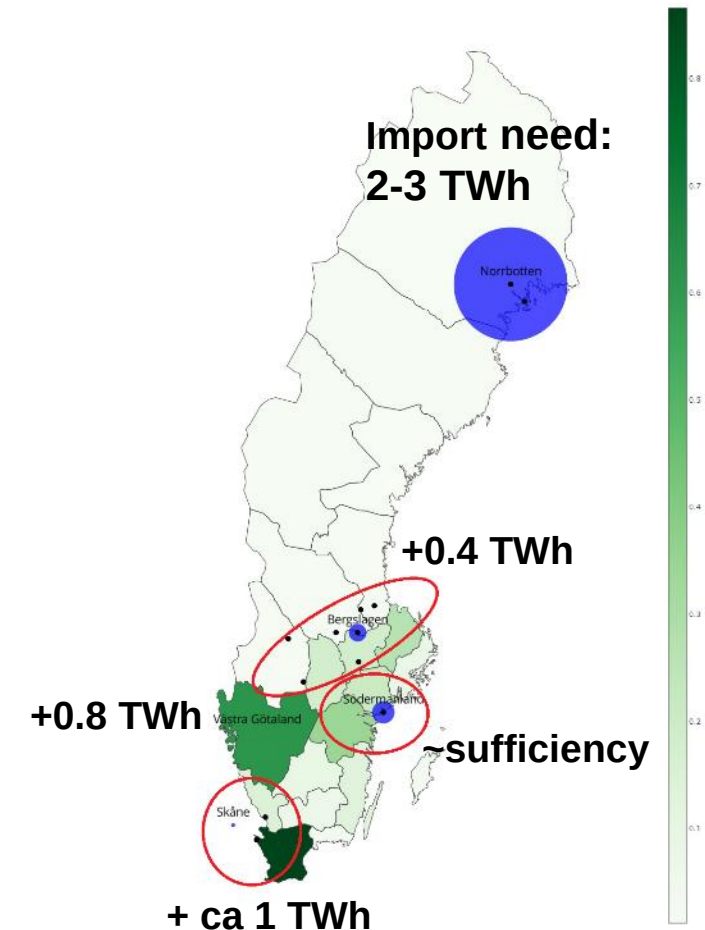
Biogas prouduction potential

- Biomethane potential by region, digestion of manure, gasification of straw (1)
- Steel mills and supply-demand (2)

(1)



(2)



Methane pyrolysis

- Alternative route to biocarbon
- $\text{CH}_4 + \text{high T} \rightarrow \text{H}_2 + \text{C}$

If Norrbotten gas need is met
with H_2 from pyrolysis

→ C-production ~ metallurgical
needs

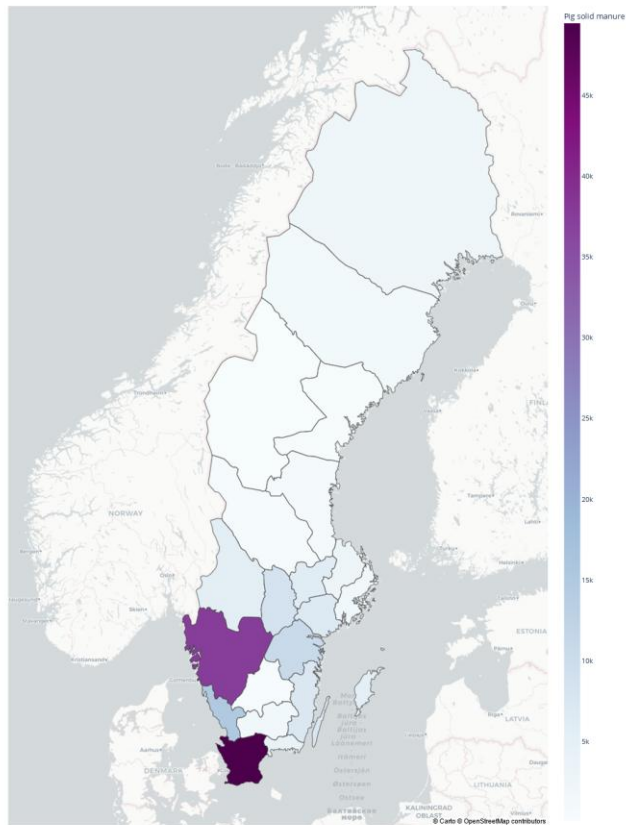
Some conclusions

- Agricultural residue biomass can be significant for metal producers
- Gasification of agricultural residues could reduce demand pressures on some forestry products
- Digestion alone unlikely to supply biomethane need
- Methane preferred for distribution

Extra

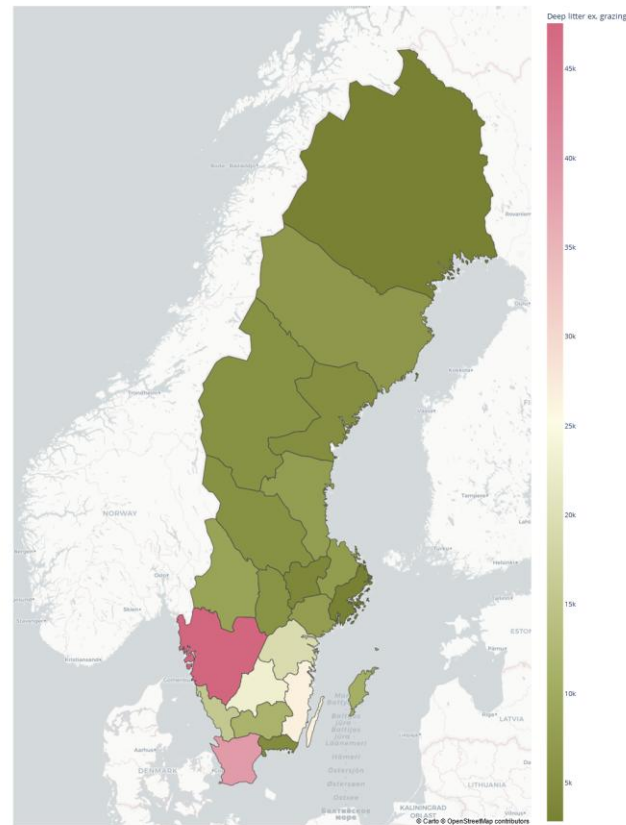
Pig manure

Pig solid manure production [t/yr]



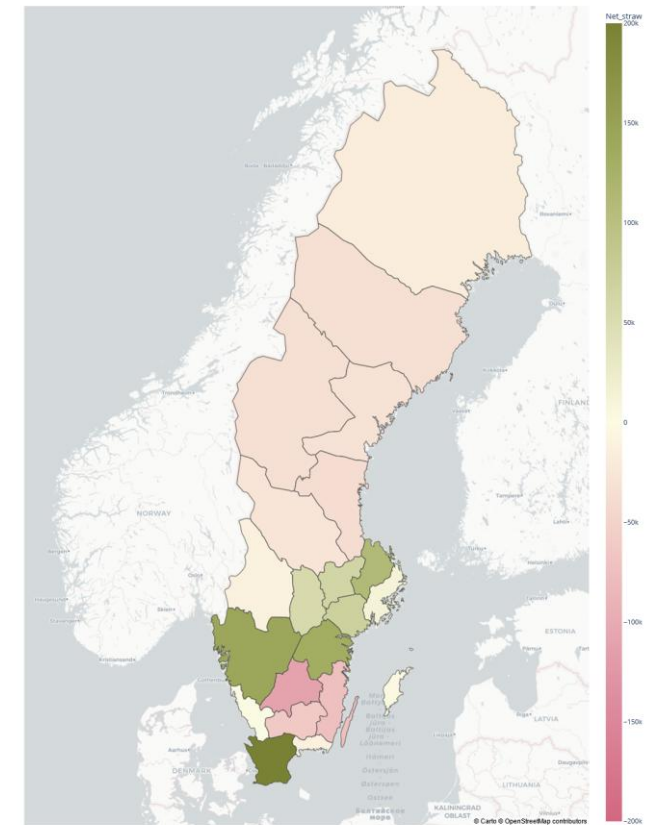
Deep litter (cow)

Deep litter manure production excluding grazing period [t/yr]



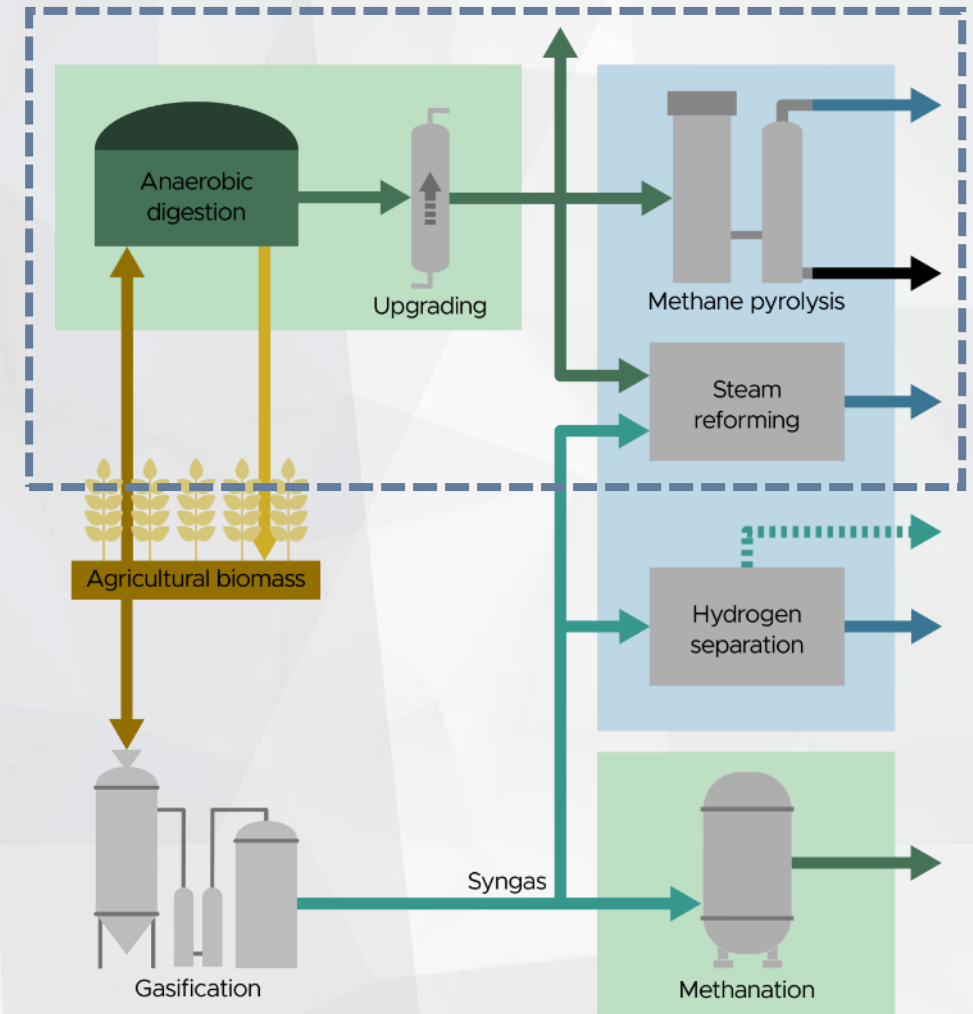
Net straw production

Net straw production per region [t/yr]



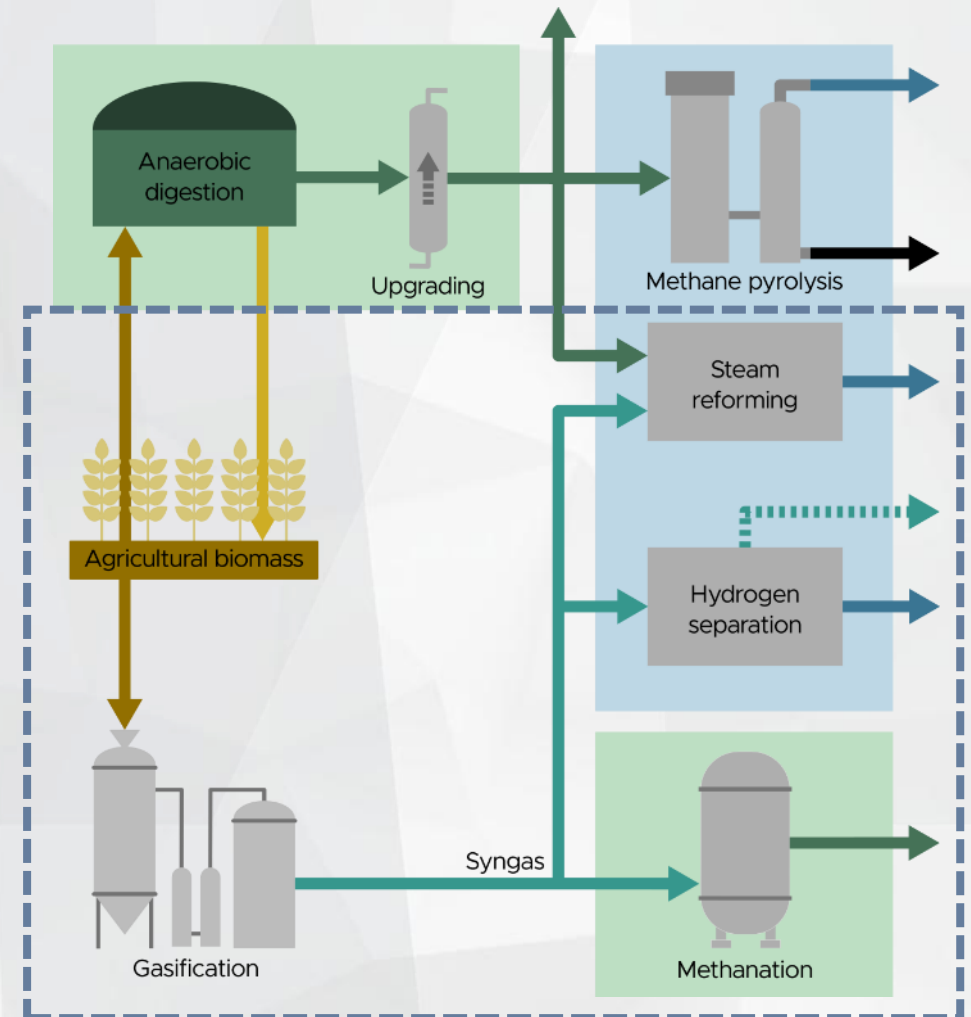
Pathways: anaerobic digestion

- Methane
 - Upgraded biogas
- Hydrogen
 - Methane pyrolysis
 - Steam reforming



Pathways: gasification

- Methane
 - Methanation
- Hydrogen
 - Hydrogen separation
 - Steam reforming





Antaganden

- Pyrolysis: 20% utbyte träråvara till biokol (efter diskussion med Kentaro)
- Grotpotentialer beräknade från Skogsforsks skattningar av hållbart och nuvarande grotuttag, och statistik från Skogsstyrelsen + Riksskogstaxeringen
- Poppelpotentialer beräknade från forskning och långtidsförsök vid SLU Alnarp
- Slampotentialer, hydrokolproduktion och användning i ljusbågsugn från OSMET 3.0 (manuskript)
- Fiber- och bioslam antas kunna samprocessas i HTC

Källmaterial

Omvandlingsfaktorer mellan enheter

- Skogsstatistisk årsbok (äldre publikation, senast utgiven 2014)
- Skogsstyrelsen (2022), Skogliga konsekvensanalyser 2022 – syntesrapport (SKA22), rapport 2022/11

Poppel / snabbväxande lövträd

- Böhlenius et al. (2023) Biomass production and fuel characteristics from long rotation poplar plantations, Biomass & Bioenergy 178:106940, <https://doi.org/10.1016/j.biombioe.2023.106940>

Grot och andra skogsbränslen

- Skogforsk m.fl. (2021), Skogskunskap: Skogsbränslemängd i beståndet, <https://www.skogskunskap.se/skota-barrskog/skorda-skogsbransle/skogsbransle-grunder/skogsbranslemangd-i-bestandet/>
- Skogforsk (2023), Fakta skogsbränsle, <https://www.skogforsk.se/kunskap/temasidor/skogsbransle/faktasammanstallning-grot/>
- Skogsstyrelsen (2023), Avverkningsstatistik, tabell 06 "Bruttoavverkad volym och areal per region, ägarklass, huggningsart", <https://www.skogsstyrelsen.se/statistik/statistik-efter-amne/avverkning/>
- SLU/Riksskogstaxeringen (2023), Skogsdata 2023, https://www.slu.se/globalassets/ew/org/centrb/rt/dokument/skogsdata/skogsdata_2023_webb.pdf

Källmaterial

Jämförelser

- Ahlström et al. (2023), Sustainable aviation fuels – Options for negative emissions and high carbon efficiency, International Journal of Greenhouse Gas Control 125:103886, <https://doi.org/10.1016/j.ijggc.2023.103886>
- Biometria (2023), Skogsindustrins virkesförbrukning 2018-2022, <https://www.biometria.se/media/iugefh4w/skogsindustrins-virkesfoerbrukning-2018-2022.pdf>
- Energimyndigheten (2023), Energiläget i siffror 2023, <https://www.energimyndigheten.se/statistik/ovrig-energistatistik/energilaget/>
- Svebio (2023), Rekord för pelletsproduktion i Sverige 2022, <https://www.svebio.se/press/pressmeddelanden/test/>

HTC & hydrokol i ljusbågsugn

- Wang et al. (2023) A Pilot Trial Investigation of Using Hydrochar Derived from Biomass Residues for EAF Process, in: Fleuriault et al. (Eds.), Advances in Pyrometallurgy. Springer Nature Switzerland, Cham, pp. 153–163. https://doi.org/10.1007/978-3-031-22634-2_15

Massa- och pappersindustri

- Svensson et al. (2023), Kartläggning av biogena kolflöden i de skogsbaserade värdekedjorna i Sverige, RISE Rapport: P116313.
- von Schenck et al. (2016), Info från LignoJet-projektet (RISE inhouse-info)
- Thuresson & Johansson (2016), Bioenergi från skog och skogsindustri. Stockholm: Pöyry Management Consulting.

More facts about grot

Temasida SKOGSBRÄNSLE + Faktablad och FILM om grot

- [Skogsbränsle - Skogforsk](#)
- [faktasammanställning-grot_20231025_press.pdf \(skogforsk.se\)](#)
- FILM på Youtube [Grot - YouTube](#)
- [Lunchseminarium om grot 25 oktober - Skogforsk](#)

KUNSKAPSARTIKLAR & ARBETSRAPPORTER

- [Arbetssätt för uttag av skogsbränslen - Skogforsk](#)
- [Hur mycket grot lämnas kvar i skogen? - Skogforsk](#)
- [Fuktig eller torr - hur blir groten i år? - Skogforsk](#)
- [Vad kostar det att ta ut mer biobränsle från skogen? - Skogforsk](#)
- [Effektiv lagring av skogsflis möjliggörs av täckning och sållning av flisen - Skogforsk](#)
- [Simulera först – asfaltera sedan! - Skogforsk](#)
- [Skogsbränsle - Skogforsk](#)
- [Snabb fukthaltsmätning av trädbränsle - Skogforsk](#)
- [Kan spån bidra till att Sverige blir världens första fossilfria välfärdsland? - Skogforsk](#)
- [Undvik de största misstagen! Systemval för transport och sönderdelning av grot - Skogforsk](#)
- [Stora regionala skillnader i förutsättningarna att leverera skoglig råvara till framtidens hållbara samhälle - Skogforsk](#)

Tack till Mia Iwarsson Wide, Skogforsk, för sammanställningen!



HåBiMet Nulägesseminarium

Johnny Kjellström

30 januari 2025

Johnny Kjellström



- Näringspolitisk chef, Svebio, sedan i mars 2024
- LRF, 2021-2024
- Länsstyrelsen Sthlm, 2016-2021
- Regeringskansliet, 1999-2016
- Jordbruksverket, 1996-1999

- Smålänning
- Lundaekonom
- Nackabo sedan 2011

Vilka är vi?

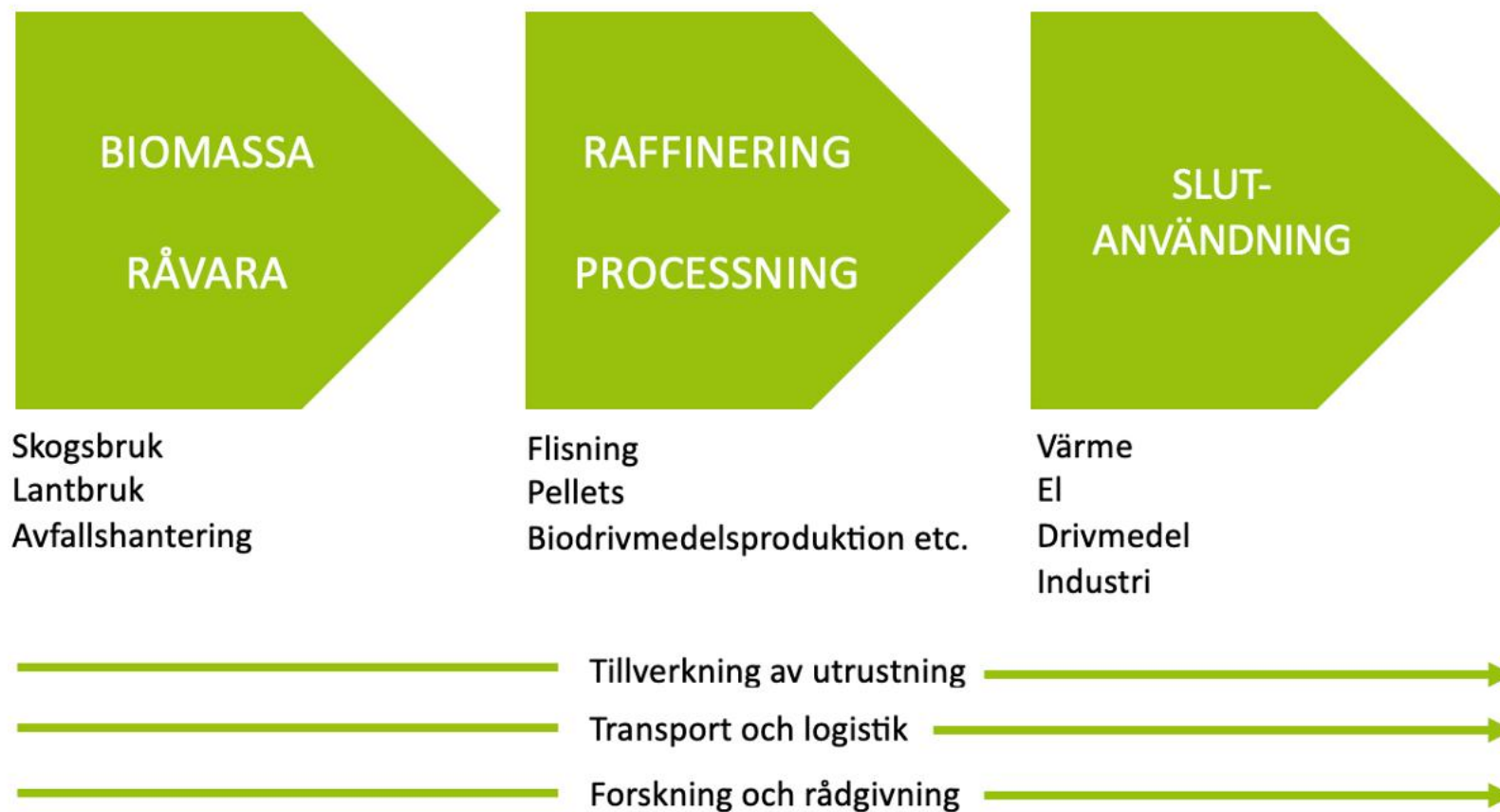
Svenska Bioenergiföreningen (Svebio) är en branschorganisation för drygt 250 företag, organisationer och personer som är verksamma i bioenergibranschen i Sverige. Vi är starkt grundade i våra värderingar som bygger på ett hållbart och tryggt energisystem, företagande och marknadsekonomi. Är medlemmar i Bioenergy Europe och World Bioenergy Association.

Vision och verksamhet

- Vara den ledande företrädaren och ett internationellt föredöme för att utveckla bioenergi i ett hållbart samhälle.
- Ta tillvara medlemmarnas intressen genom bl.a. politiskt påverkansarbete.
- Vi företräder företag som tillverkar och använder bioenergi i fast, gasformig och flytande form.
- Vara en mötesplats för företag, forskare, opinionsbildare och beslutsfattare.
- Organisera konferenser och seminarier
- Två tidningar: Bioenergitidningen och Bioenergy International



Svebio i hela näringskedjan



250 medlemmar: företag, institutioner och privata medlemmar

Bioenergi i Sverige

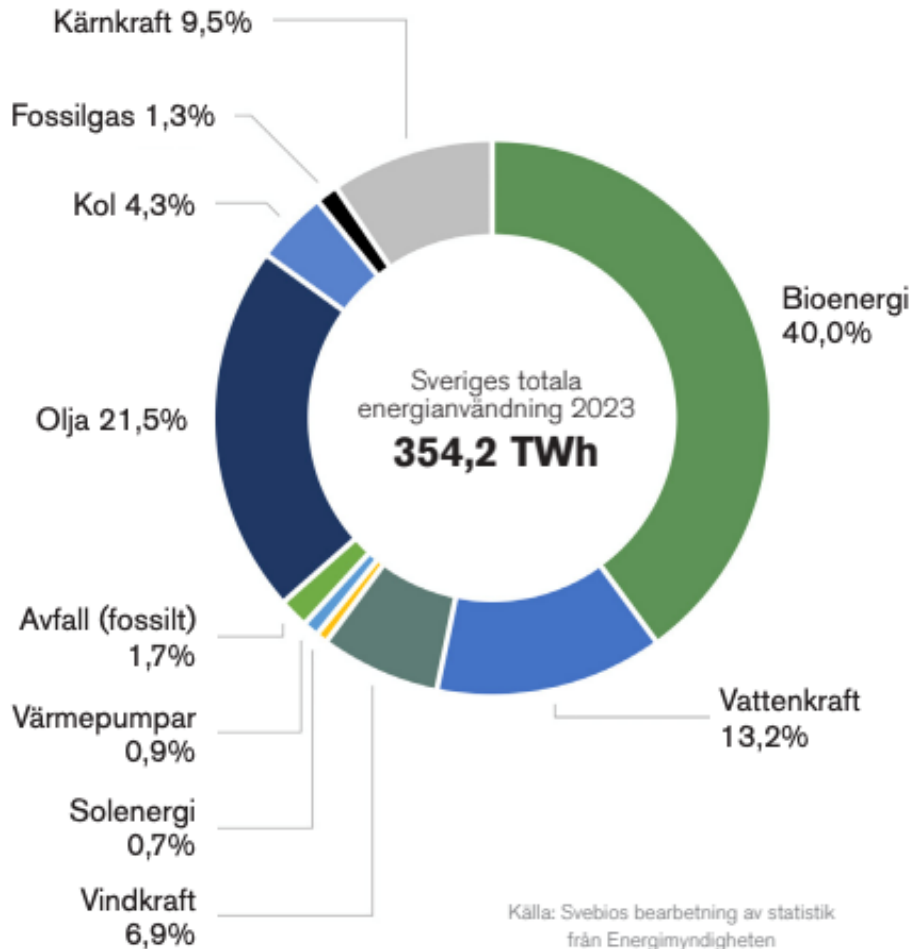
Sveriges energianvändning 2023

Bioenergi är Sveriges största energislag och stod **2023 för 40 procent** av den slutliga energianvändningen i Sverige.

Andelen förnybar energi var 61,7 procent.

Export och energiförluster är ej medräknade

	TWh	%
Bioenergi	141,5	40,0
Olja	76,2	21,5
Vattenkraft	46,9	13,2
Kärnkraft	33,5	9,5
Vindkraft	24,6	6,9
Kol	15,1	4,3
Avfall (fossilt)	6,1	1,7
Fossilgas	4,6	1,3
Värmepumpar	3,3	0,9
Solenergi	2,4	0,7



Källa: Svebios bearbetning av statistik från Energimyndigheten
(Kortsiktsprognos mars 2024)



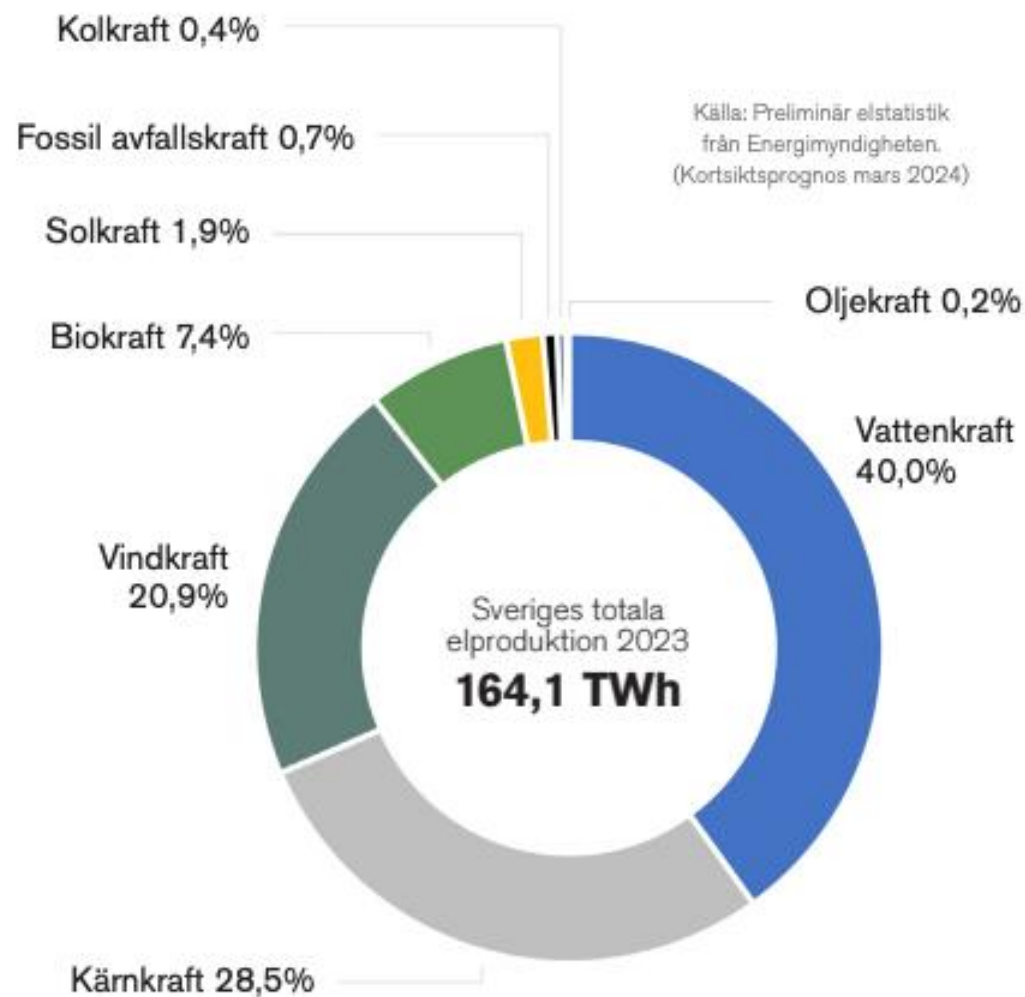
Sveriges elproduktion 2023

Det fossilfria står för 98,6 procent.

Biokraften ligger på fjärde plats inom svensk elproduktion.

Fossilkraft (olja, kol och naturgas) stod endast för 1,5 procent av Sveriges elproduktion 2023.

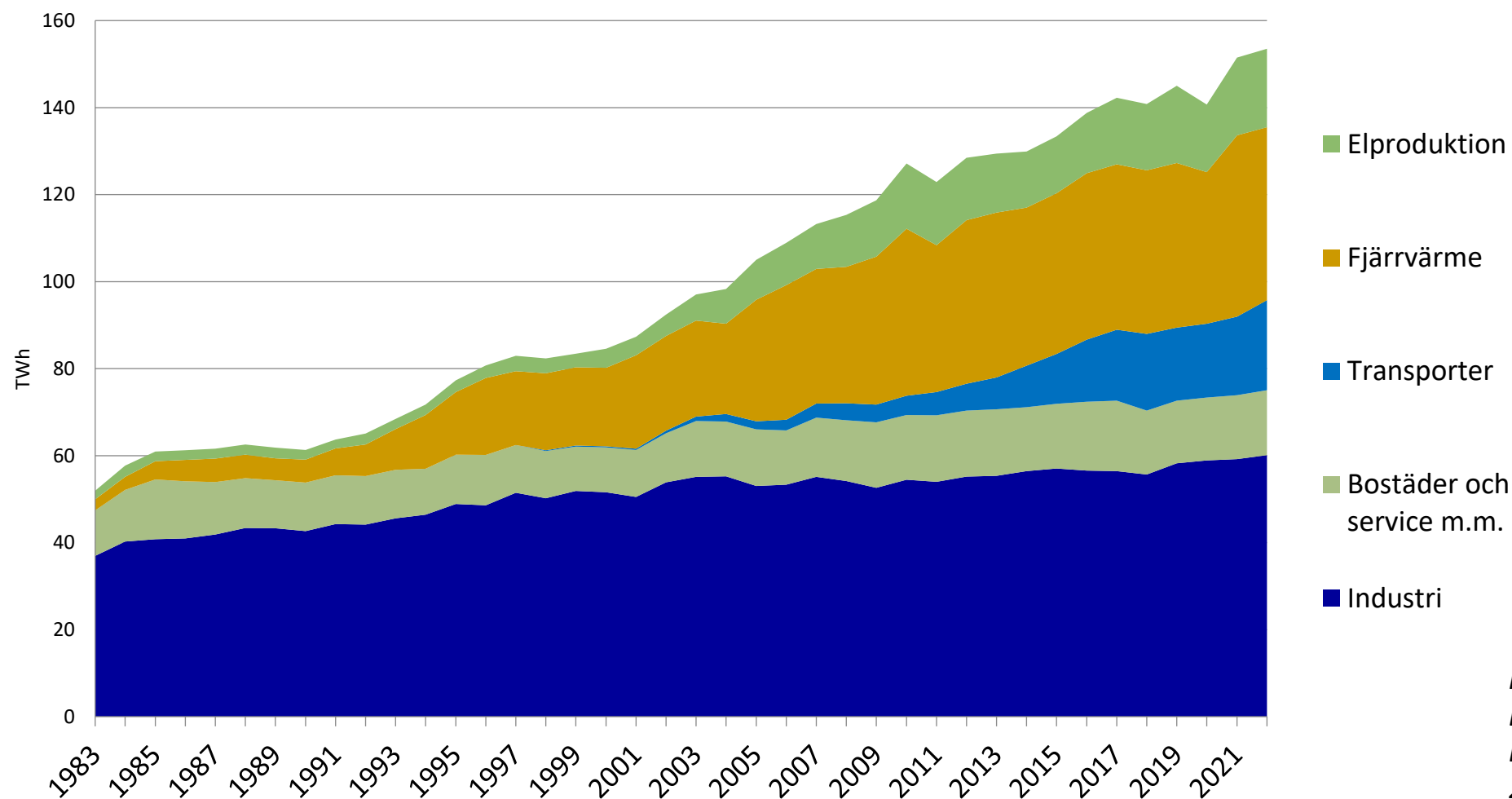
	TWh	%
Vattenkraft	65,7	40,0
Kärnkraft	46,7	28,5
Vindkraft	34,3	20,9
Biokraft	12,1	7,4
Solkraft	3,1	1,9
Fossil avfallskraft	1,2	0,7
Kolkraft	0,7	0,4
Oljekraft	0,3	0,2



Användning av bioenergi per sektor (TWh)

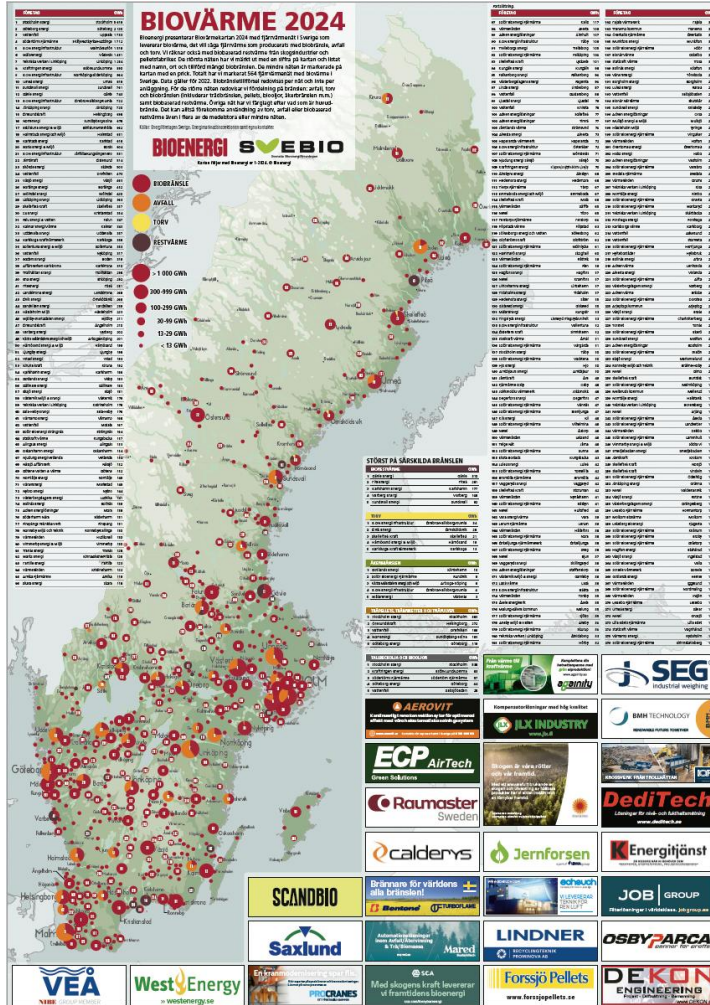


Användning av biobränsle per sektor fr.o.m. 1983, TWh



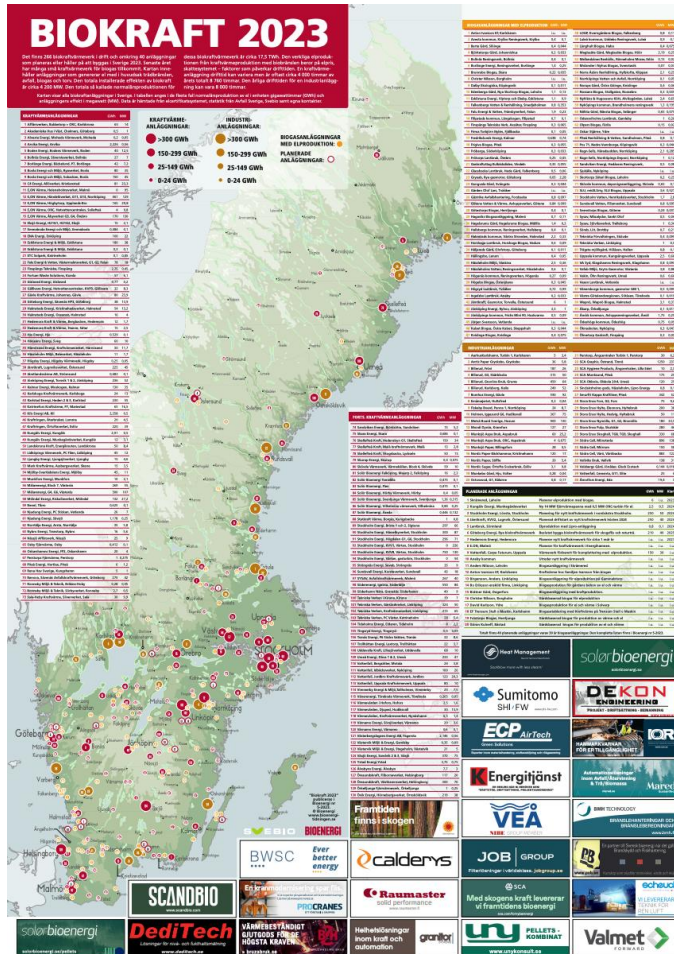
Källa:
Energimyndigheten,
Energiläget i siffror
2023

Biovärme



- År 2024 fanns det 564 fjärrvärmenät som levererar biovärme i Sverige
- Ca 90 procent av flerfamiljshus värms idag upp genom fjärrvärme
- Många fjärrvärmeverk eldas med avfall, som till 70 procent består av biogena avverkningsprodukter från till exempel skogsindustri som inte går att återvinna
- Biobränslen står för omkring 70% av all fjärrvärme + spillvärme från skogsindustri

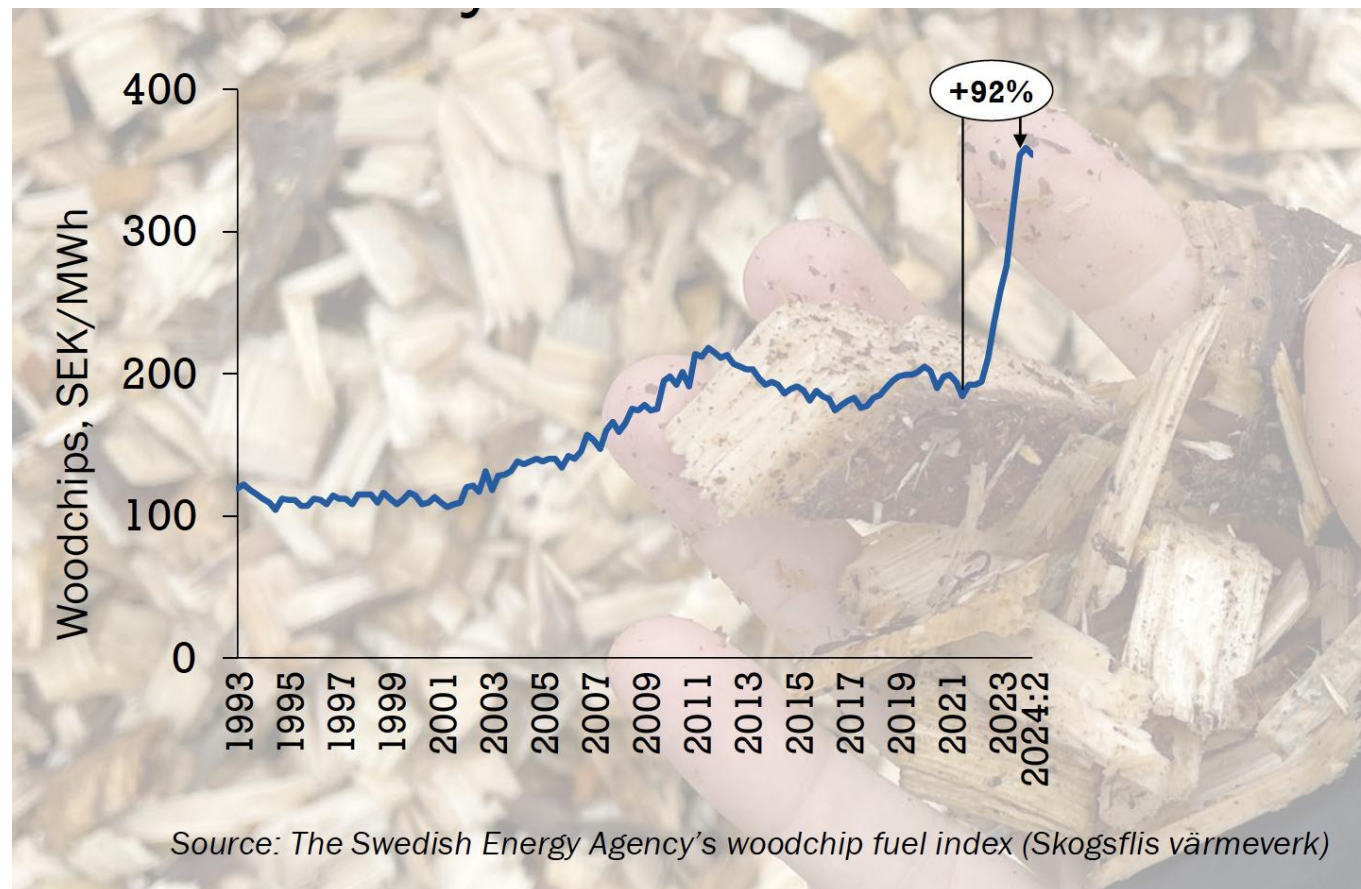
Biokraft



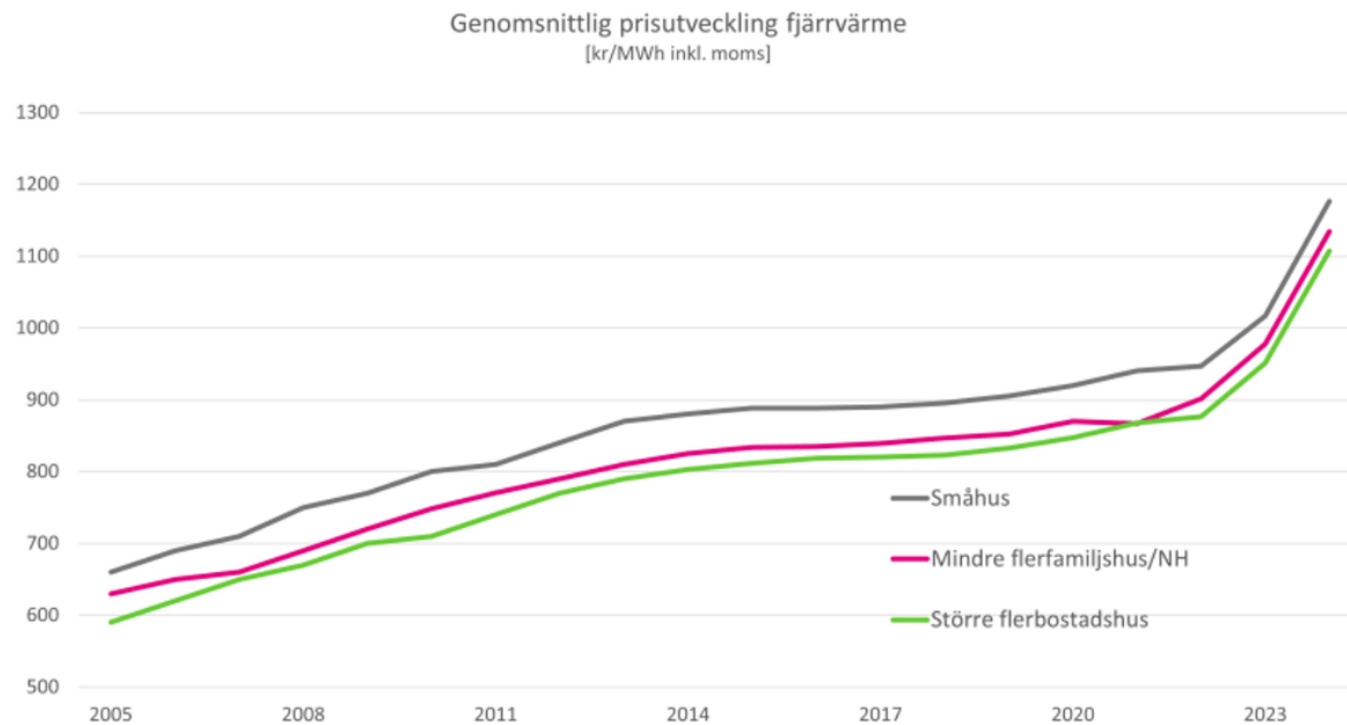
- Det finns 266 biokraftvärmeverk i drift och omkring 40 anläggningar som planeras eller håller på att byggas.
- Den totala installerade effekten av biokraft är cirka 4 800 MW.
- Den totala normalårsproduktionen för dessa kraftvärmeverk är cirka 17,5 TWh el.



***Priserna på biomassa
har fördubblats under
de senaste två åren***



Fjärrvärmen ökar i pris



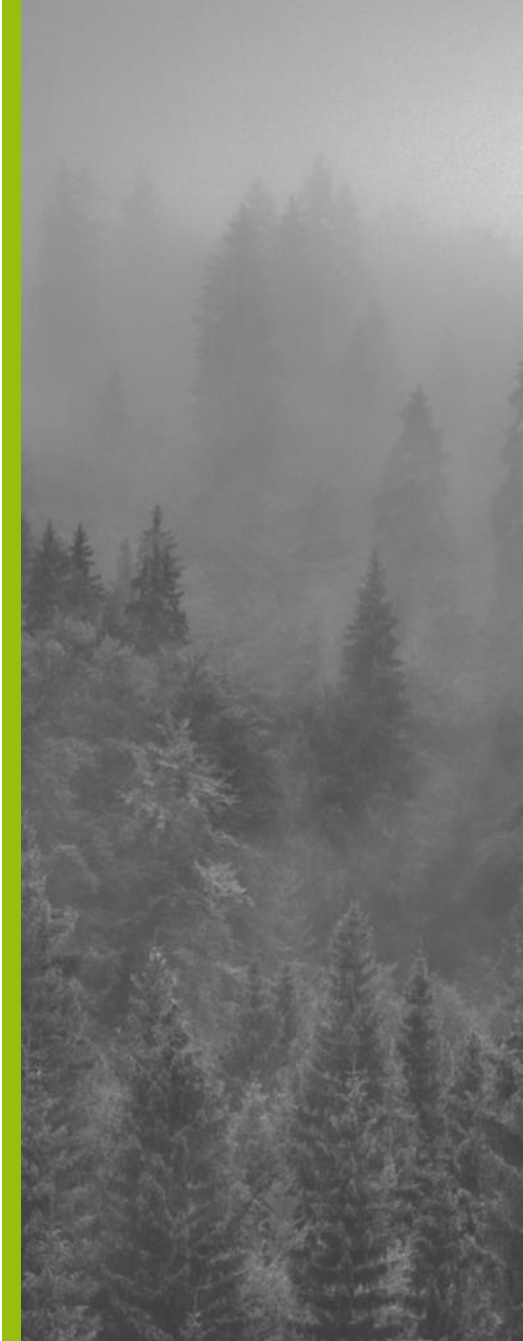
Källa: Nils Holgersson, 2024

- Prisökning i snitt ca 16 procent 2024
- Orsaker: Minskad import av biomassa från Ryssland, Ukraina och Belarus. EU-länder köper från Sverige (låg kronkurs), minskat byggande (mindre restavfall) höjda ETS-priser

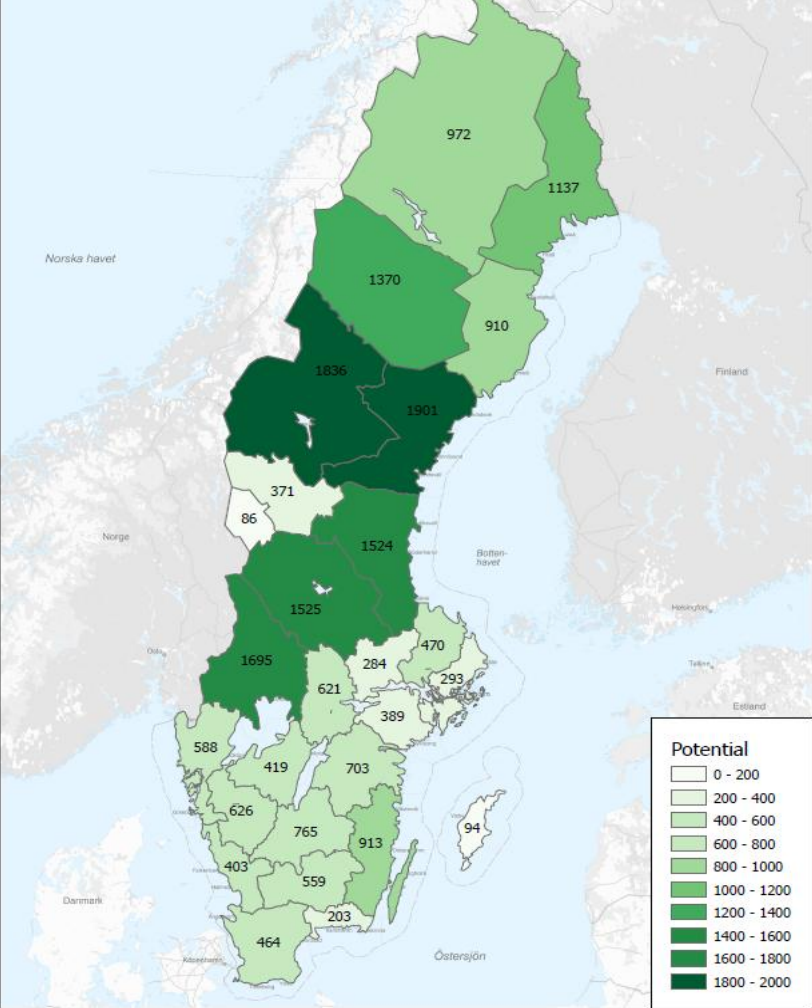
Ökad biomassapotentzial

Ökad potential jordbruksbaserad bioenergi	Energi (TWh)	Ökad potential skogsbaserad bioenergi	Energi (TWh)
Halm (spannmål och oljeväxter)	2-3	Grenar och toppar (grot)	13-16
Gödsel och organiska restprodukter (biogas)	8-10	Skadad rundved (insekter, storm m.m.)	3-4
Biomassa från outnyttjad åkermark m.m.	5-10	Klen rundved (eftersatta röjningar m.m.)	2-3
Slytäkt (åkerkanter, igenväxande betesmarker, ledningsgator m.m.)	8-10	Biprodukter (bark, spån, lignin m.m.)	6-12
Summa	18-26	Summa	24-35
<i>Medeltal</i>	22	<i>Medeltal</i>	29

Källor: Baserat på sammanställd statistik från Skogforsk, Skogsstyrelsen, Energimyndigheten, Jordbruksverket och KSLA.



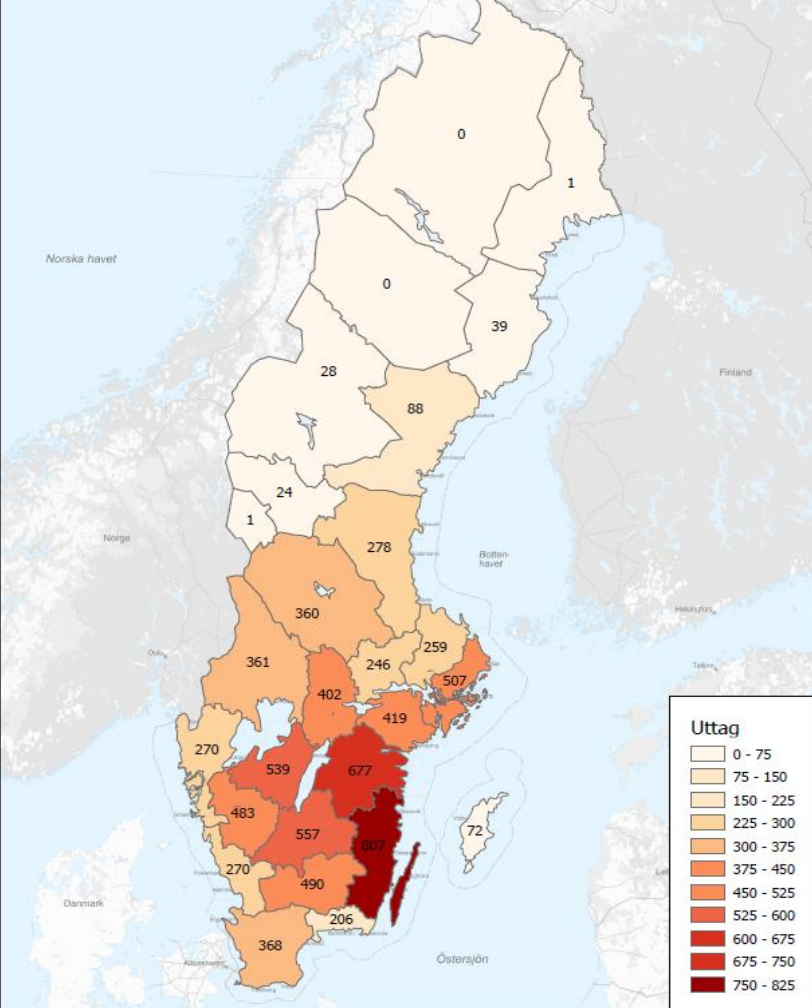
Potential Grot 2020
GWh



Hållbar potential 21 100 GWh

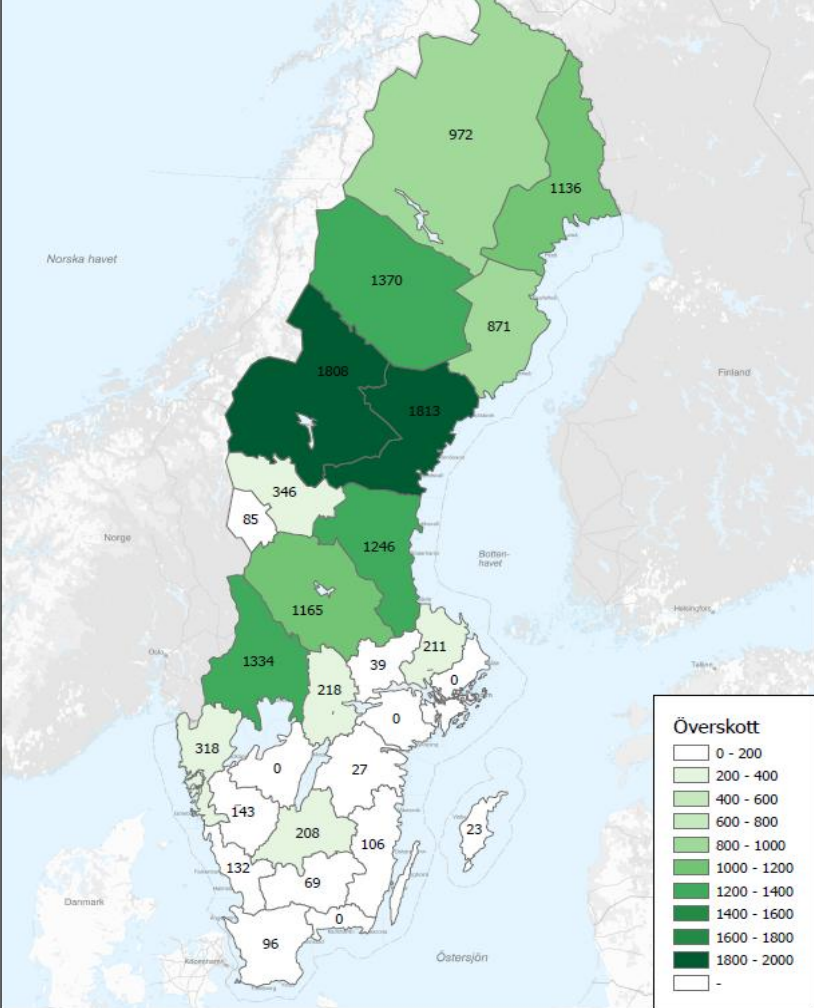
Källa: Skogforsk

Uttag Grot 2020
GWh



Nuvarande uttag 7 400 GWh (37%)

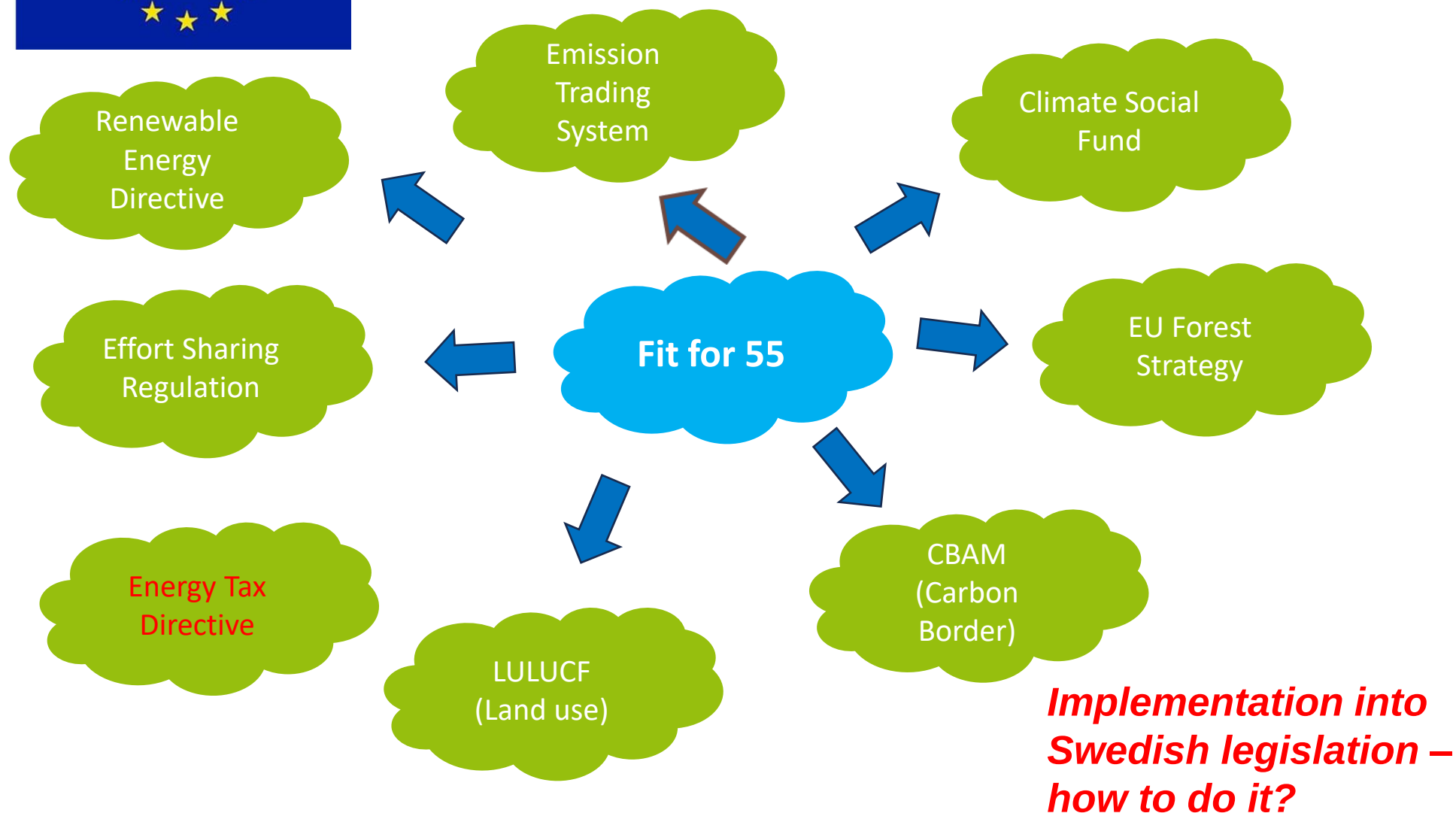
Överskott Grot 2020
GWh



Utrymme för expansion 13 700 GWh



Fast Development of New Legislation



More clouds...





**Johnny Kjellström,
näringspolitisk chef**

johnny.kjellstrom@svebio.se

+(46) 72 148 28 70

Svenska Bioenergiföreningen
www.svebio.se

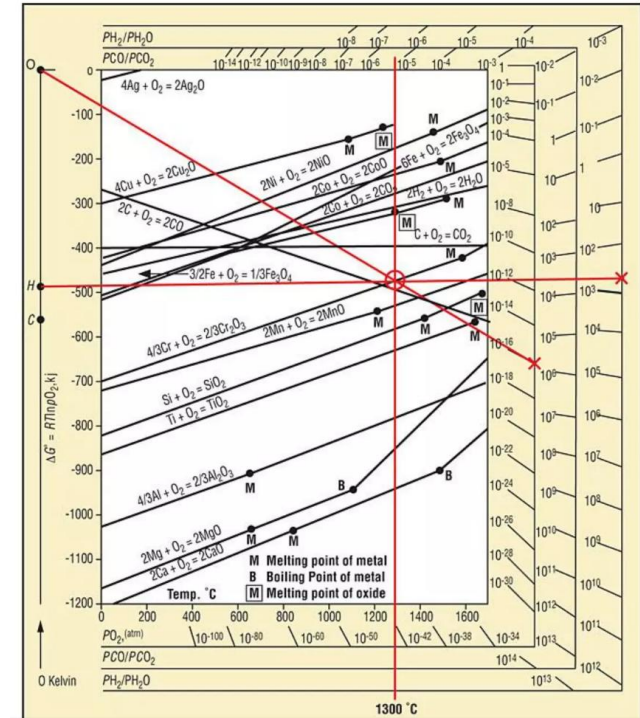


Tekniska försök biokol i metallurgi

Chuan Wang

Why biocarbon is needed in various metallurgical processes?

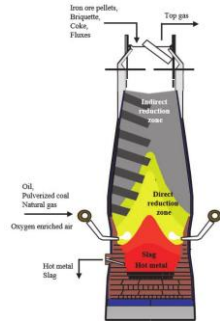
- Fossil carbon (coal, coke, natural gas, etc.) is still in use, thus leading to the emission of fossil CO_2 ;
- Thermodynamic constraints: not all carbon can be replaced by hydrogen, e.g. Cr_2O_3 , SiO_2 , TiO_2 , etc.;
- Carbon is still needed as carburizing agent, slag foaming agent in EAF, etc.;
- Economic feasibility: hydrogen vs. biocarbon.



Ellingham Diagram

Carbon for iron- and steelmaking

BF



(450-500 kg/thm)

- Reducing agent
- Fuel
- Carburization
- Skeleton (coke)

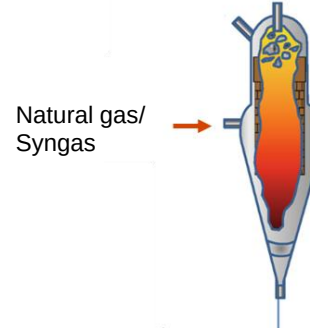
EAF



(12-55 kg/t-steel)

- Slag foaming agent
- Reducing agent
- Carburizing agent
- Fuel

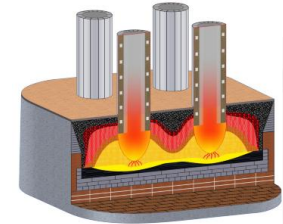
DR-SF



0.2-0.6 MWh/t-DRI

- Carburizing agent
- Fuel

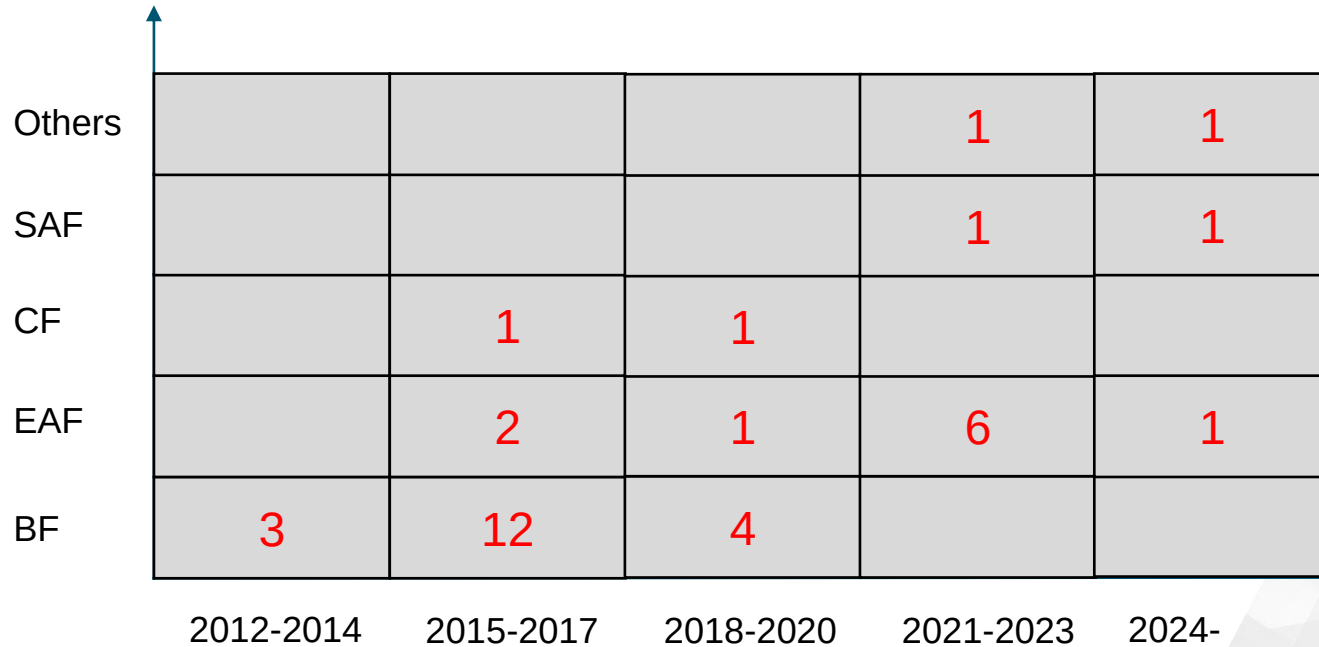
SAF



(300-500 kg/thm)

- Reducing agent
- Fuel
- Carburization

Number of biocarbon projects at Swerim



Others				1	1
SAF				1	1
CF		1	1		
EAF		2	1	6	1
BF	3	12	4		
	2012-2014	2015-2017	2018-2020	2021-2023	2024-

Required properties of biocarbon for metallurgical applications

In general, it requires high heating value, low P and S, low alkali (Na and K), low ash content.

For injection

- Good grindability/fluidability
- Combustability/burnt-out rate

For top charging

- High density
- High mechanical strength

Fuel

- High heating value
- High C and H

Carburization

- High fixed carbon
- Low reactivity

Reductant

- High C and H
- High volatile content

Slag foaming agents

- High C and H
- High volatile content



Biocarbon powder



Biochar

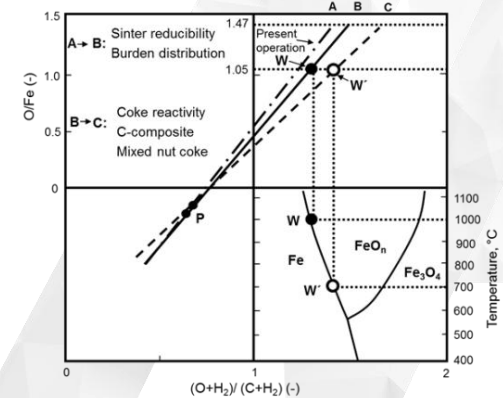
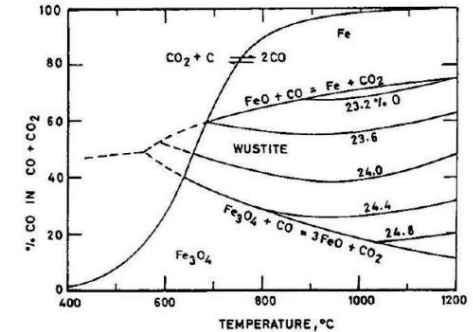
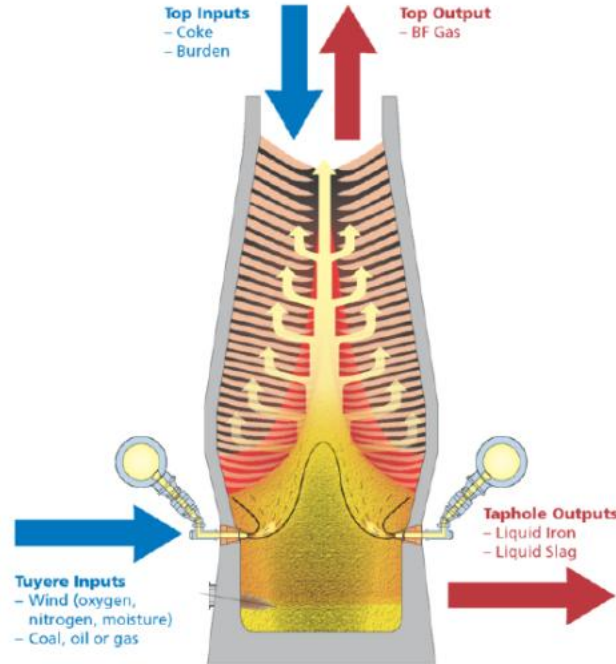
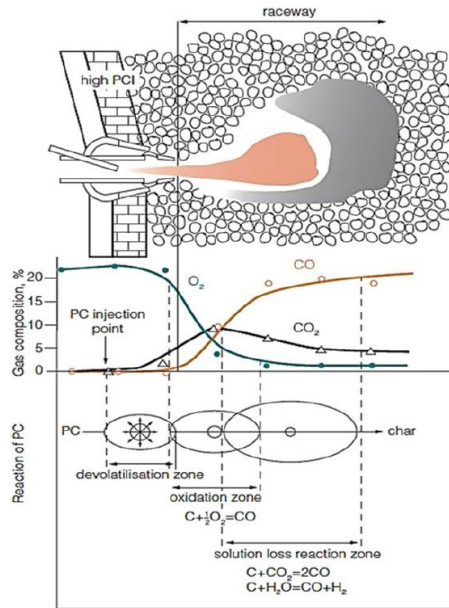


Torrefied material



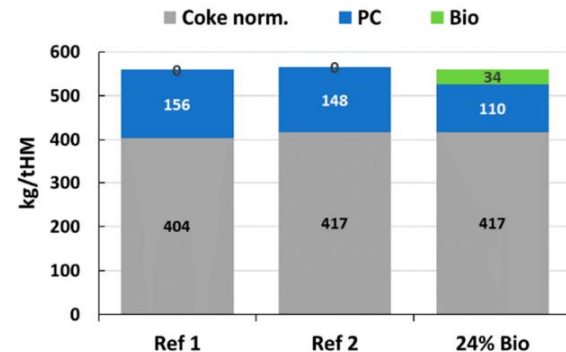
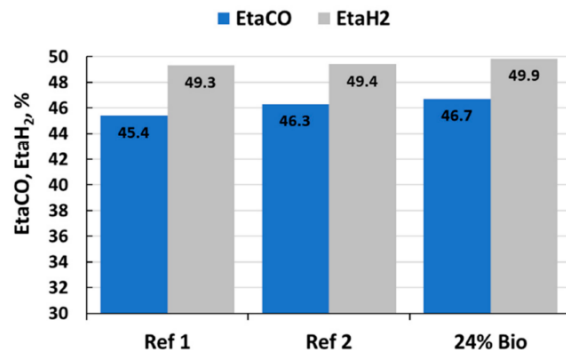
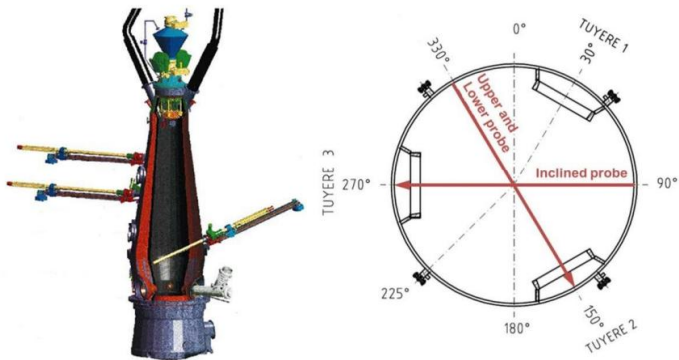
Hydrochar

Utilization of biomass in the blast furnace



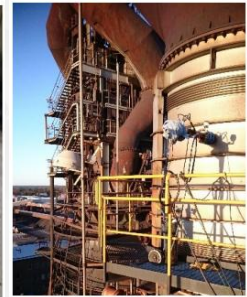
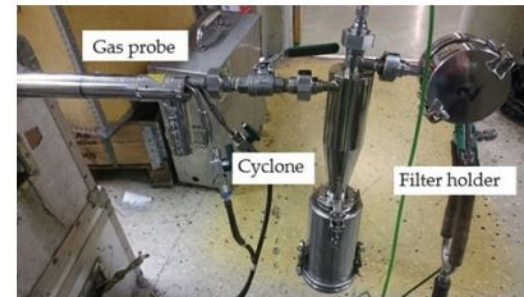
Injection of bio-coals – EBF trials

- Pilot test in the Experimental blast furnace (EBF) with torrefied material of bio-coal
 - ✓ The gas efficiency was somewhat higher during the test period with biocoal
 - ✓ In comparison to the reference periods, the fossil CO₂ emissions could be reduced compared with an average of approximately 8% in the two reference periods



Bio-coal for lowering fossil greenhouse gas emissions from the blast furnace ^{SWERIM}

- Practically demonstrate the potential of industrial use of biomass (**charcoal** and **TS**), consisting of renewable energy, in Swedish blast furnaces to reduce fossil CO₂ emissions from the process in the short term.
- Full scale trials with charcoal in SSAB BF No. 4 in Oxelösund with coal injection through **one tuyere**.
- Injection of up to 10% of charcoal (CC) with PC can be safely achieved without negative impacts on PC injection plant or BF operational conditions and **without losses of CC with the dust**.



Biocoal injection at SSAB Raahe

SWERIM

Hearth diameter: 8.0 m
Working volume: 1220 m³
Tuyere: 21
100% pellets since 2011



System designed for fossil coal



The most straightforward option would be to utilize existing system also for biocoal



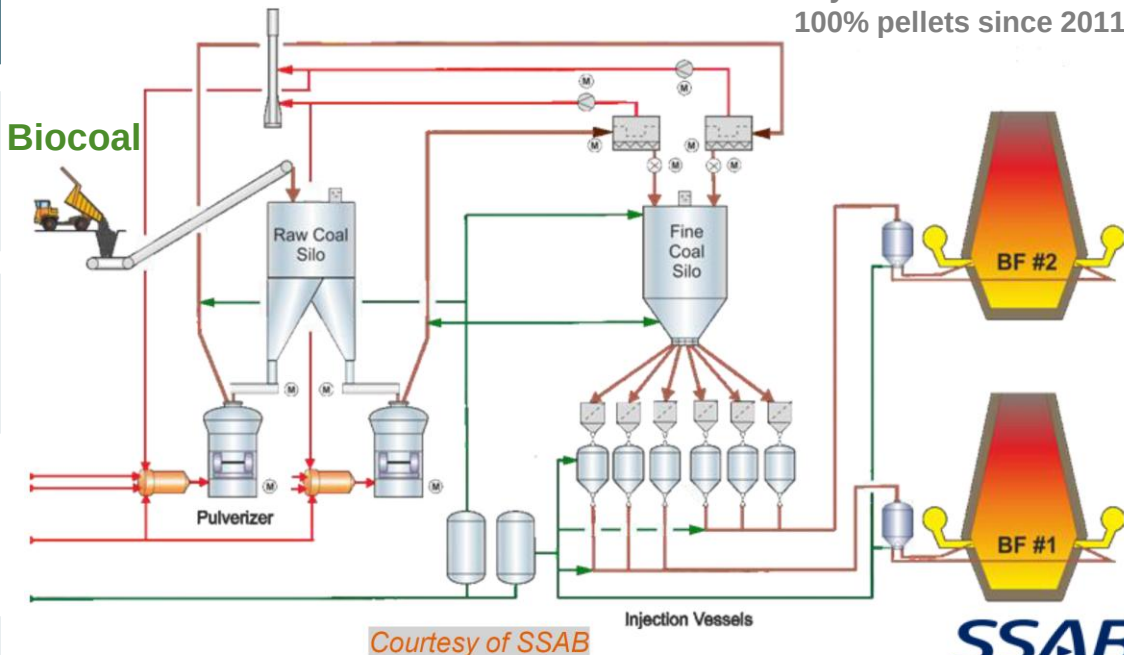
Successful 9-days trial run by SSAB Raahe Steelworks to replace 10% of PCI in August 2019



Lower need of limestone due to low ash and low S content in biocoal



Up to 20% could be possible with the current technical solutions



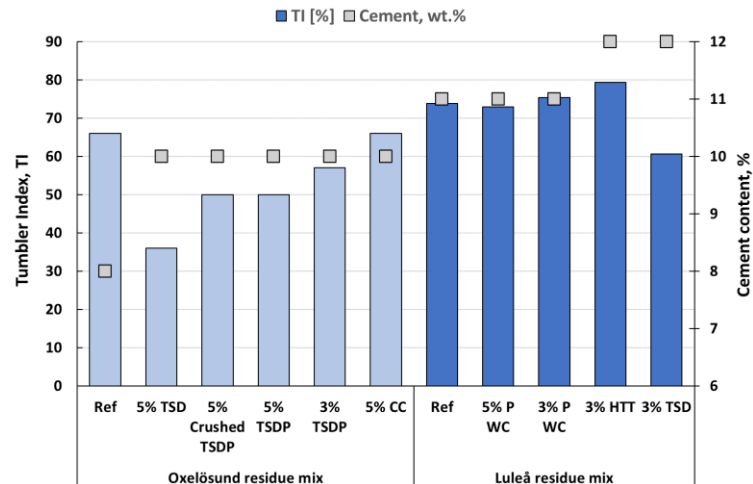
SSAB

Trials with sawdust pellets CBBs

Industrial trials at SSAB Öxelsöund

1.8% of torrefied sawdust (TS) pellets and 12% cement, November 2019

- ❑ Improved gas utilization
- ❑ Lowering of thermal reserve zone temperature by 45 °C with 55% bio-briquette addition reduced the C-consumption with ~ 9-11 kg/tHM
- ❑ Compared to the reference period, no negative effects were noticed regarding the hot metal analysis, slag and dust analysis.

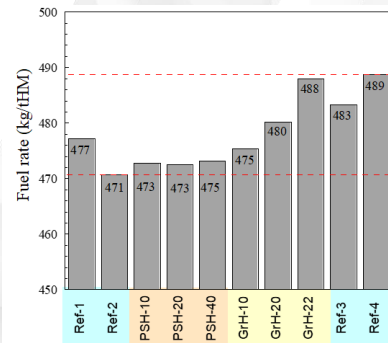


Swedish energy agency
(energimyndigheten) project:
Bio-agglomerate

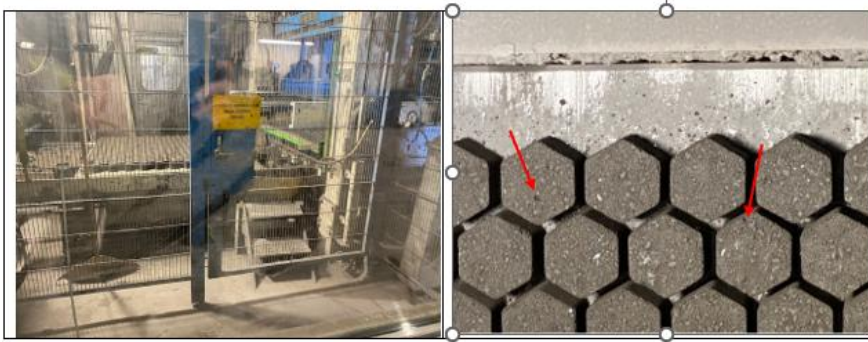
Industrial trials in BF at SSAB

Hydrochar containing cold bonded briquettes (CBBs) 418 ton were top-charged into BF, January-February, 2020.

- ❑ No negative effects were noticed regarding the hot metal analysis, slag analysis and their properties, carbon and sulfur content in dust and sludge.
- ❑ The trials with hydrochar from paper sludge showed a slightly better results than green waste.



Industrial Scale CCBs trials at BDX/SSAB



- Full-scale tests, but then with a higher admixture of biochar from 1.8% to 12%.
- 5500 tons of biochar CCBs were produced and top charged in the BF at Luleå.

EAF - Carburization test at Swerim

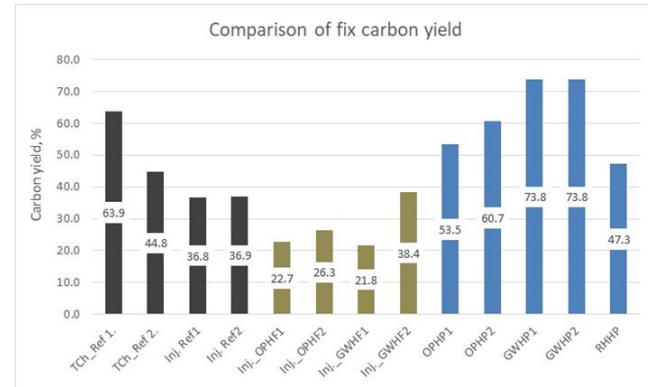
EAF trials in Swerim's test bed were performed in Week 50, 2021 to investigate the use of various types of hydrochar as carburizers to replace anthracite.



EAF injection charge



EAF top charge



Carbon yield/carburization

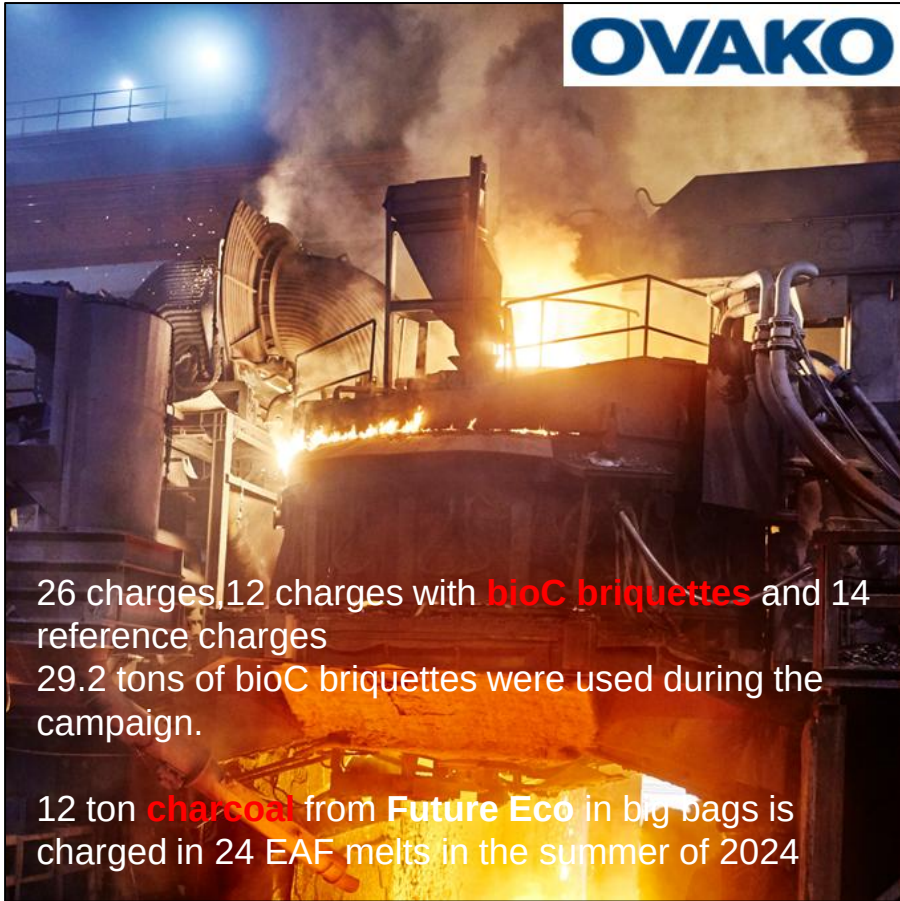
BioChargeEAF project

SWERIM

44 tons of bioC briquettes



Compon ents	Biocarbon		Mill scale	Lignin	FP-P (liquid lignin)		Lime		water								
	wt. %																
Ratio	40.1		26.7	15.0	13.4		0.5		4.3								
Component	Total C	VM	Ash/oxides		Moisture	S	H	O	N	Cl							
wt. %	50	30.8	40.3		4.1	1.5	2.2	5.9	<0.11	<0.01							
Aska/ Ash	Al	P	Fe	Ca	Mg	Si	K	Na	Mn	Ti	Co	Cu	Cr	Mo	Ni	V	Zn
Wt. %	0.53	0.033	51	3.4	0.61	1.8	0.46	0.42	0.37	0.023	0.008	0.072	0.46	0.08	0.23	0.016	0.01



26 charges, 12 charges with **bioC briquettes** and 14 reference charges

29.2 tons of bioC briquettes were used during the campaign.

12 ton **charcoal** from **Future Eco** in big bags is charged in 24 EAF melts in the summer of 2024

EAF industrial trials with at Uddeholm

Uddeholm trial 1: 3 ton charcoal from **Envigas** in big bags is charged in 7 EAF melts in November and December 2023.

Uddeholm trial 2: 2.4 ton charcoal from **Future Eco** in big bags is charged in 7 EAF melts in February 2024

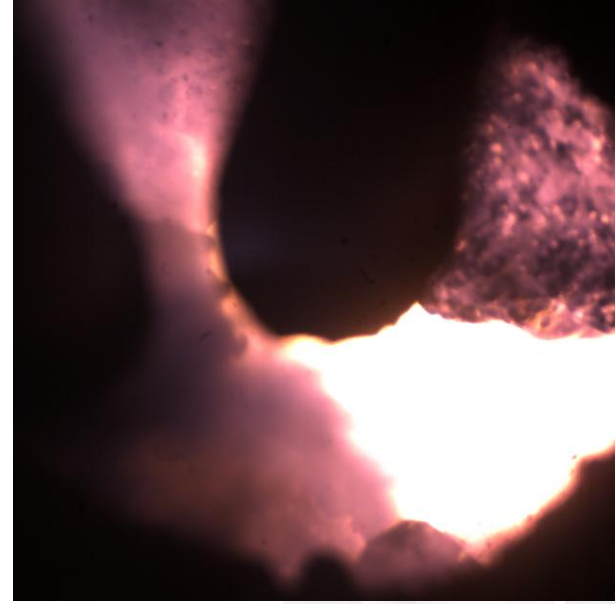
4 reference charges with petcoke for comparison.



Cupola furnace injection

- Hydrochar injection at Volvo Power Truck, Skövde, Sweden
- 1600 kg injection through one tuyere in May, 2019

Vinnova project: OSMET 2.0



Cupola furnace top charging

Bio-briquettes developed:

- Dimensions: Ø 80-150 mm, H= 50-150 mm
- C-content: 50 – 70 %
- S-content: 0.2 - 0.35 %
- CCS: up to 14 MPa
- Density: up to 1.000 kg/m³
- Abrasive losses: < 4.5 %

In 2020 - 2022 over 50 pc. different test series with durations 6-120 hours using a total amount of about 800 ton of testing material were carried out at 13 different cupola plants all over europe:

- Hot- and cold-blast cupola furnaces
- Nominal melting rates 6-75 t/h
- Dry and wet gas cleaning systems
- GJL and GJS products
- Automotive parts and other castings (e.g. tubes etc.)







Pre-trials
Week 39-40 2023

Scale up from lab scale to industrial scale

- 24 recipes with biocarbon

Evaluation of briq:

- Mechanical strength
- Hot strength



Large-scale briq
Week 50 2023

Briquettes 360t = 36t
biocarbon

- Dust to silo

Evaluation of briquettes

- Drop test
- Tumbler index



Furnace campaign
Week 5&6 2024

Week 5

- Charge REF Briquette

Week 6 & 7

- Charge Bio briq
- Charge REF briq



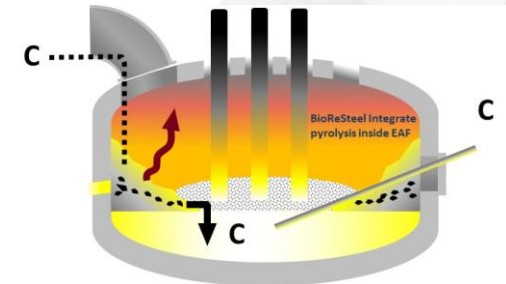
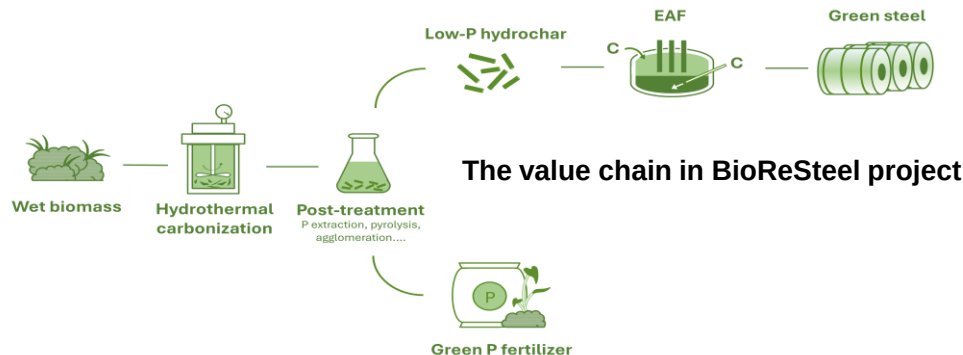
Ongoing BioReSteel prroject



SWERIM

Objective: to replace fossil carbon in the electric arc furnace (EAF) by biocoal, produced from low-value locally available wet biomass residues by means of a hydrothermal carbonization (HTC) process.

Methodology: The BioReSteel concept will be proved by the means of laboratory and EAF testbed trials. Furthermore, the industrial EAF trials will be performed at three EAF plants to test hydrochar injection, hydrochar top charging and bio-oxides agglomerates in order to prove the concept's flexibility and generality.



Functions: heating; carburization; reductant; slag foaming

Industrial trials at EAF steel plants



EAF (150 ton), PITTINI, Italy

Top charging of hydrochar as slag foaming agent and fuel to reduce natural gas and anthracite assumption.



EAF (85 ton), ORI Martin, Italy

Top charging of bio- agglomerates (made of hydrochar and iron oxides) for the function tests of carburizing agent and reductant.



EAF (150 ton), CELSA, Spain

Injection trials for hydrochar at different blending ratio with anthracite for slag foaming and fuel.

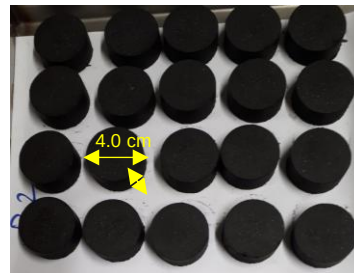
Briquetting at lab scale



manual piston press



semi-automatic piston press



2.0 cm

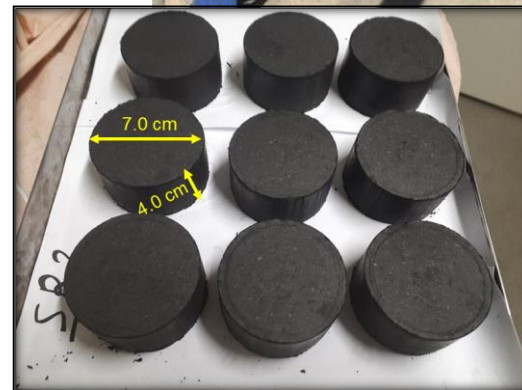
Ø 70 mm



up to 60 tons

Ø 20 mm

Ø 40 mm



Briquetting at technical and pilot scale

SWERIM

Pilot scale briquetting



Roller press

Vibro press



Extruder



Pillow shape: 40 x 30 x 20 mm



Hexagonal shape briquettes



Summary

- Many projects on using biocarbon in metallurgical applications.
- Biocarbon (different types) has been tested in BF via tuyeres injection and top charging in the form of CCBs.
- The current work about EAF industrial pilots has been focusing on topcharging of biocarbon as carburizing agents, and in the future other functions of heating, reductants and slag foaming agent will be also tested.
- Research interests in other metallurgical processes, for instance, SAF, DR, etc. have been increasing.
- Woody biomass to organic waste to produce biocarbon (e.g. hydrochar) in the view of economic feasibility and sustainability.

Block 2 – Användning av biokol och tekniska erfarenheter

HåBiMet

Position, requirements and wishes for metal industry`s use of
carbonaceous materials

Gunnar Ruist, GRU Konsult jan 2025

Background

- Beside blast furnaces (that have existed in a 1000 years but beeing outphased in Nordic countries) and in Höganäs, where carbon is a reduction agent for iron ore, steel industry uses carbon as:

alloying element

fuel

reactions in slag (foaming where formation of CO/CO₂ is used)

also for reduction of internal oxidic residual products

The volumes are significantly lower than in a blast furnáce

Also carbon is used for reduction of oxidic cromite ore for making of ferrochrome

Background

- Requirements on productivity and energy efficiency
- Safety
- Simplicity in handling
- Stability, conformity in properties
- Standardisation

Demands on

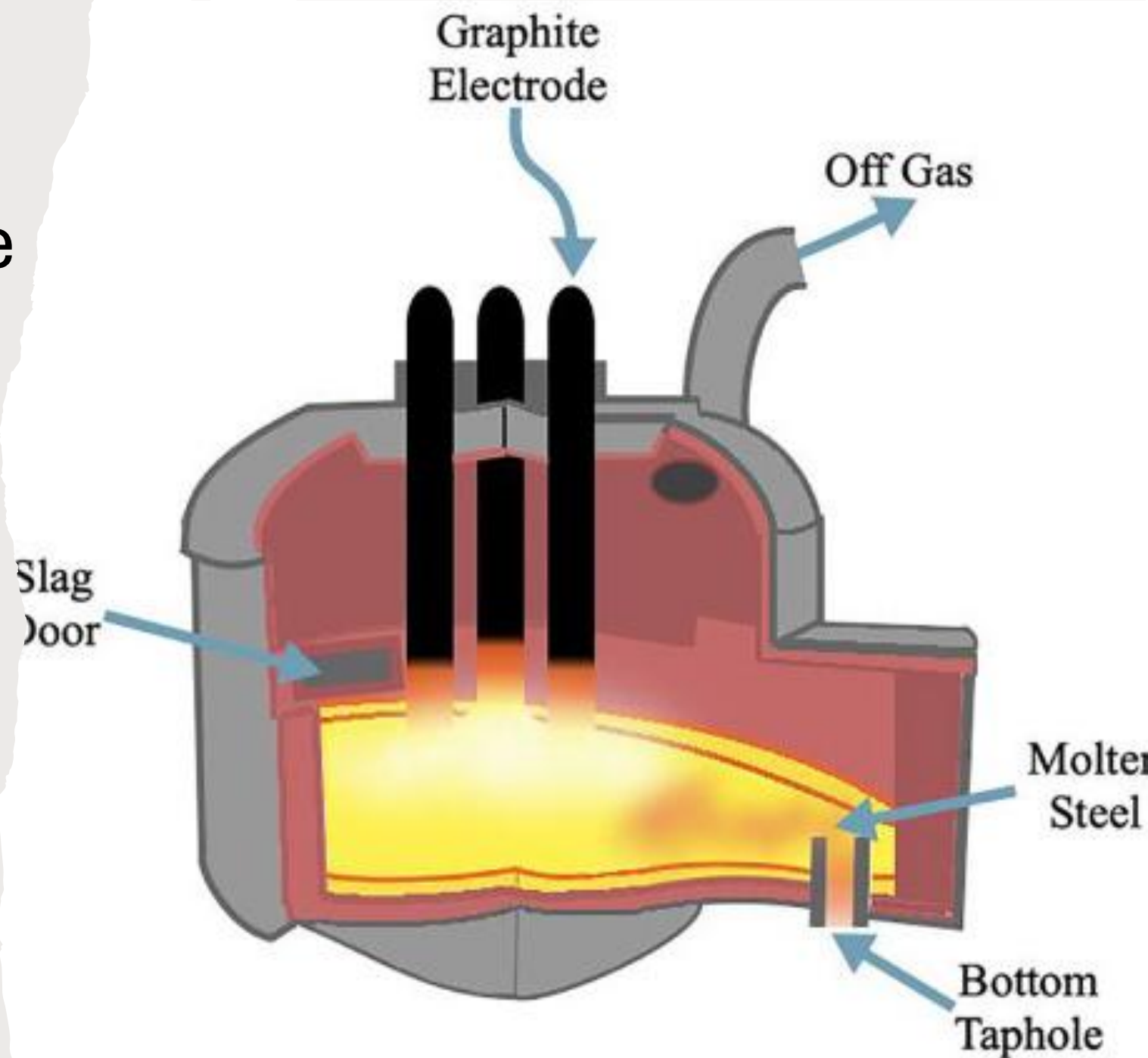
- Reactivity
- Density
- Grain size
- Composition

Wishes

- "Lagom"
 - Reactivity, not too quick
 - Density
 - Grain size
 - Level of minor elements
 - Strength

EAF, electric arc furnace

- Carbon added during the process
- Lump or injection
- Reacts with the melt and/or the slag
- Heavy stirring, gas formation, heat generation



Vad vill vi undvika?

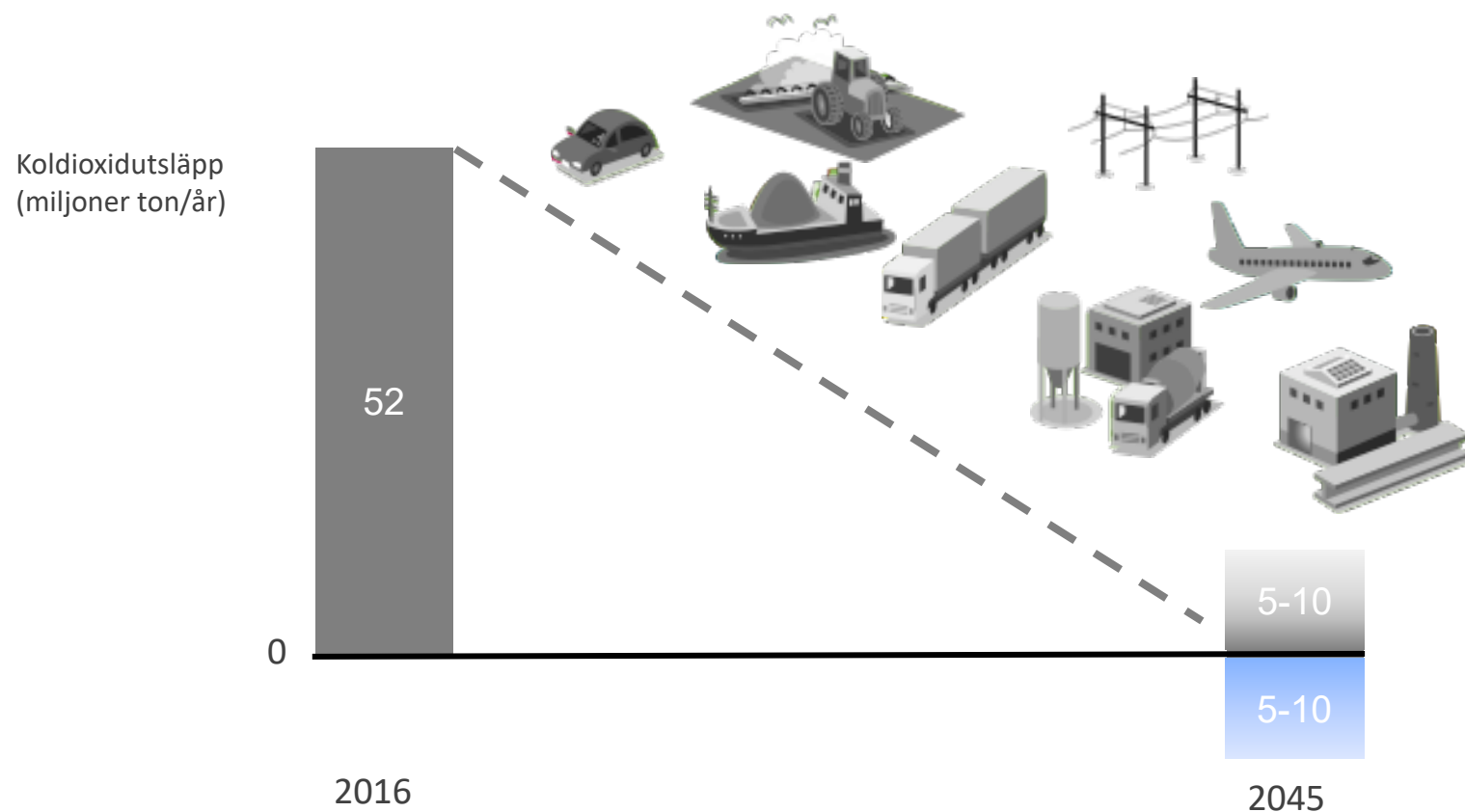
- P, fosfor (kan raffineras bort till vis del i vissa processer)
- Alkali
- Utbytesförluster

Biokol i marken – en introduktion

Cecilia Sundberg
Energi och teknik, SLU

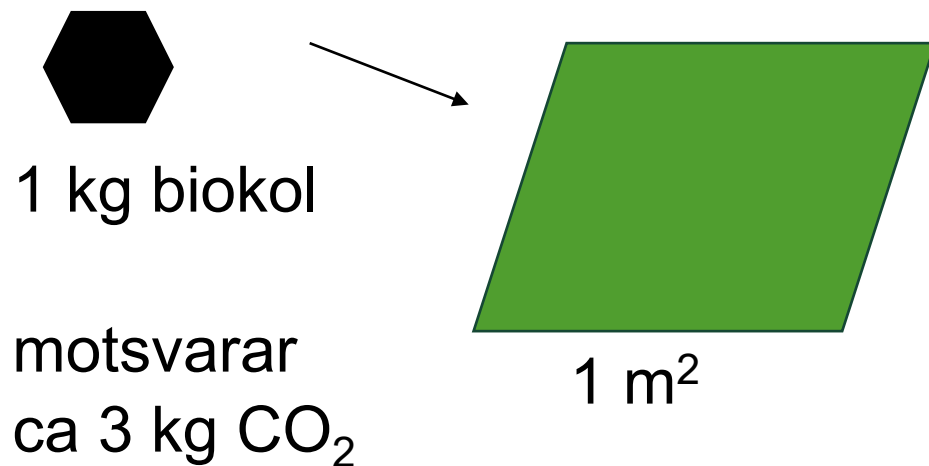


Sweden needs negative emission technologies



Biochar is one of few identified methods

Biokol som kolsänka



Stor andel kvar i marken om 100år



Climate change mitigation with biochar:
carbon storage $\pm$ soil effects

$\pm$ substitutions

– supply chain

Biokols klimatpåverkan

- Kolinlagringen!

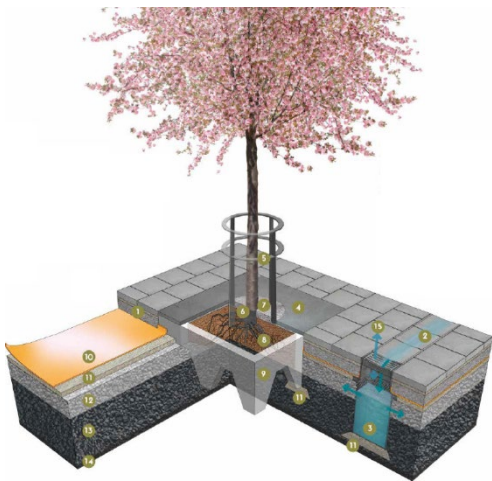
Men också:

- Klimatpåverkan i produktion, distribution, användning
- Ersätts andra produkter? **substitution viktig faktor (energi och material)**
- Påverkan på växthusgaser i mark (N_2O , CH_4 , markkol) **stor osäkerhet**
- Påverkan på skörd
- Albedo-effekt

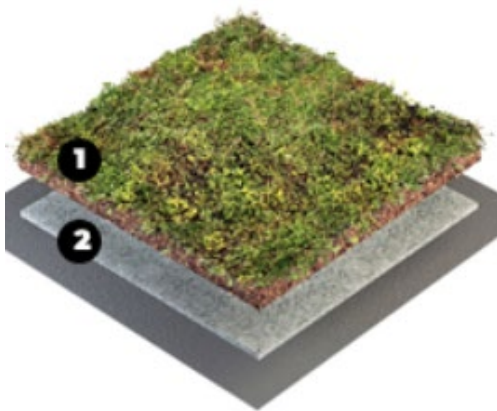


Biokolanvändning i Sverige

- Främst i stadsmiljö: trädplantering, gröna tak, anläggningsjord
- Nya produkter under utveckling: biokolsbetong, vattenfilter
- Jordbruksanvändning: Liten experimentell användning. Biokol och gödselblandningar
- Efterfrågan större än produktionen i landet – biokol importeras



© Stockholms stad



© VegTech AB



© Hasselfors AB



© BiokolProdukter AB

20-tal anläggningar i Sverige

- Lantbruk
- Återvinningsföretag
(Stockholm, Helsingborg, Södertälje)
- Företag i Gröna näringarna
(Skånefrö, VegTech)
- Solör - fjärrvärme
- Skanska
- Envigas

Nuntorps
Naturbruksskola
400 kW

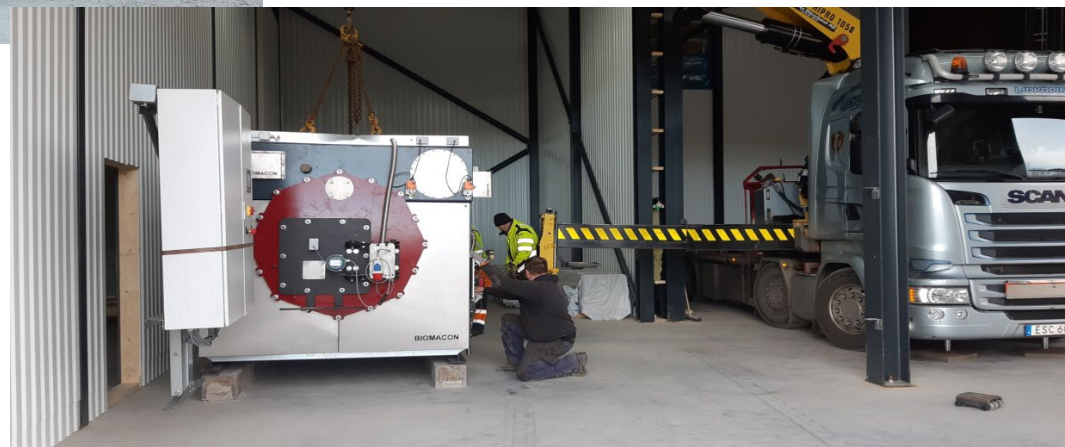


Kiplingebergs Gods
Uppsala
224 kW



Lindeborgs gård 2017

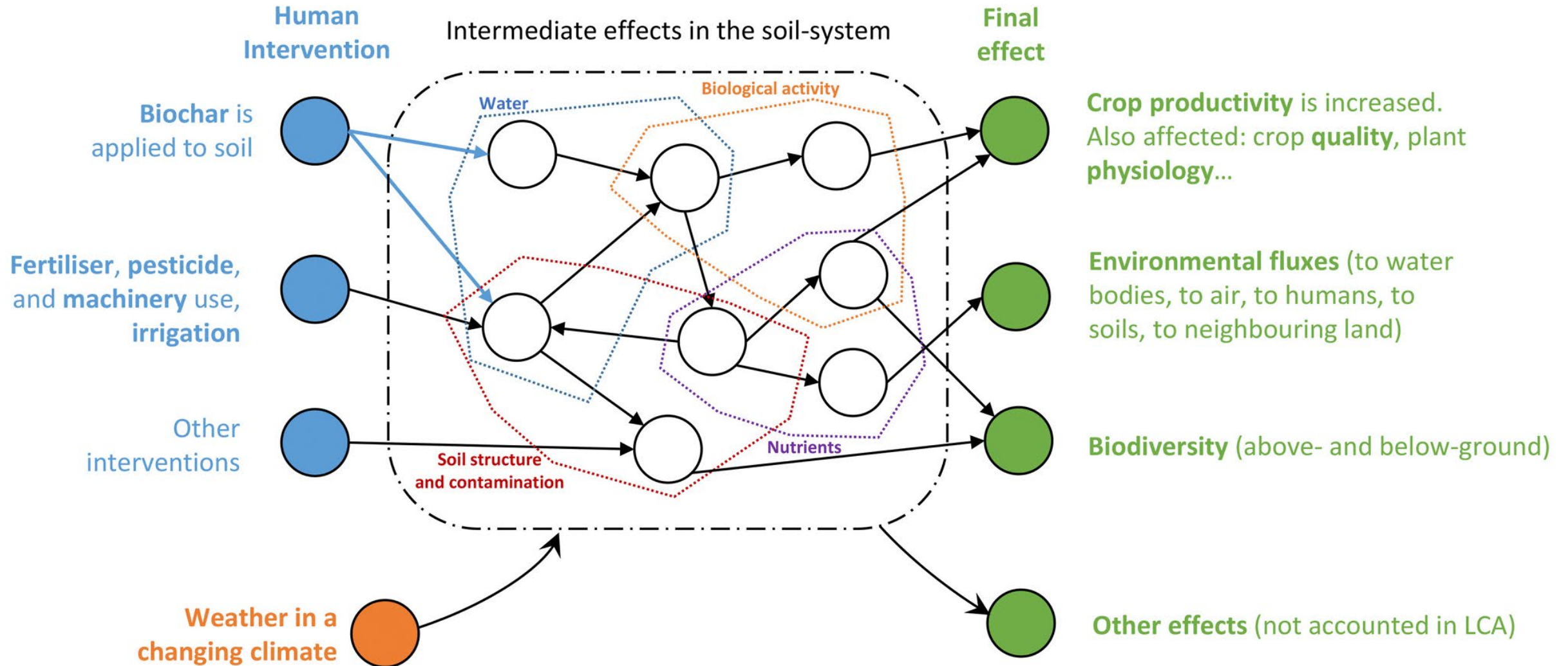
Foto Elias Azzi



Hasta gård, Arboga 160 kW

Foton Edvard Hamilton

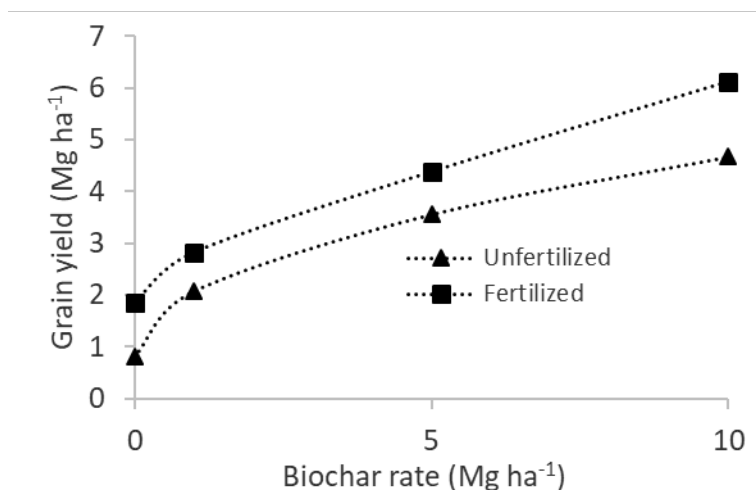
Biochar effects in soil



Biochar affects yield and water retention

Maize yield, 8 sites in Kenya

Grain yield response (increase relative to control)



Kätterer m.fl. 2022

<https://doi.org/10.1007/s13593-022-00793-5>

Meta analysis:

- On average 25% yield increase in the tropics
- No significant yield effect in temperate regions

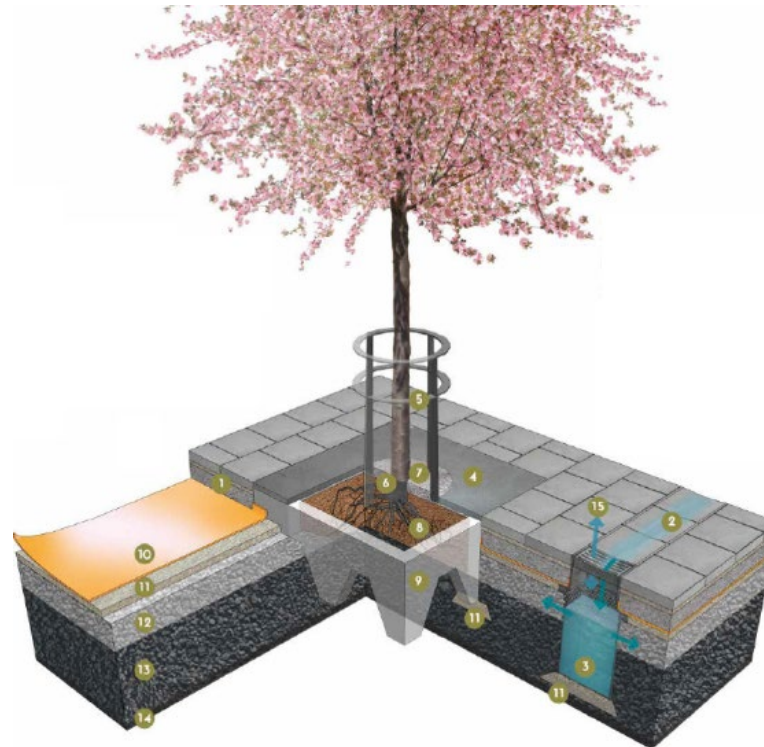
Jeffery m.fl. 2017. Environ. Res. Lett. 12, 053001

- Biochar increases long-term evapotranspiration rates, and therefore plant water availability, by increasing soil water retention capacity – especially in water-limited regions
- Variable impact highlights the need for targeted research on how biochar affects the soil-plant-water cycle.

Fischer et al 2018 Sci. Tot. Environ.

Biochar effect on soil

- Other significant effects on crop growth are possible, also in temperate climate!
- Dependent on
 - soil quality,
 - crop type,
 - climate,
 - biochar quality



Biochar as filter material

- General: biochar known to be a good filter material. Less so for N than other pollutants
- Specific: dependent on
 - Biochar characteristics
 - Specific pollutants
 - Pollutant concentration
 - Temperature
 - Retention time
 - Filter saturation

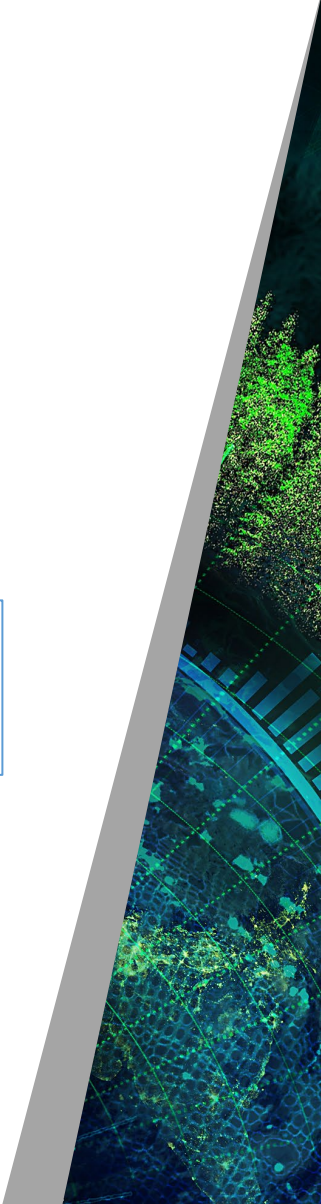
European Biochar Certificate

For gaining the European biochar certificate, criteria have to be met regarding

- the biomass feedstock,
- the production method,
- the properties of the biochar
- the way it is labelled
- the way it is applied

Coupled to C-sink
climate certification

<https://www.european-biochar.org/en/ct/2-EBC-and-WBC-guidelines-documents>

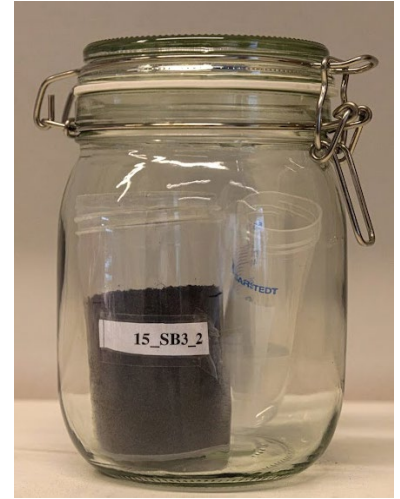


EBC -Certification Class		EBC-FeedPlus	EBC-Feed	EBC-AgroOrganic	EBC-Agro	EBC-Urban	EBC-ConsumerMaterials	EBC-BasicMaterials
Elemental analysis	Declaration of Ctot, Corg, H, N, O, S, ash							
	H / Corg	< 0.4		< 0.7				
Physical parameters	Water content, dry matter (as received and @ < 3mm particle size), bulk density (DM), WHC, pH, salt content, electrical conductivity of the solid biochar							
TGA	Needs to be presented for the first production batch of a pyrolysis unit							
Nutrients	Declaration of N, P, K, Mg, Ca, Fe							
Heavy metals	Pb	10 g t ⁻¹ (88%DM)	10 g t ⁻¹ (88%DM)	45 g t ⁻¹ DM	120 g t ⁻¹ DM	120 g t ⁻¹ DM	120 g t ⁻¹ DM	declaration, no limit values for certification
	Cd	0.8 g t ⁻¹ (88% DM)	0.8 g t ⁻¹ (88% DM)	0.7 g t ⁻¹ DM	1,5 g t ⁻¹ DM	1,5 g t ⁻¹ DM	1,5 g t ⁻¹ DM	
	Cu	70 g t ⁻¹ DM	70 g t ⁻¹ DM	70 g t ⁻¹ DM	100 g t ⁻¹ DM	100 g t ⁻¹ DM	100 g t ⁻¹ DM	
	Ni	25 g t ⁻¹ DM	25 g t ⁻¹ DM	25 g t ⁻¹ DM	50 g t ⁻¹ DM	50 g t ⁻¹ DM	50 g t ⁻¹ DM	
	Hg	0.1 g t ⁻¹ (88% DM)	0.1 g t ⁻¹ (88% DM)	0.4 g t ⁻¹ DM	1 g t ⁻¹ DM	1 g t ⁻¹ DM	1 g t ⁻¹ DM	
	Zn	200 g t ⁻¹ DM	200 g t ⁻¹ DM	200 g t ⁻¹ DM	400 g t ⁻¹ DM	400 g t ⁻¹ DM	400 g t ⁻¹ DM	
	Cr	70 g t ⁻¹ DM	70 g t ⁻¹ DM	70 g t ⁻¹ DM	90 g t ⁻¹ DM	90 g t ⁻¹ DM	90 g t ⁻¹ DM	
	As	2 g t ⁻¹ (88% DM)	2 g t ⁻¹ (88% DM)	13 g t ⁻¹ DM	13 g t ⁻¹ DM	13 g t ⁻¹ DM	13 g t ⁻¹ DM	
Organic contaminants	16 EPA PAH	6±2.4 g t ⁻¹ DM	CSI-declaration	6±2.4 g t ⁻¹ DM	6.0+2.4 g t ⁻¹ DM	CSI-declaration	CSI-declaration	CSI-declaration
	8 EFSA PAH	1.0 g t ⁻¹ DM						4 g t ⁻¹ DM
	benzo[e]pyrene benzo[j]fluoranthene	< 1.0 g t ⁻¹ DM for each of both substances						
	PCB, PCDD/F	See chapter 10		Once per pyrolysis unit for the first production batch. For PCB: 0.2 mg kg ⁻¹ DM, for PCDD/F: 20 ng kg ⁻¹ (I-TEQ OMS), respectively				

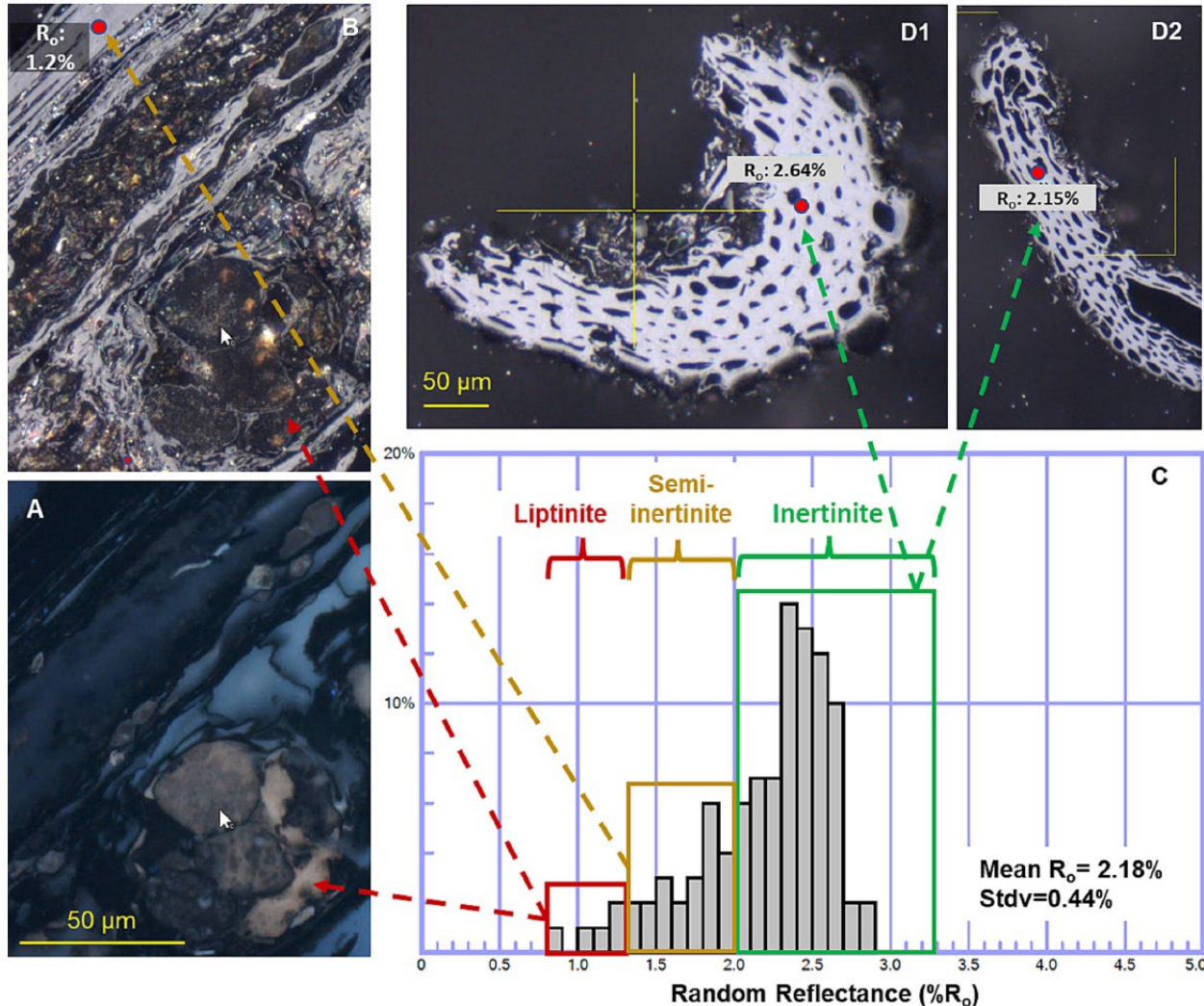
* medical and health care products are not included

How persistent is biochar in soils?

- Biochar, like other material in soil, is decomposed by microorganisms
 - The most persistent fractions decompose very slowly, or not at all
- The persistence of biochar depends on
 - Biochar characteristics
 - The surrounding environment
- Biochar characteristics depend on
 - The feedstock
 - The production process



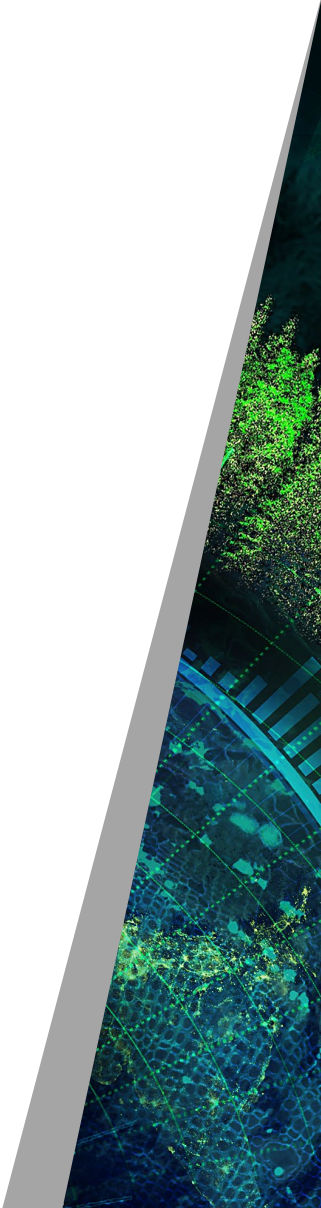
Biochars are different & consist of fractions with fundamentally different chemical properties



- Higher pyrolysis temperature = more persistent biochar
- Lower molar H/C ratio = more persistent biochar
- Other chemical structure analyses and tests: chemical oxidation tests, BPCA, hydrogen pyrolysis, Extended Slow Heating[®] pyrolysis, reflectance, ...

Biochar in the Voluntary Carbon Market

- New, Carbon Dioxide Removal (CDR)-oriented actors (Puro, Carbon Future and others)
- Established carbon offset organisations (Verra and others)



EU – Carbon Removal and Carbon Farming

- New law (voluntary regulation, sv. förordning) for certification of carbon removals, decided in 2024.
- Methodologies for BECCS, biochar, soil carbon etc. under development.

Biomass sources of interest for biochar in soil

- Agricultural residues
 - Woody park and garden waste
 - Wood
 - Sewage sludge?
- 
- Circular systems

NORDIC BIOCHAR NETWORK

Connecting stakeholders across the Nordic and Baltic countries

Transfer of knowledge and research results

nordicbiochar.org



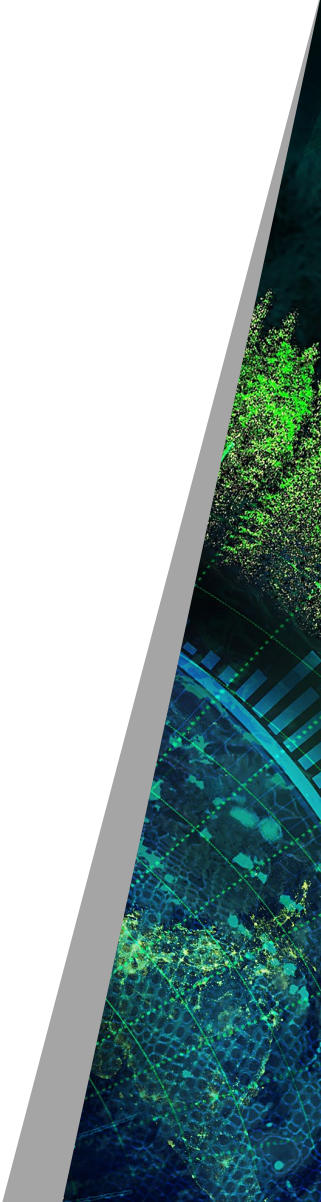
Ändamål

Innovationsklustret Biokol Sverige har som ändamål att bidra till ett mer resurs- och energieffektivt biobaserat samhälle med fokus på biokol och dess klimatnytta. Genom att samla aktörer i ett nationellt nätverk ska föreningen:

- ✓ stimulera innovation inom produktion och användning
- ✓ ta fram och sprida kunskap
- ✓ främja ökad produktion och användning
- ✓ främja biokolets roll som negativ utsläppsteknologi
- ✓ bidra till marknadsutveckling och kommersialisering

Biokolforskning på SLU - forskningsfrågor

- Ger biokol klimatnytta - och i så fall hur mycket?
- Hur utvärdera hållbarhet – inte bara klimat?
- Kan biokol behandla förorenad jord?
- Hur kan biokol användas för vattenrening (inkl. PFAS och pesticider)?
- Kan biokol vara till nytta i djurhållningen?
- Hur stabilt är biokol i marken, på lång sikt?
- Hur påverkar biokol bildningen av växthusgaser i mark?
- Vad har biokol för effekter på växter i urbana växtbäddar, skogsmark, jordbruksmark?



Biokolssystem

Things of concern to us

Climate system

Affected surrounding activities

System boundaries

Markets for biomass and waste

Biomass production

Biomass conversion

Biochar use

Co-product use

Agricultural markets

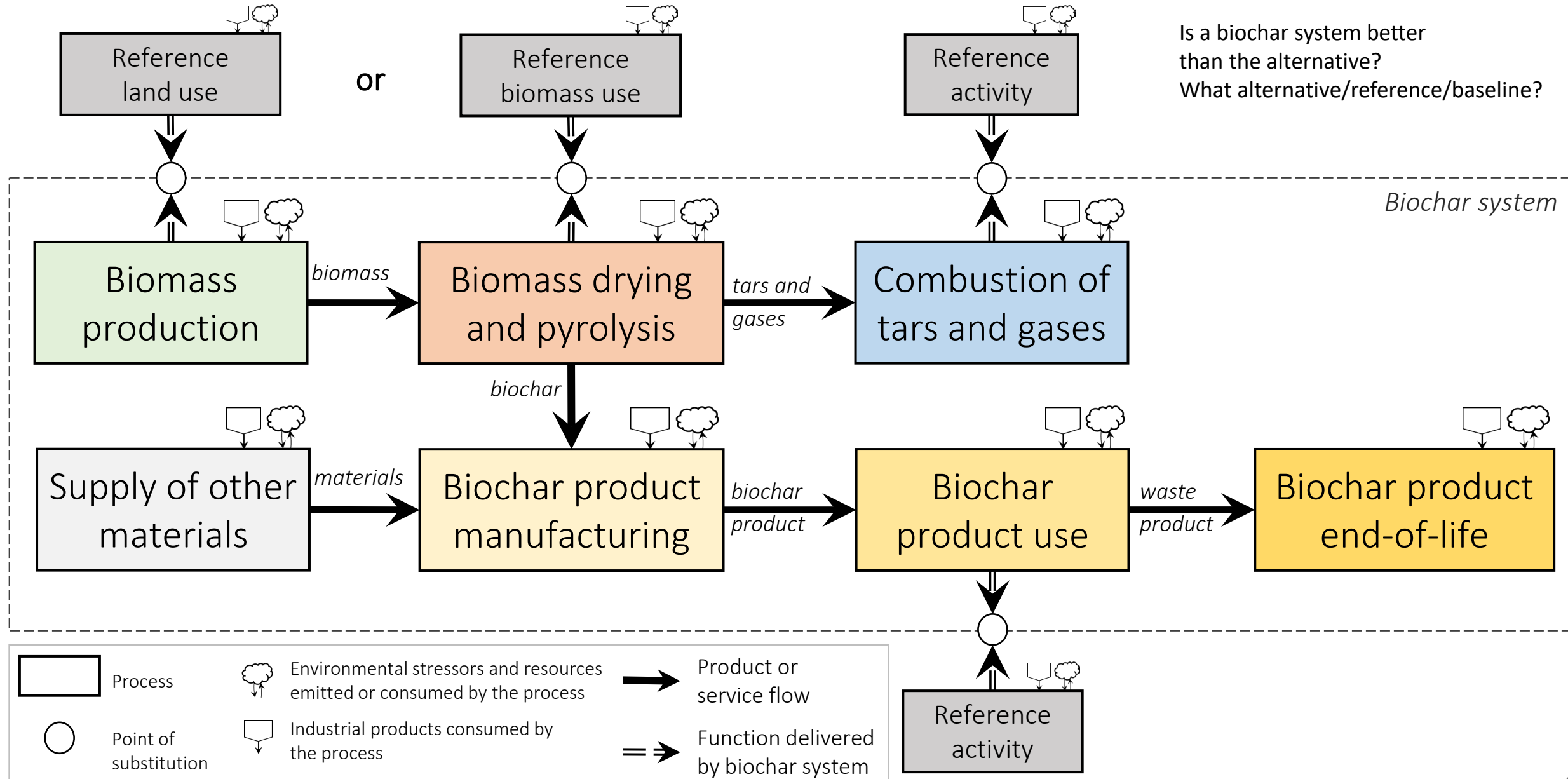
Adsorbent markets

Markets for fuels and chemicals

Land system

Energy system

Systematic description of biochar systems





Upparbetning av HTC

Yu-Chiao Lu (Ishana)

29 Jan, Energiforsks, Stockholm

Agenda

- Self-introduction
- Why hydrochar?
- Technical performance ↔ properties
- Summary

About me

- MSc at Material Science and Engineering Department (MSE) of KTH
- Defended my PhD last year in scope of the Swedish **OSMET 3.0** project at KTH, MSE

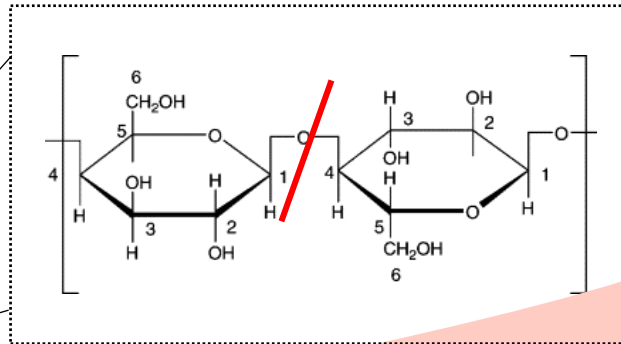
Title—"Application of **Hydrochar** for Low-CO₂-Emission Steel Production"

- Now a postdoc working in **EU RFCS BioReSteel** project

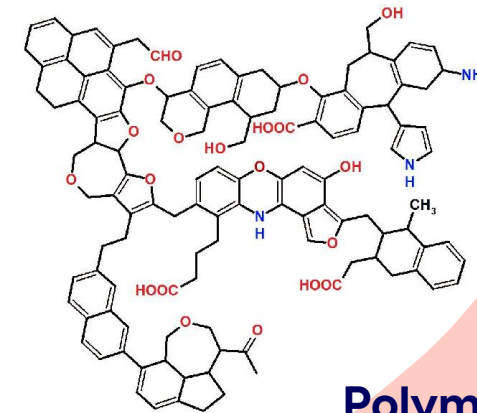


What is a hydrochar?

Low temperature, high pressure process!
180-250 °C
2-10 MPa



Chemical dehydration



Polymerization,
Aromatization

Hydrochar



Why hydrochar?

Hydrochar



- **Low-grade** (i.e. wet) biomass
- High mass yield (**~50%**)
- Lower price
- Easy to **pelletize**/transport
- High energy density
- Recycling of **nutrinets (NPK)**
- Removes **alkalis**

Charcoal



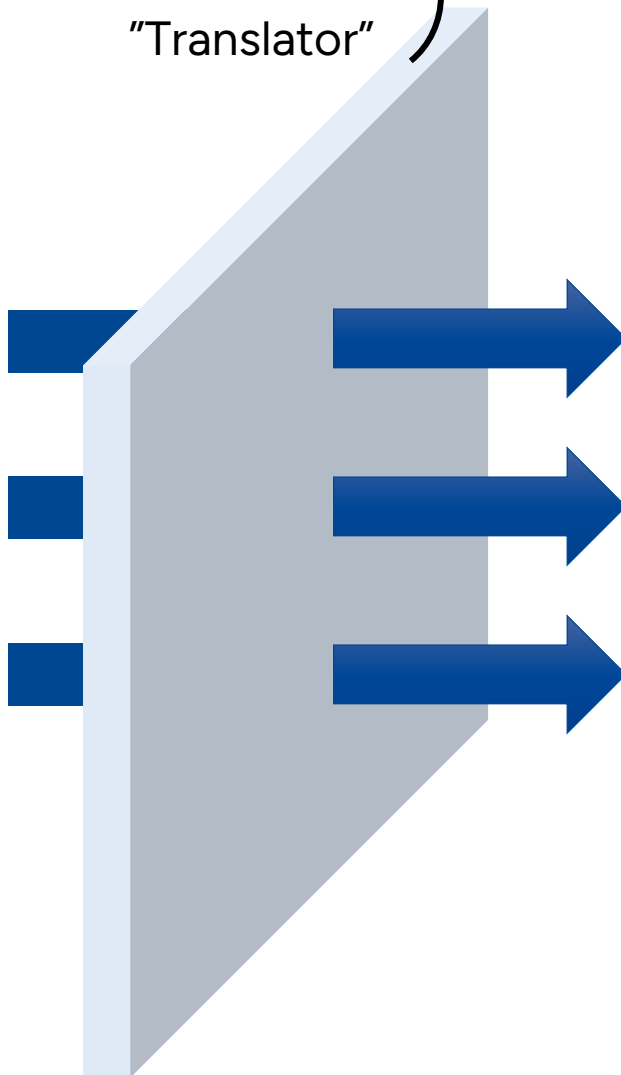
- Woody biomass
- Mass yield (**~30%**)
- High price
- Difficult to densify (binder needed)
- High energy density



"Translator"

Technical performance

Steel companies



Material Properties

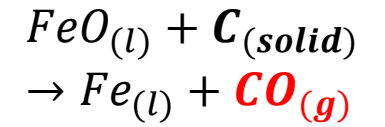
Biochar supplier

Electric arc furnace (EAF)

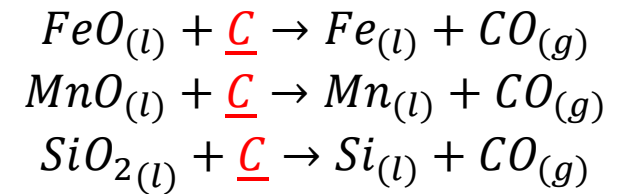
1. Heating

4. Slag foaming

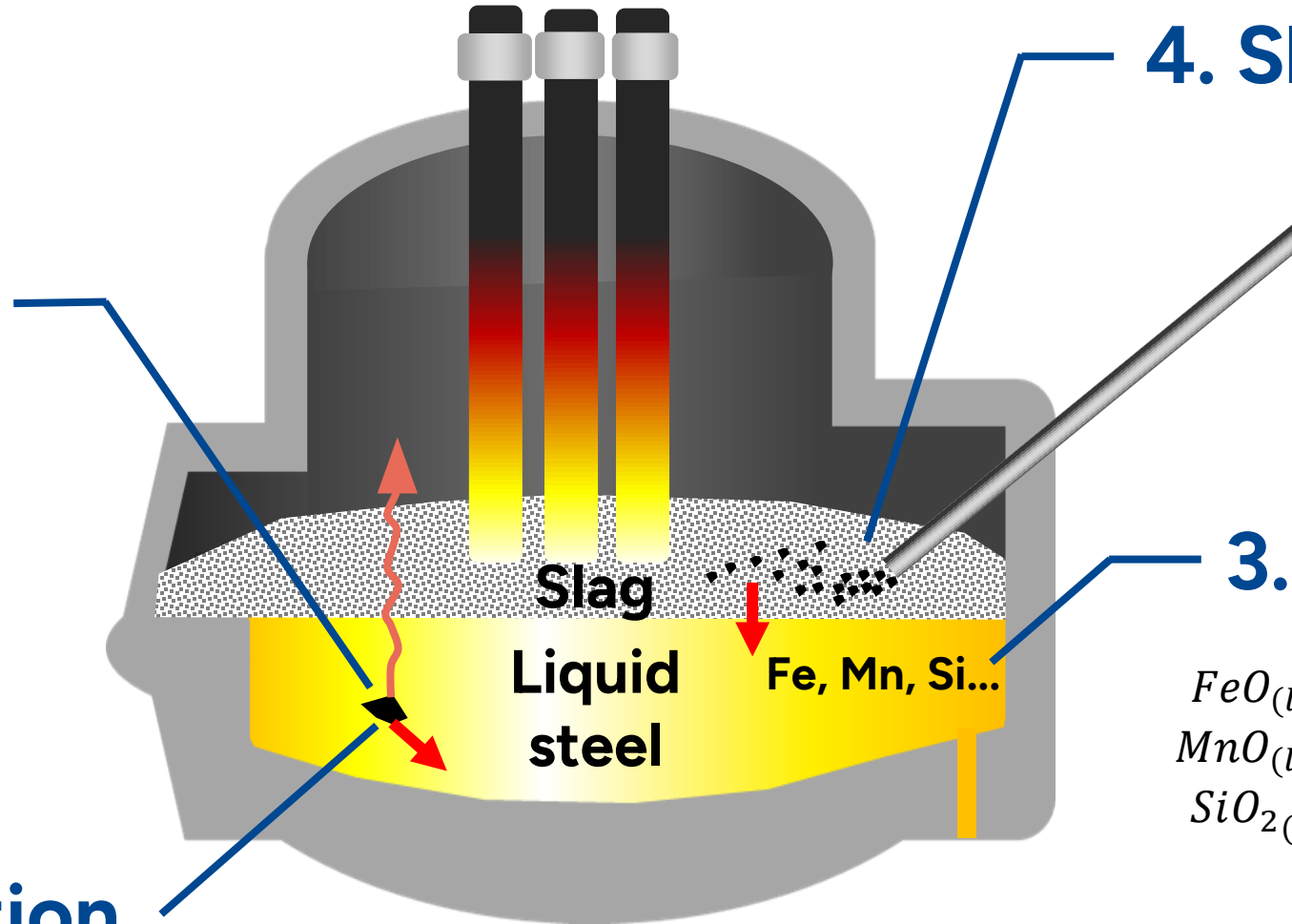
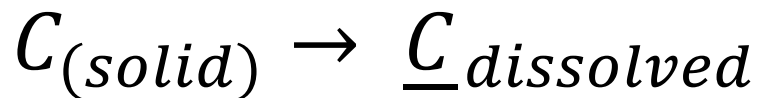
Injected
carbon



3. Reduction



2. Carburization



Technical performance

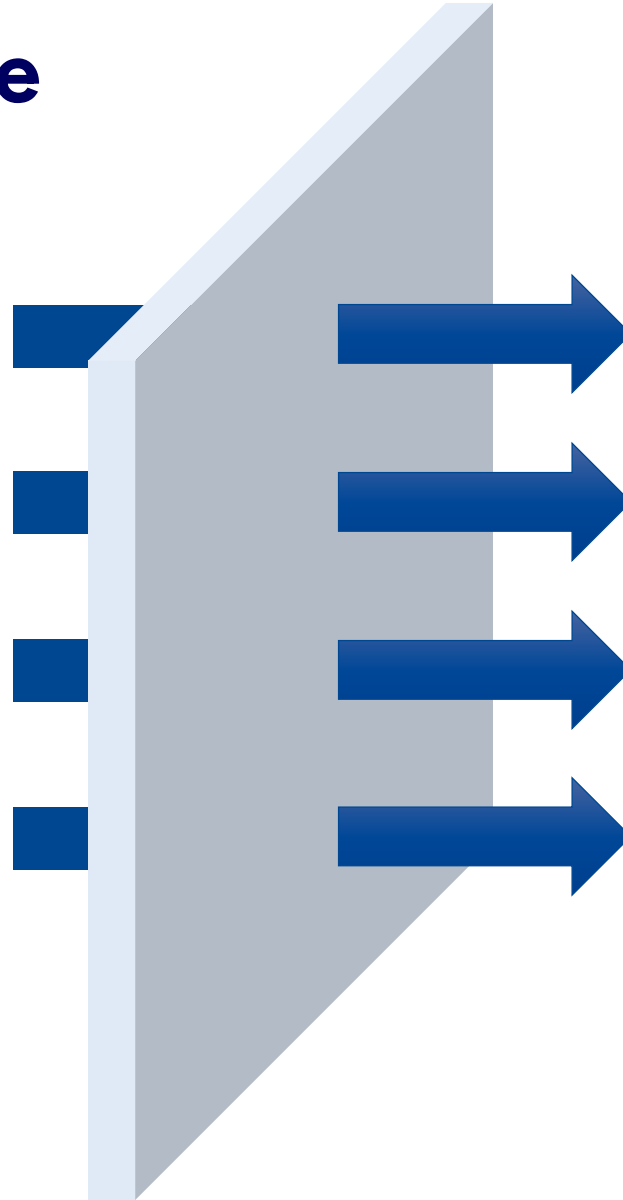
Material Properties

Heating

Carburization

Reducing agent

Impurity



Heating value, high reactivity

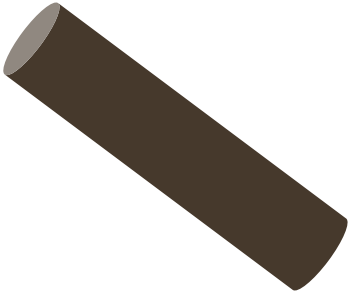
High **carbon content**, low reactivity

High amounts of **reducing gas**

Low S, P, ash (e.g. SiO_2), alkalis

Carburization - Carbon content

- **Total carbon content**
- **Fixed carbon content** = $100\text{wt}\% - (\text{wt}\% \text{Volatile matter}) - (\text{wt}\% \text{Ash})$

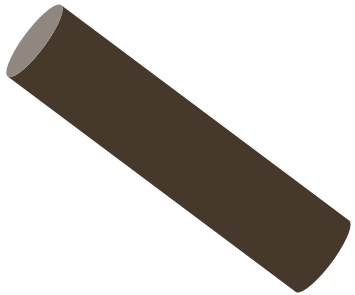


Lemon peel hydrochar

- Tot-C: **60 wt%**
- Fixed C: **27 wt%**

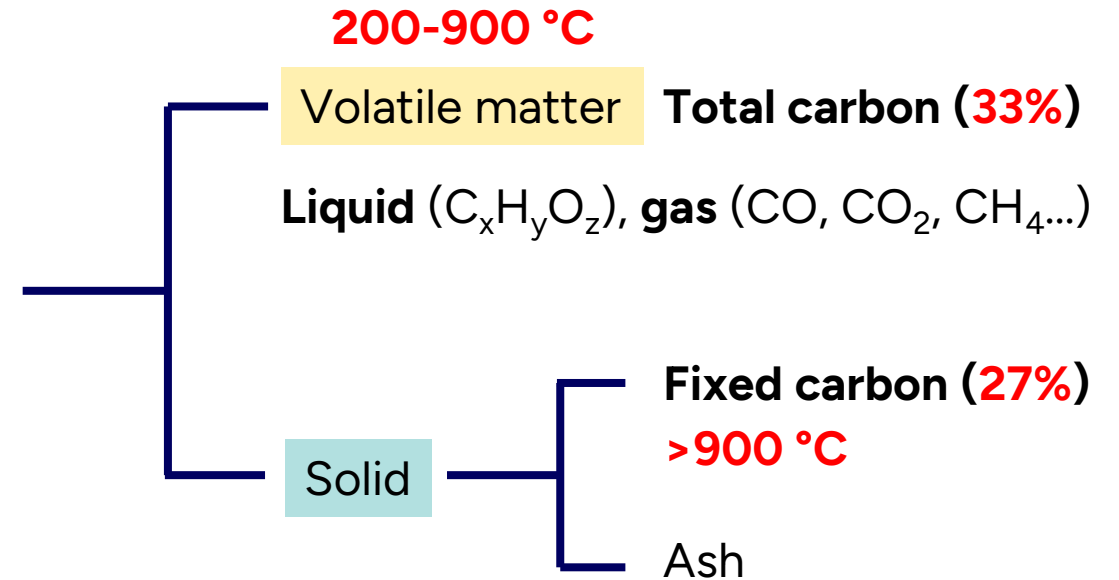
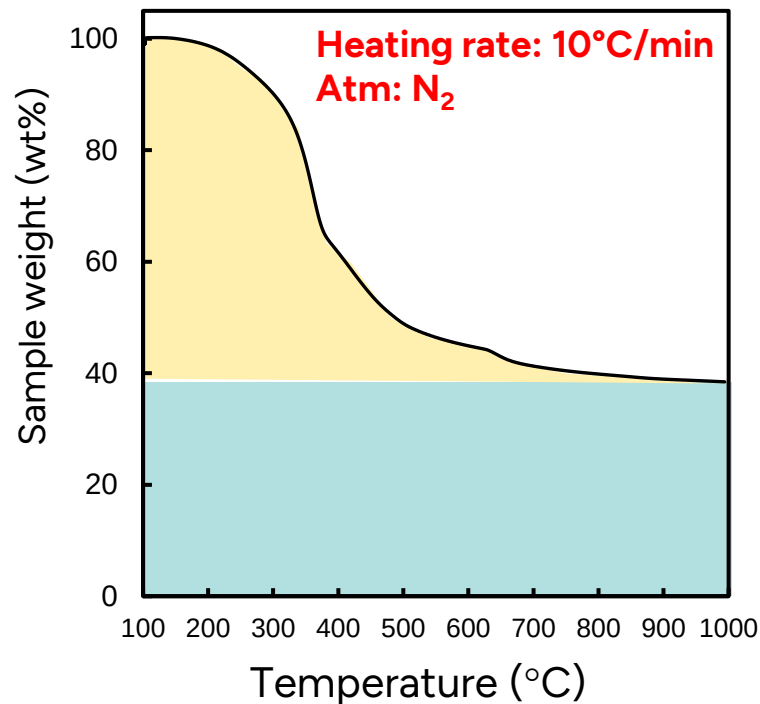
Carburization - Carbon content

- **Total carbon content**
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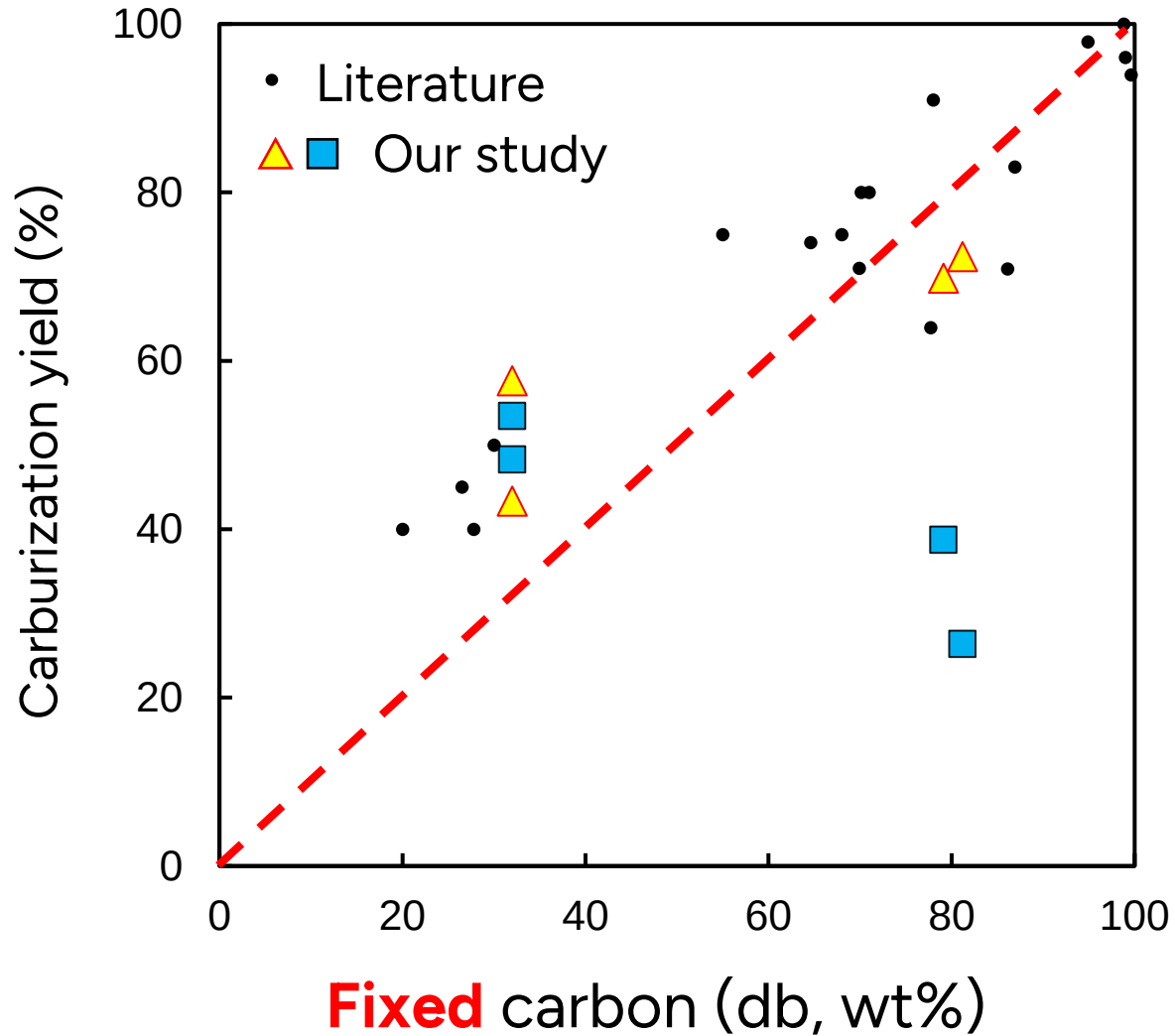


Lemon peel hydrochar

- Tot-C: **60 wt%**
- Fixed C: **27 wt%**

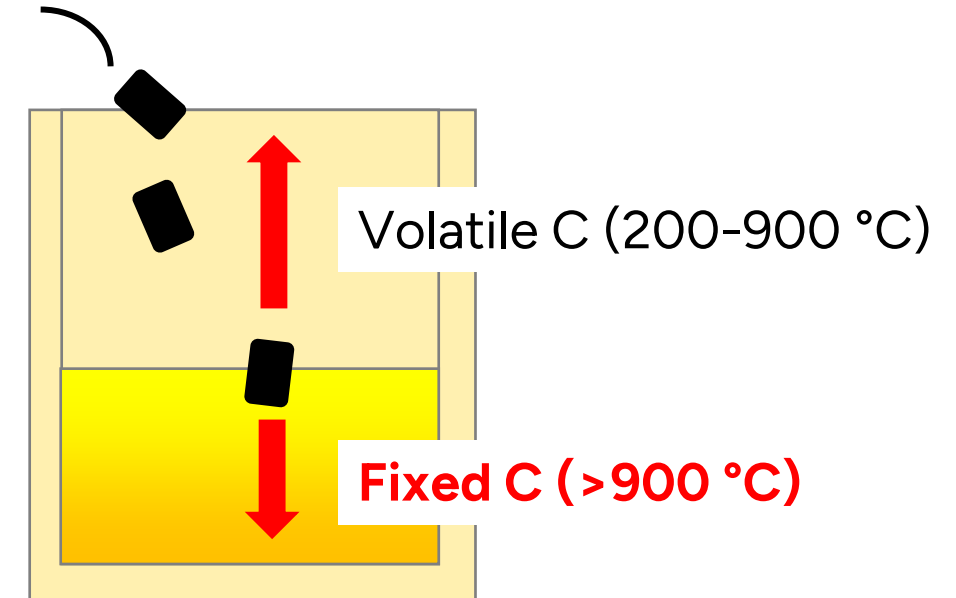


Carburization - Not all carbon are equal!



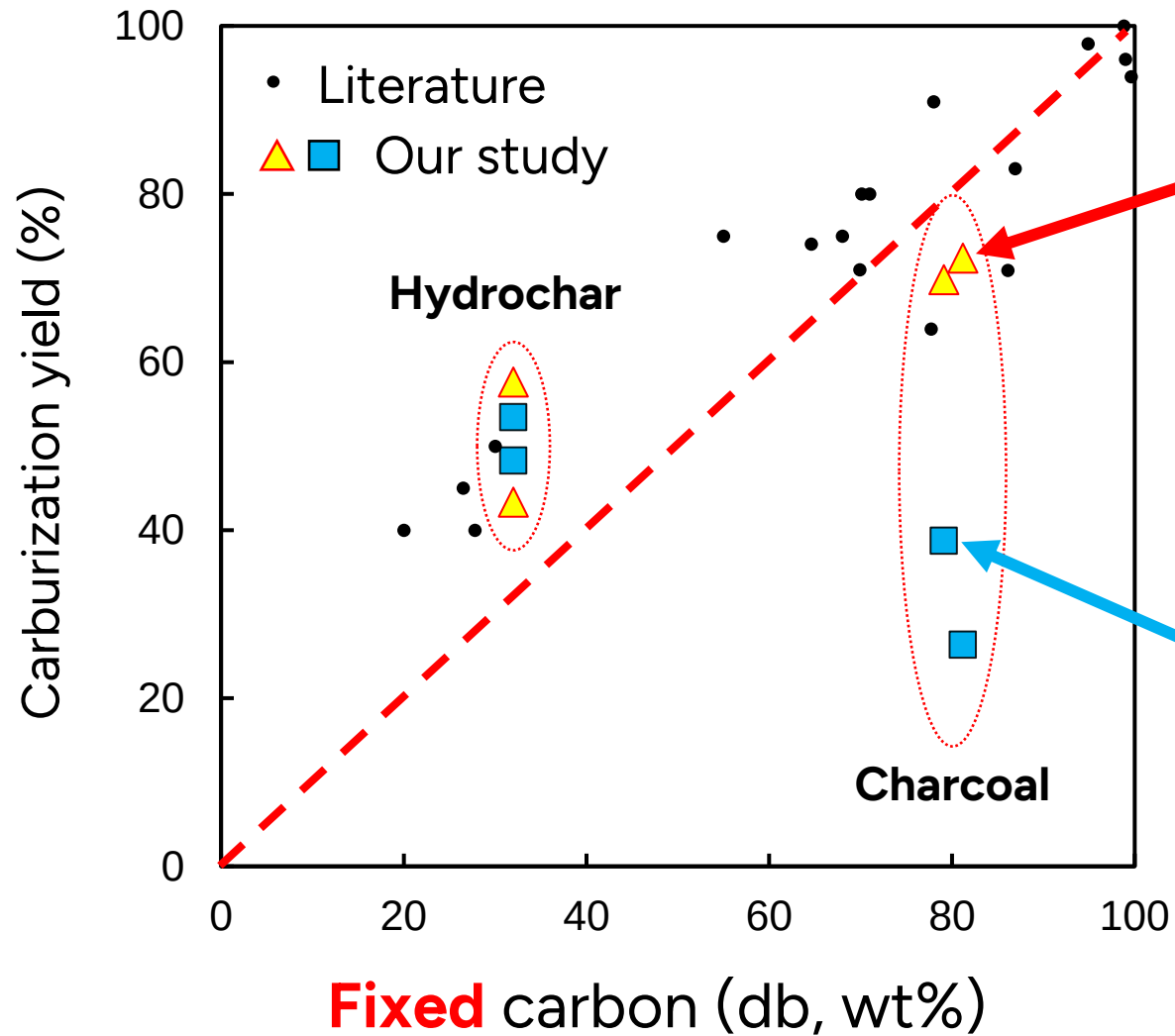
$$\text{Carburization yield} = \frac{C \text{ dissolved in steel}}{\text{Total } C \text{ added}} \cdot 100\%$$

Carbon material

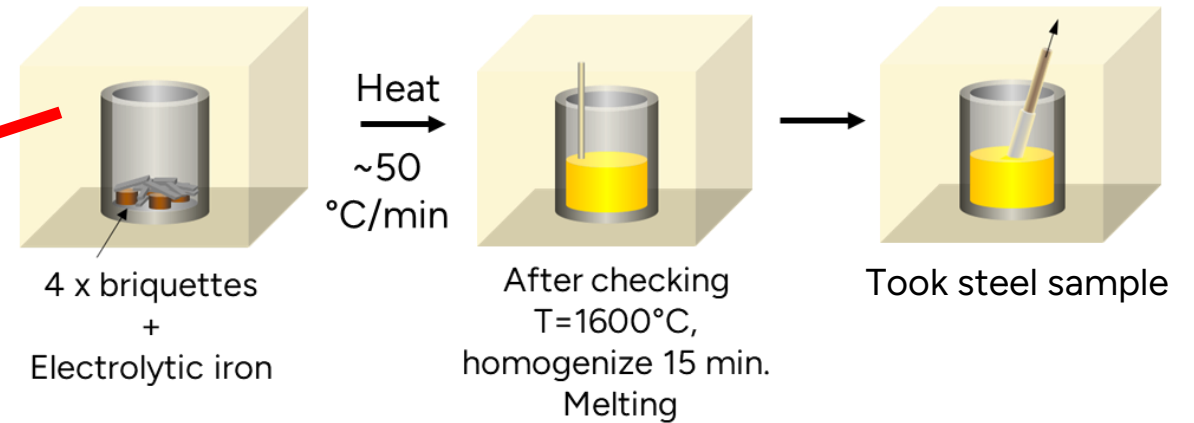


Liquid steel ~ 1600 °C

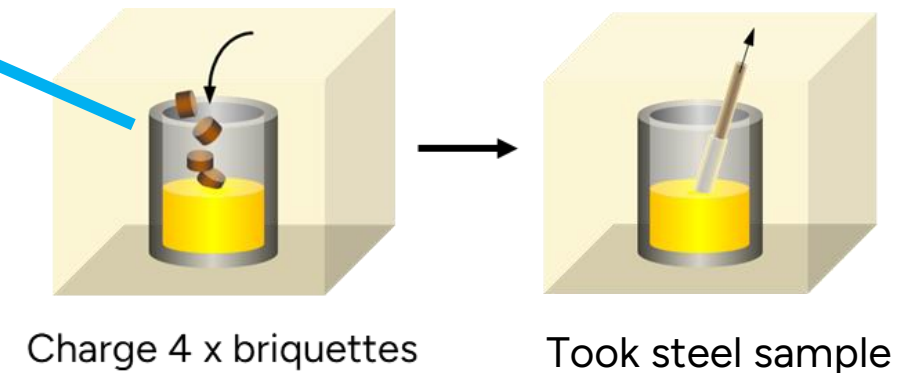
Carburization - Addition method matters!



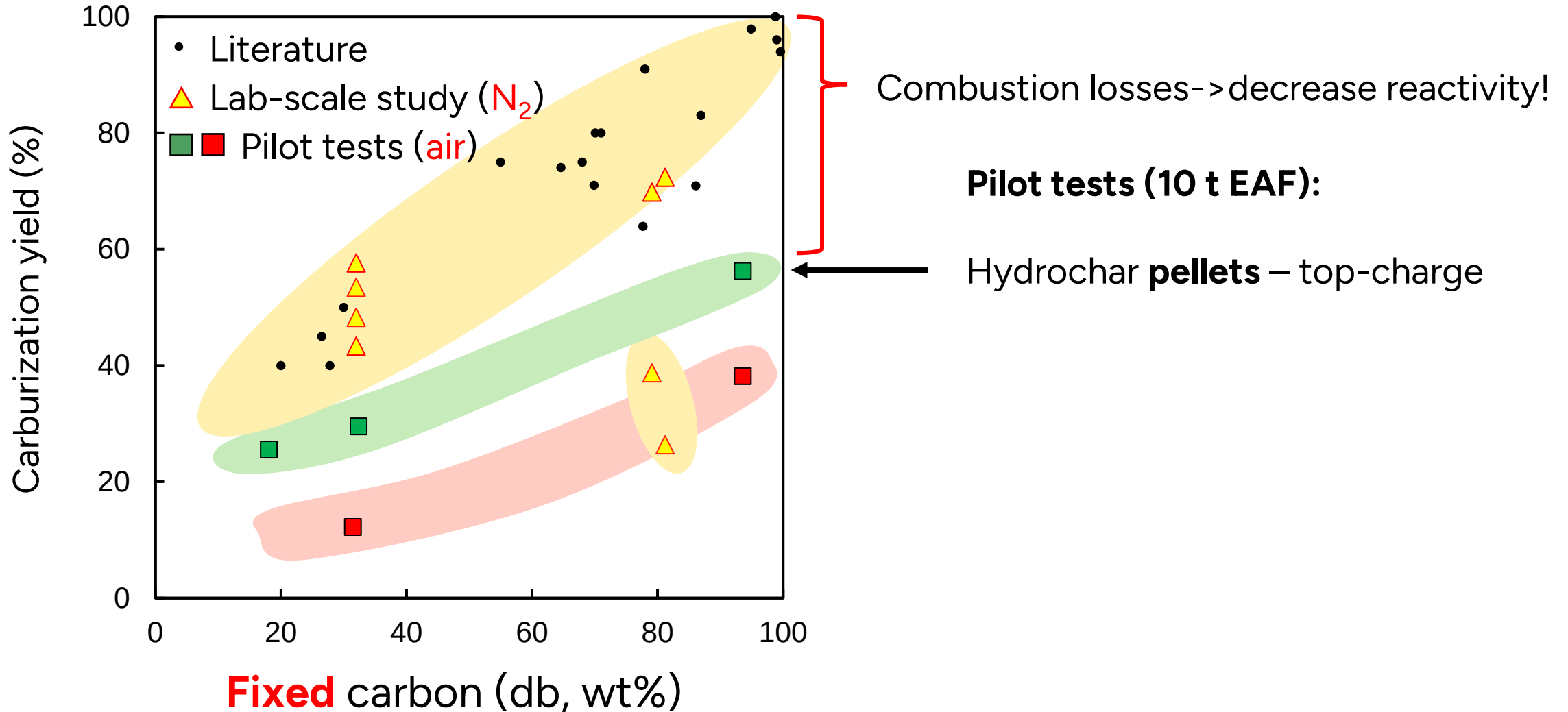
Method 1



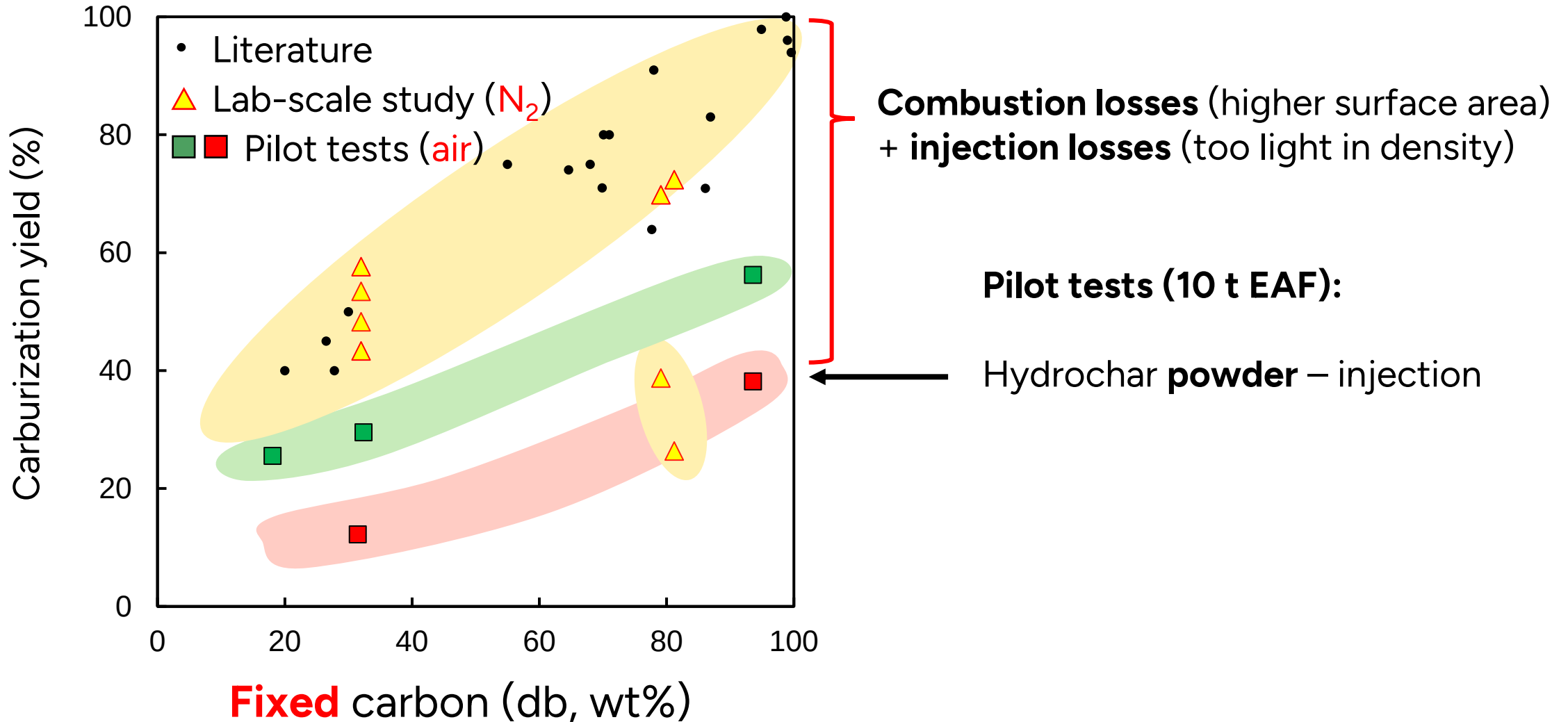
Method 2



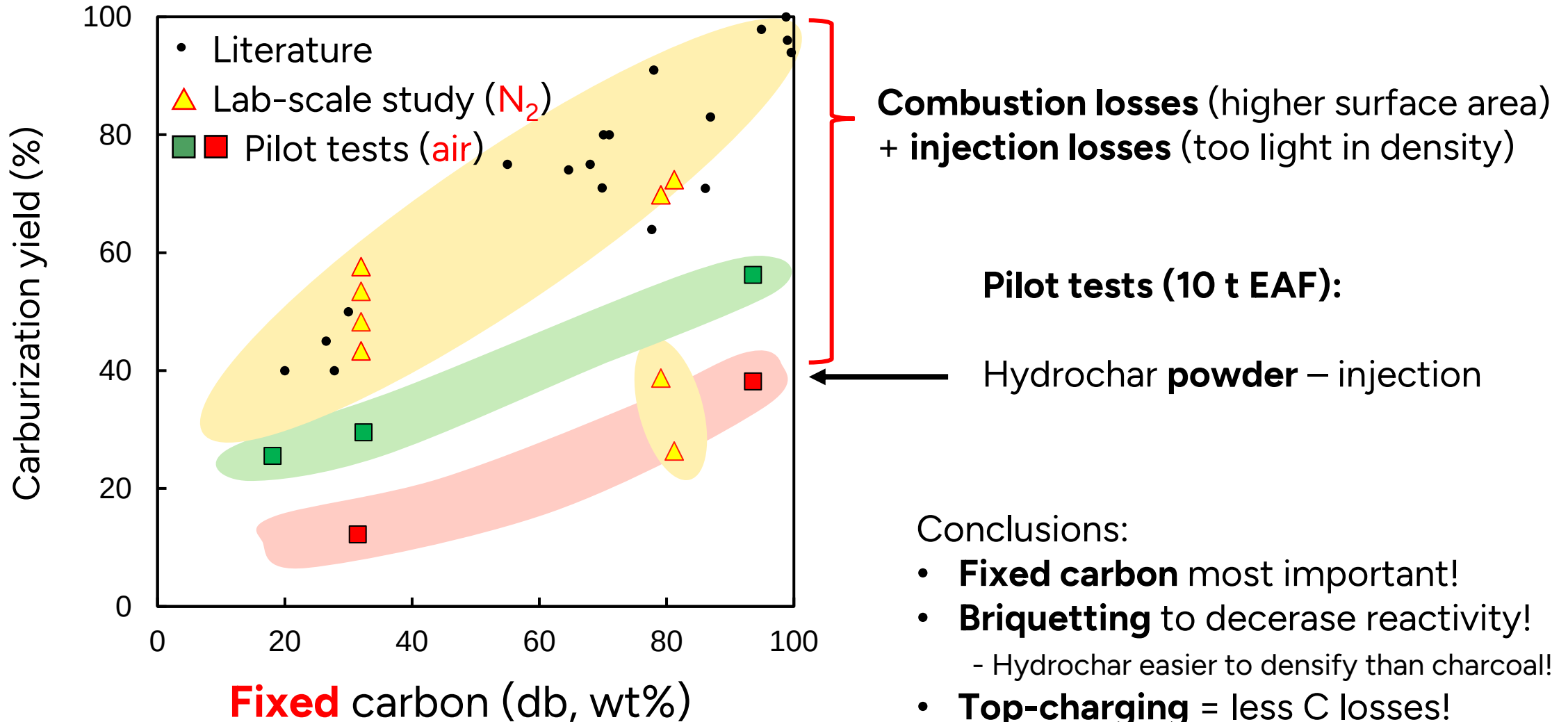
Carburization - Addition method matters!



Carburization - Addition method matters!



Carburization - Addition method matters!



Technical performance

Heating

Carburization

Reducing agent

Impurity



Material Properties

Heating value, high reactivity

High **fixed carbon**, low reactivity

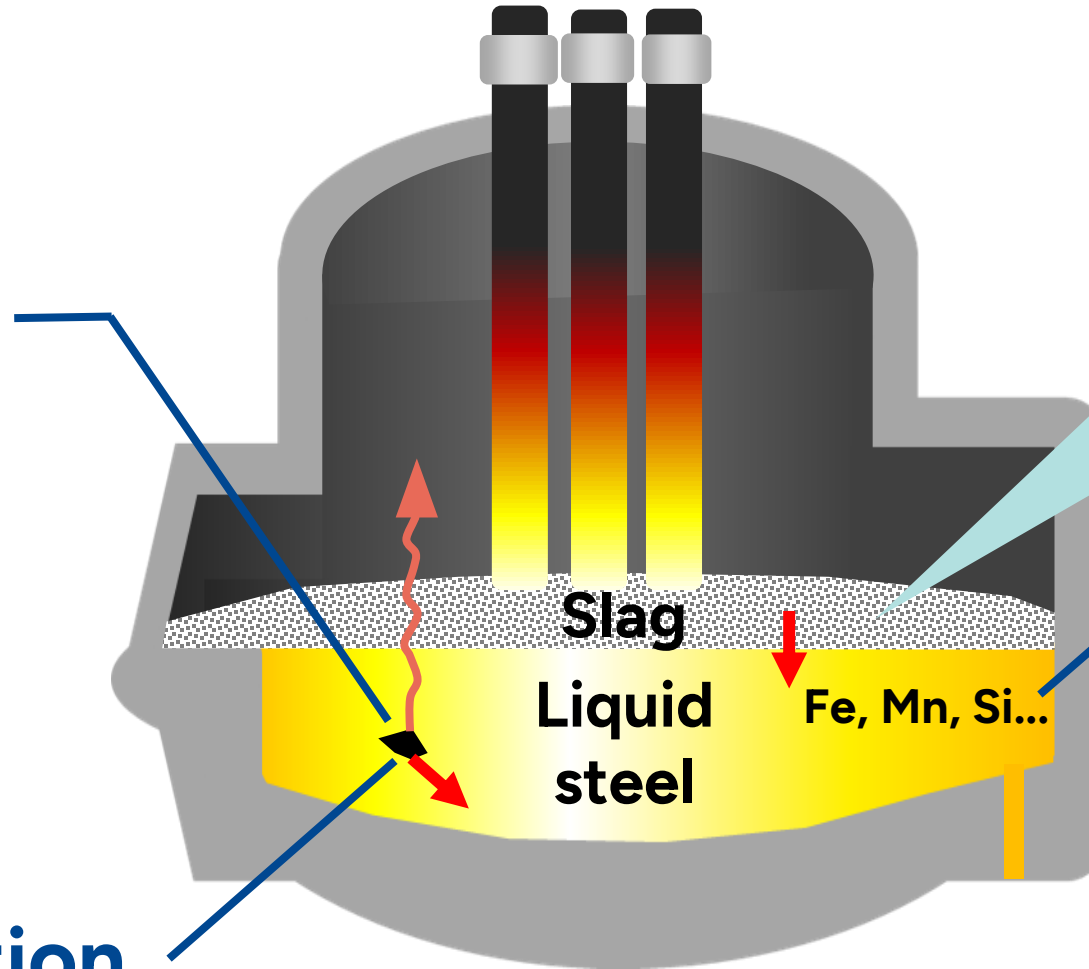
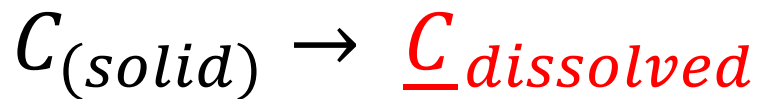
High amounts of **reducing gas** (??)

Low S, P, ash (e.g. SiO_2), alkalis

Electric arc furnace (EAF)

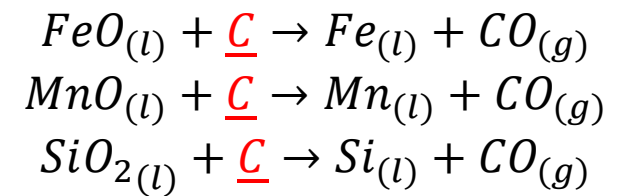
1. Heating

2. Carburization



CaO, MgO, Al₂O₃,
FeO, SiO₂, MnO...etc.

3. Reduction



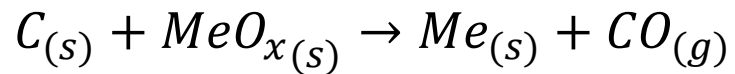
Electric arc furnace (EAF)

Self-reducing briquettes

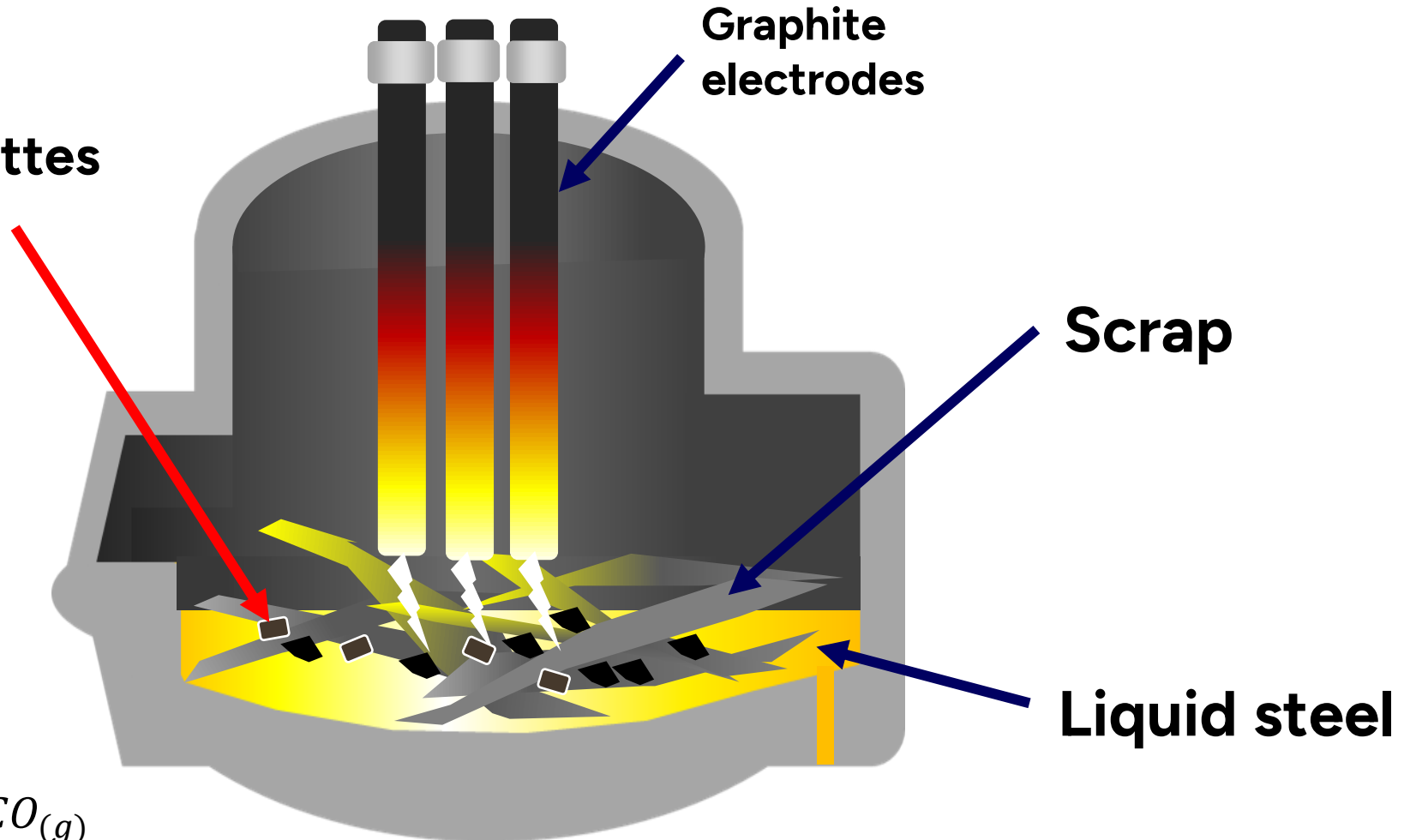


- **Carbon material**
- **Metal oxide** (e.g. Mill scale, pellet fine, DRI fine...)

$\text{FeO}, \text{MnO}, \text{Cr}_2\text{O}_3, \text{NiO}$

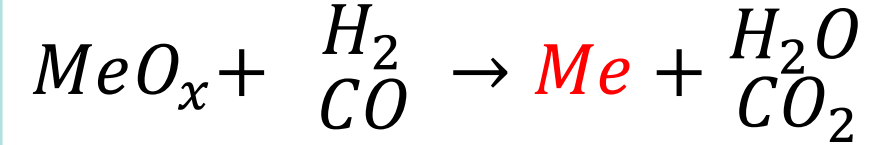


$\text{Me}_{(l)}$

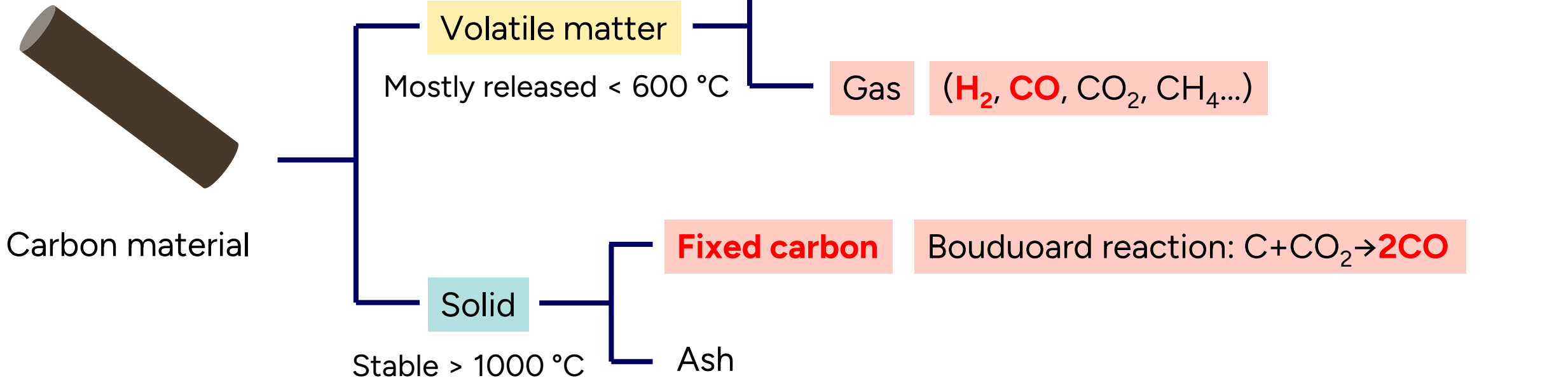


Reducing agent

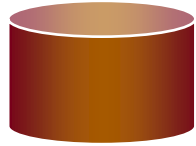
Reducing gas essentially means **H₂** and **CO**



Under slow heating rates....



Self-reducing briquettes

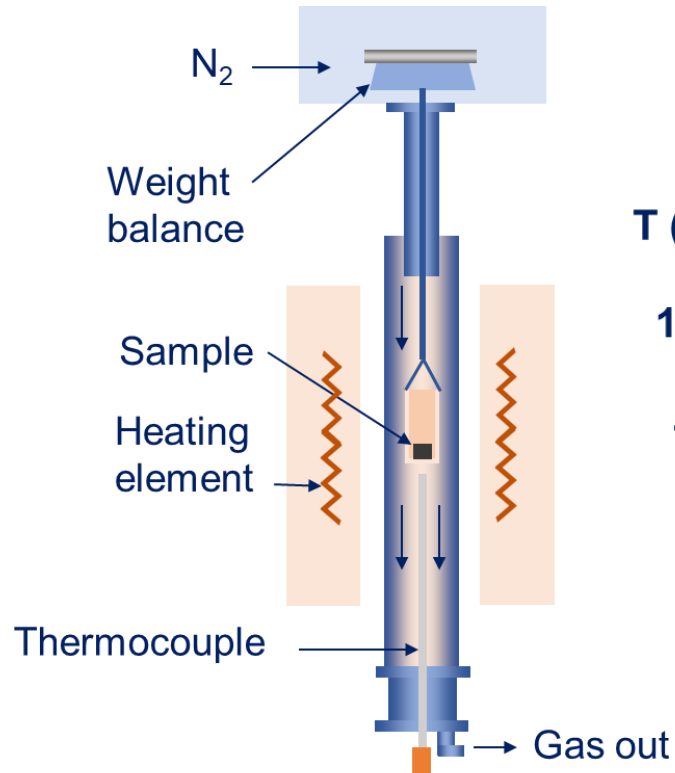


~50 g

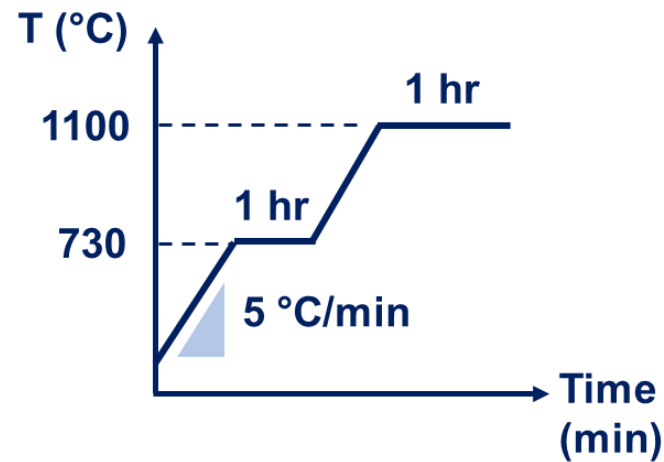
Briquette:

- Hematite (Fe_2O_3)
- Lemon Peel hydrochar
- Binder

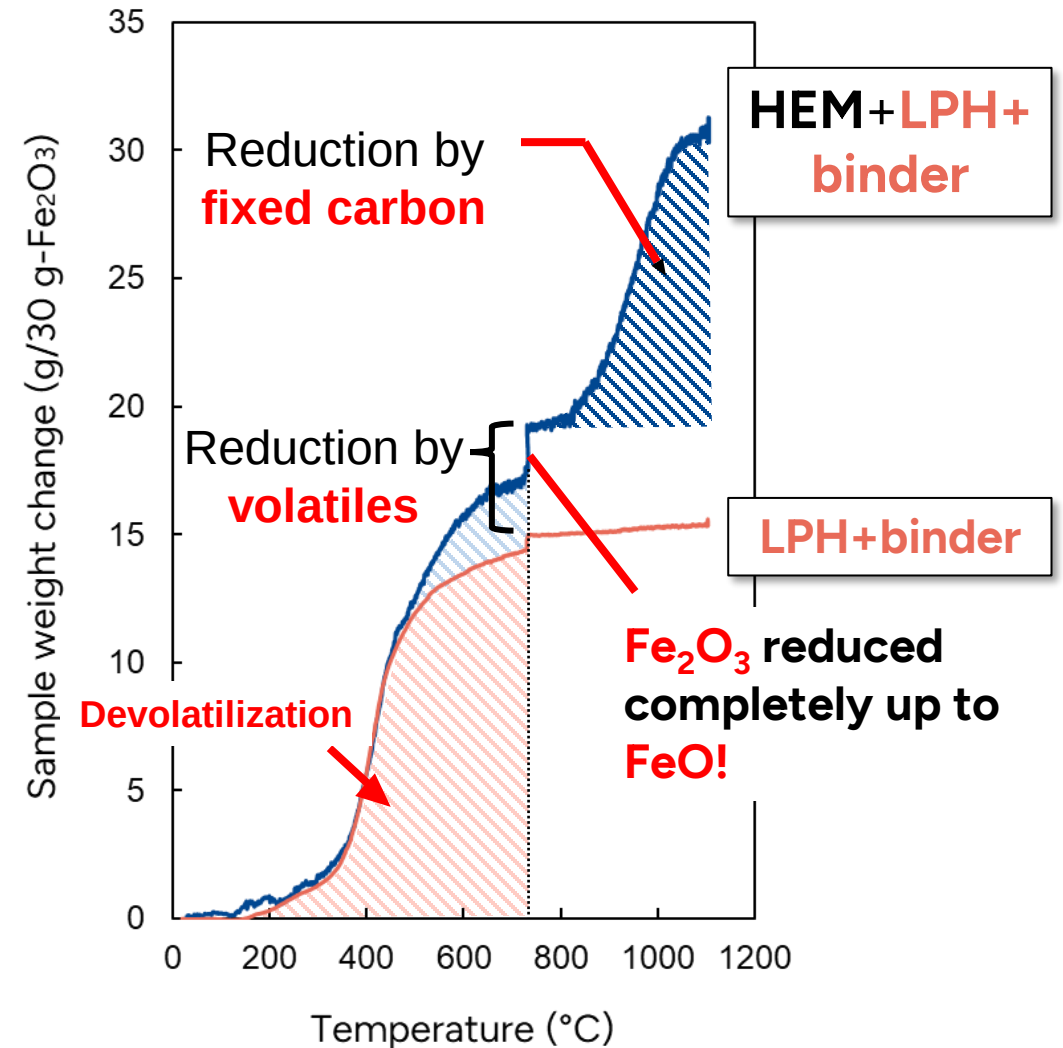
Thermogravimetric analyzer (TGA)



Temperature program

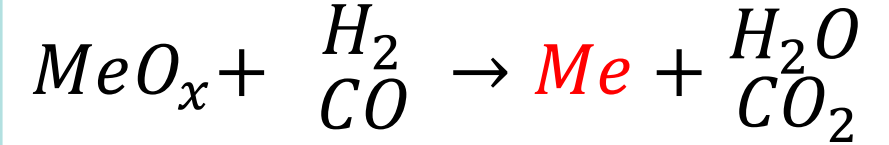


Weight loss of briquette -TGA

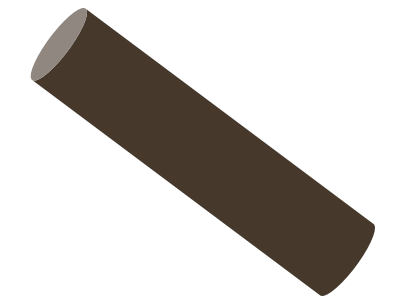


Reducing agent

Reducing gas essentially means **H₂** and **CO**

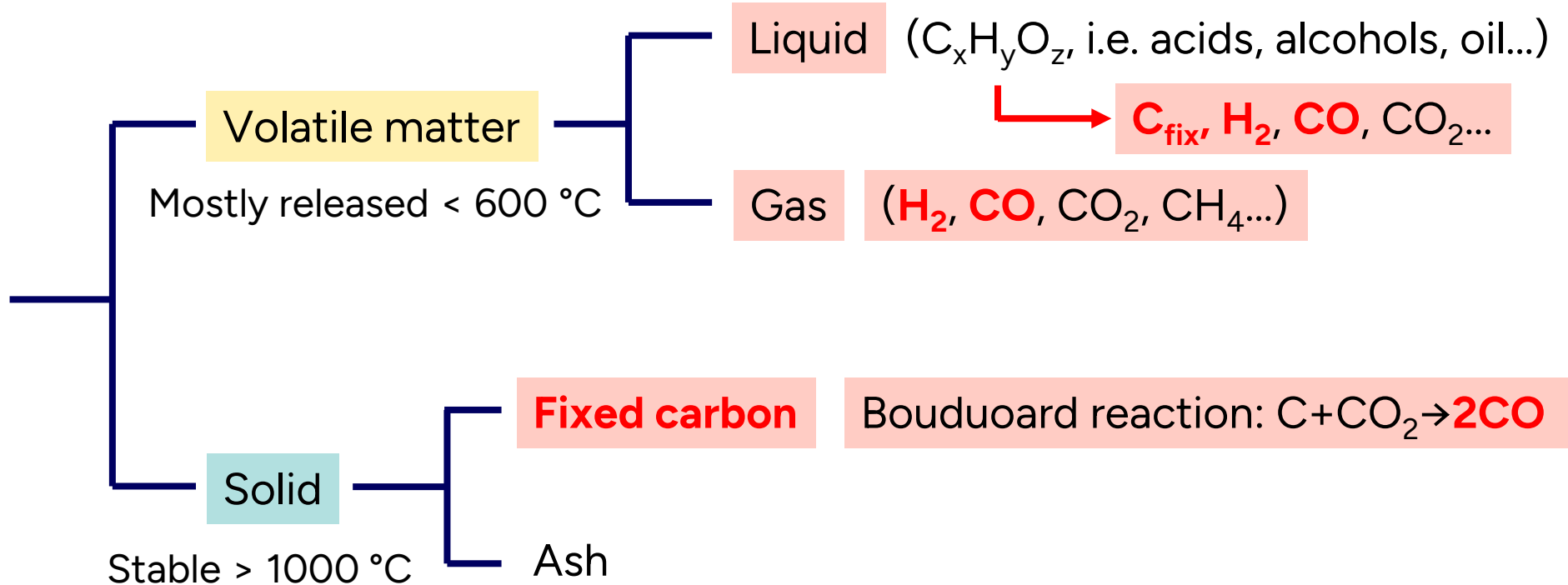


Under fast heating rates....

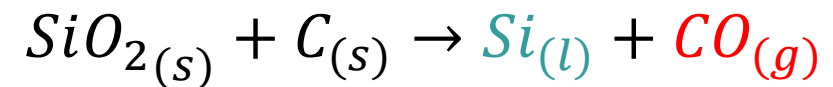
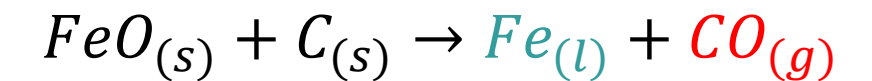
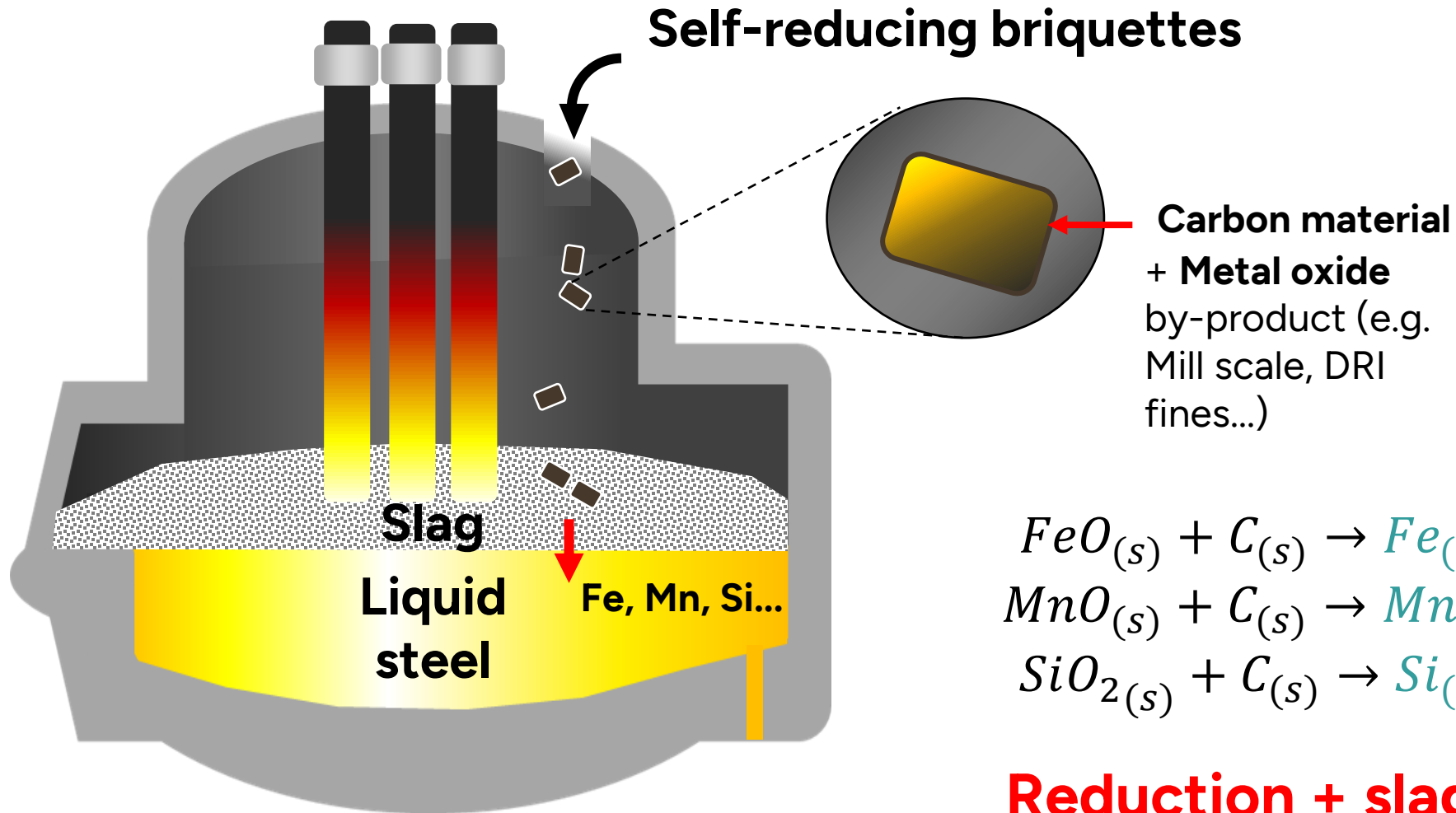


Carbon material

**High in
C, H
contents**

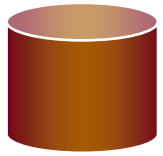


Electric arc furnace (EAF)



Reduction + slag foaming!

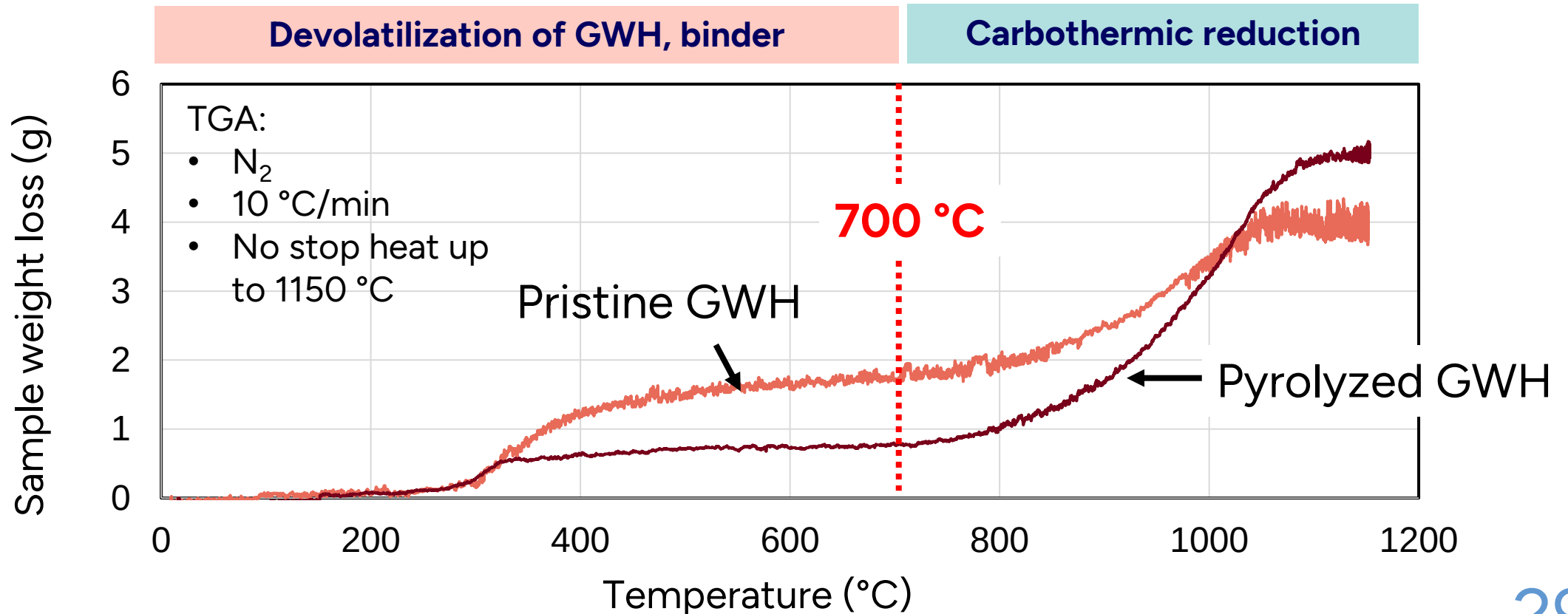
Self-reducing briquettes for slag foaming



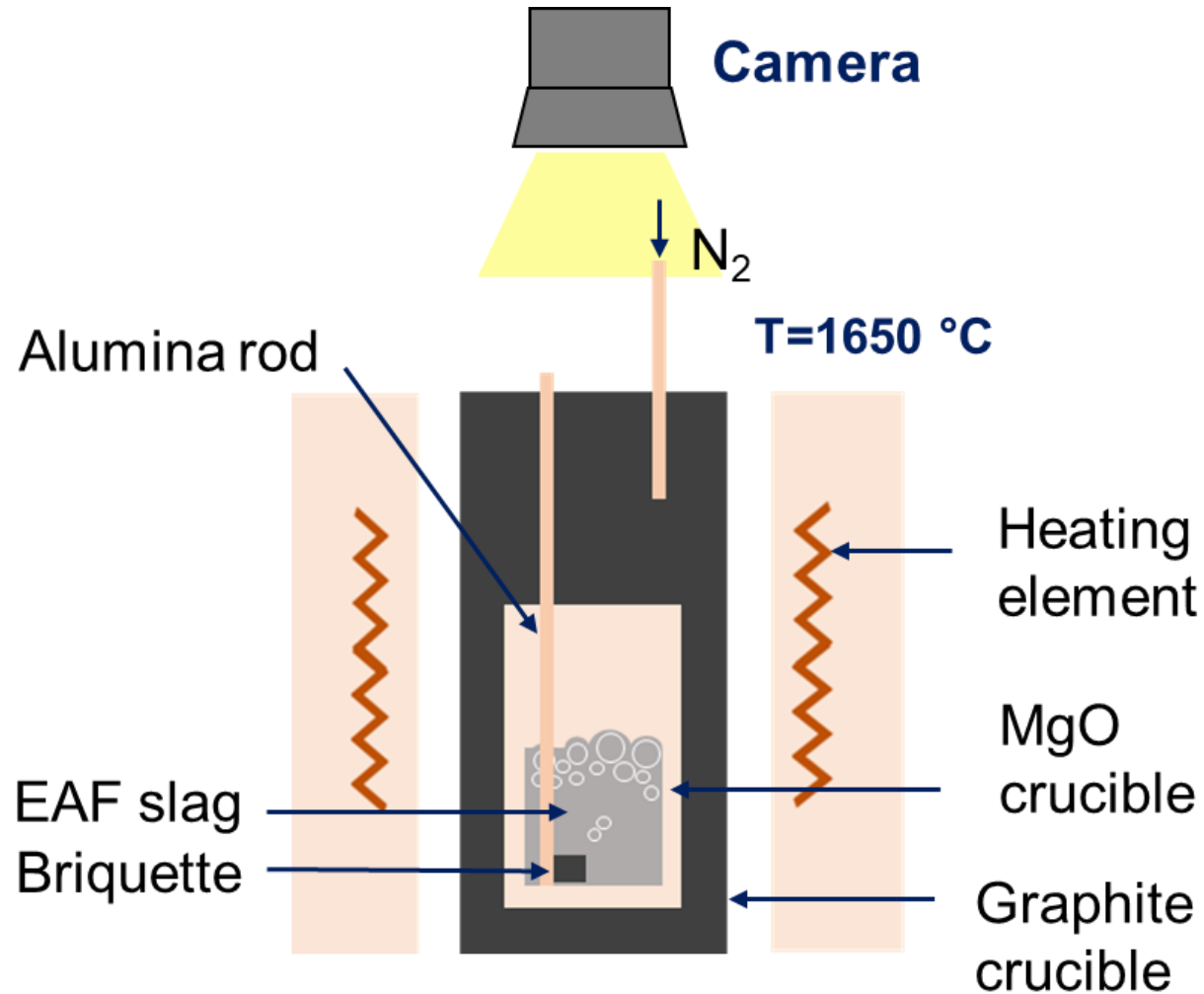
~20 g

Briquette:

- 81 wt% Mill scale
- 15 wt% **pristine** hydrochar/**pyrolyzed** hydrochar
- 4 wt% Binder



Self-reducing briquettes for slag foaming



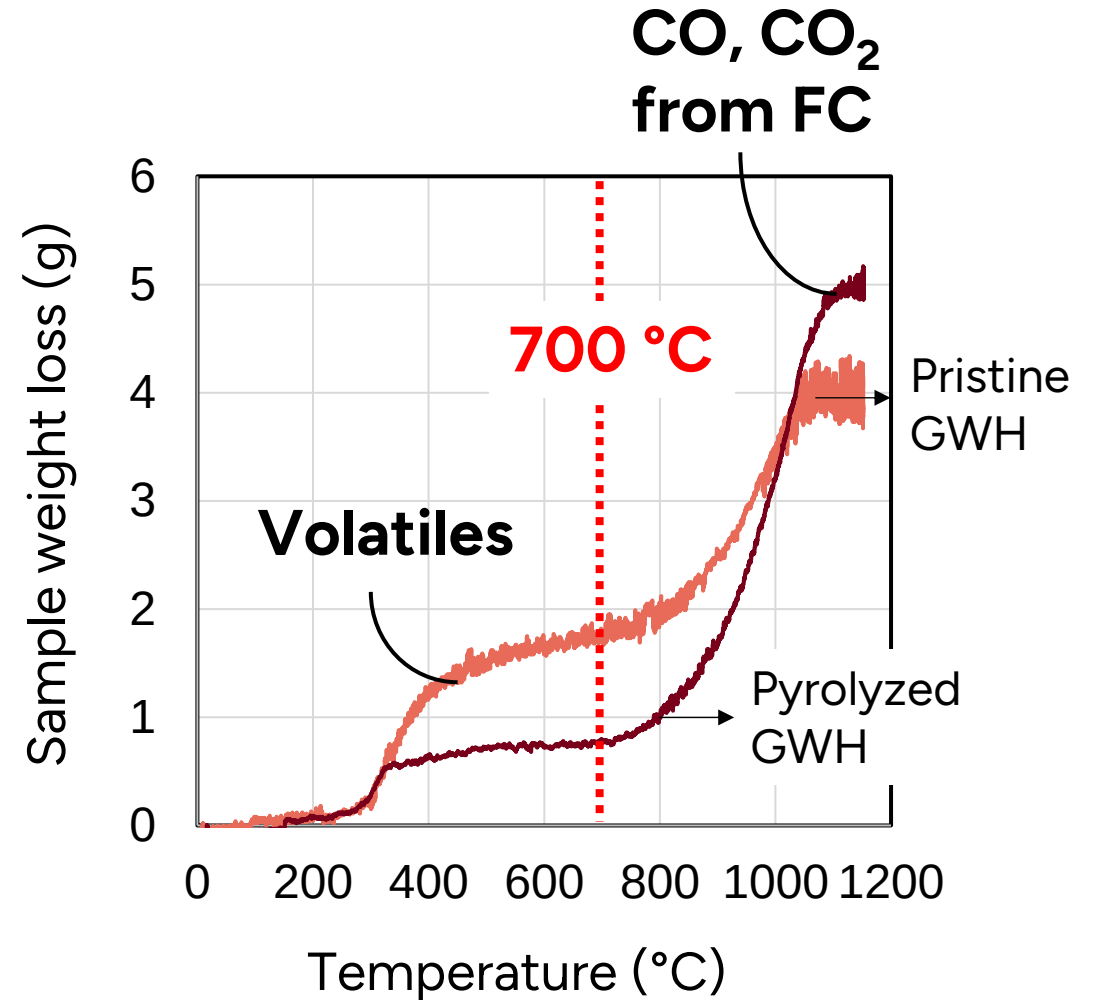
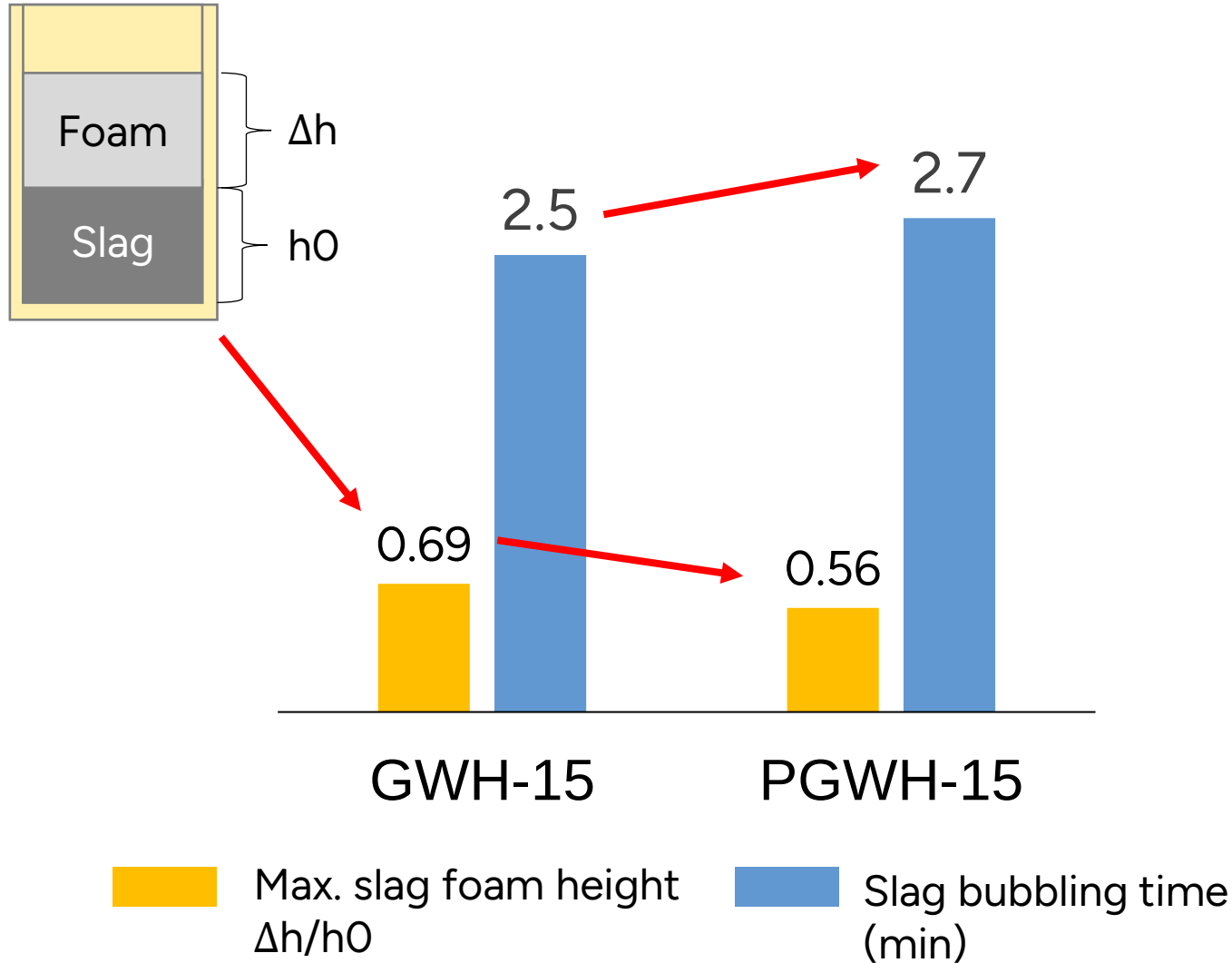
Parameters measured:

- Conditions of slag captured by camera throughout
- Slag height before and during foaming
- Slag surface bubbling time

Slag height:

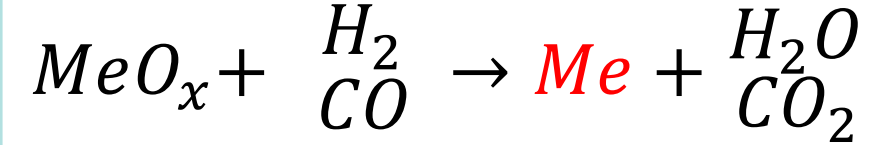


Self-reducing briquettes for slag foaming

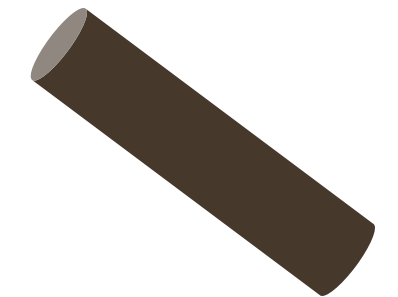


Reducing agent

Reducing gas essentially means **H₂** and **CO**

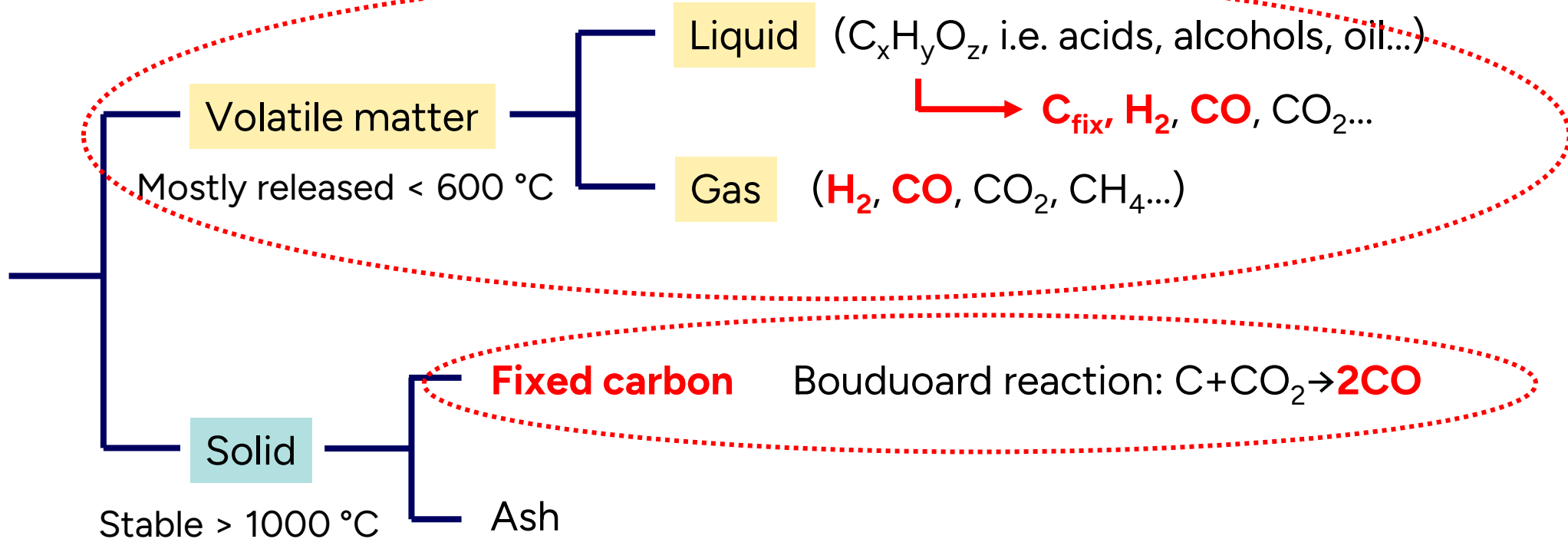


Under high heating rates....



Carbon material

**High in
C, H
contents**



Technical performance

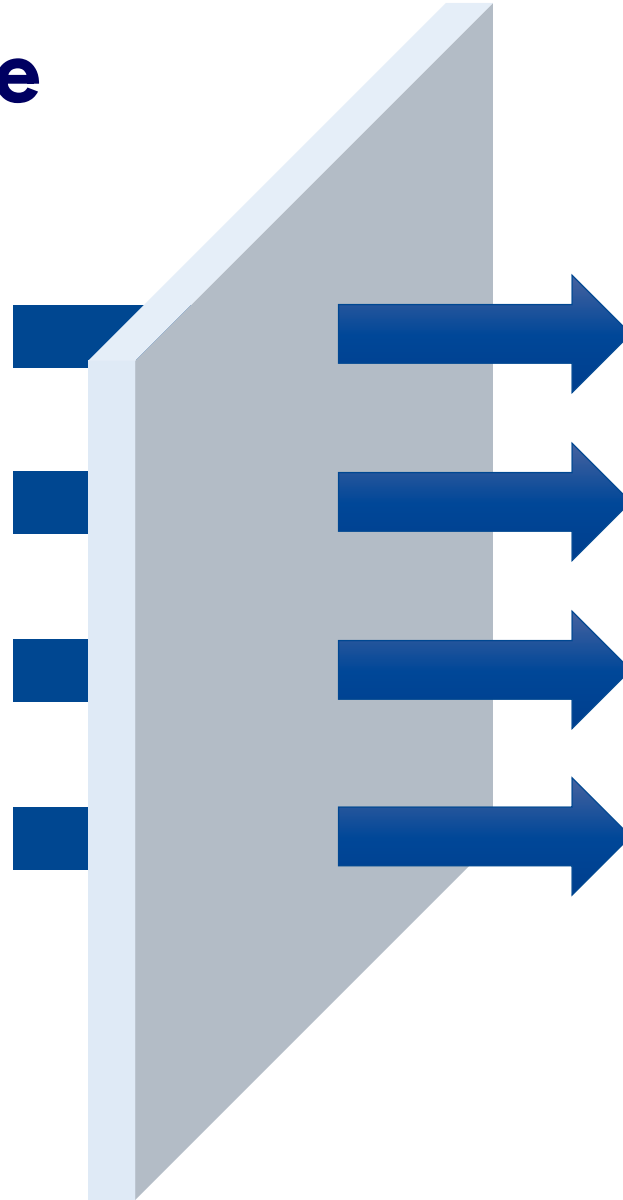
Material Properties

Heating

Carburization

Reducing agent

Impurity



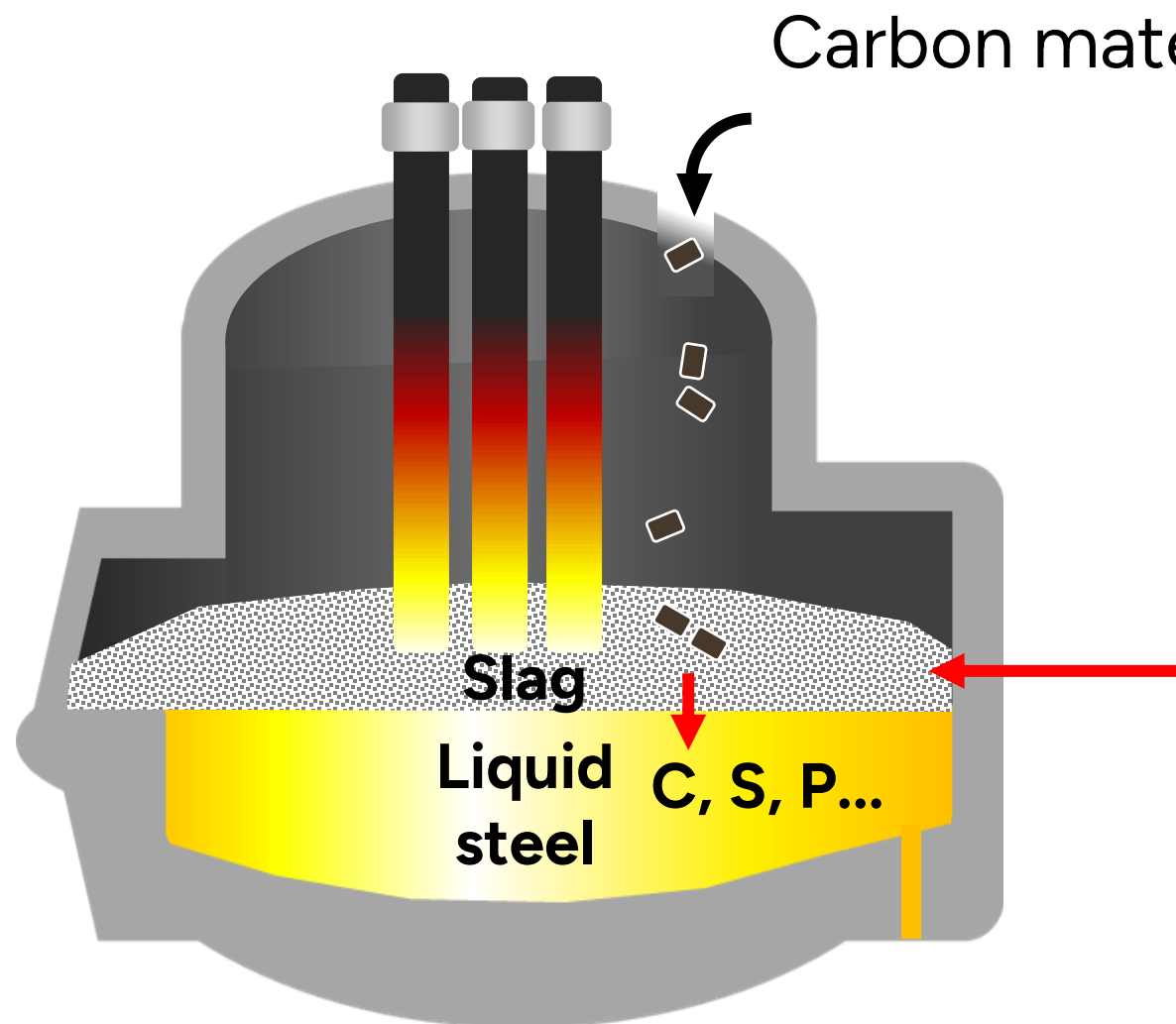
Heating value, high reactivity

High **fixed carbon**, low reactivity

High **C, H contents**

Low S, P, ash (e.g. SiO_2), alkalis

Impurity

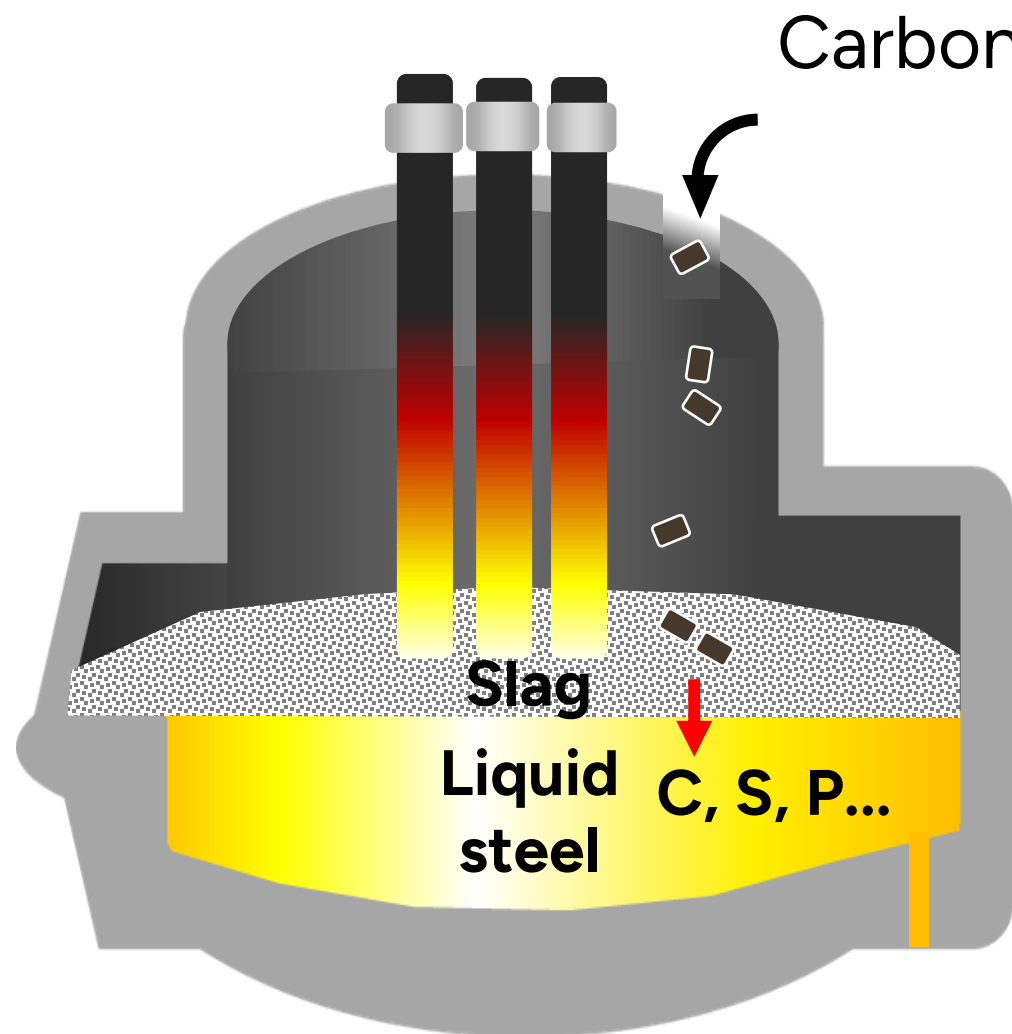


EAF Slags:

$$\text{Basicity} = \frac{\text{CaO}}{\text{SiO}_2} \sim 2$$

Biomass ash (CaO, SiO₂, **P₂O₅**, alkalis...) mostly stays in the slag!

Impurity



Carbon material (**12-55 kg/t-steel**)

S, P contents:

- Low-quality steels:
0.04-0.05 wt%
- High-quality steels:
0.02-0.03 wt%
- Very high quality steels:
 ≤ 0.01 wt%

Impurity

Properties	Hydrochar (fruit peel, rice husk)	Pyrolyzed hydrochar (fruit peel, rice husk)	Charcoal	Anthracite
Ash (wt%)	4- 21	16-44	5-7	5-11
Ash basicity	0.4 -3.1	0.2 -1.2	1.8-2.3	0.02-0.1
Alkalis (wt%)	0.4-0.7	1.2-1.5	0.6- 2.0	0.1-0.3
S (wt%)	0.07-0.15	0.20-0.23	0.03-0.07	0.18-0.59
P (wt%)	0.16-0.25	0.26-0.37	0.07-0.20	0.01-0.03

Suggested range:

S: 0.19-0.31 wt%

P: 0.14-0.16 wt% - Reduce by **1-2** times!

Summary

Technical performance

Heating

Carburization

Reducing agent

Impurity

Material Properties

Heating value, high reactivity

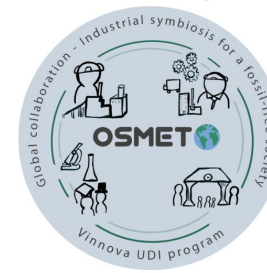
High **fixed carbon**, low reactivity

High **C, H contents**

Low S, P, ash (e.g. SiO_2), alkalis



Contacts



This research was funded by **Vinnova** under **OSMET3.0 project** (2020-04140) and **RFCS** under the **BioReSteel** project (N° 101112383).



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Derivation of S, P limits

	Very high quality steels	High quality steels	Commercial steels
Example(s)	Advanced high strength steels, low-alloy bearing steels	Stainless steels and tool steels	Carbon steels
Final S, P (wt%)	≤ 0.01 wt%	0.02-0.03 wt%	0.04-0.05 wt%
Processing routes	EAF → Ladle, VD...	EAF → AOD → Ladle	EAF → Ladle
Min. S removal (%)	~50%	~70%	~50%
Min. P removal (%)		<u>~60%</u>	~20%

Derivation of S, P limits

Percentage of element removed from melt obtained from laboratory or industrial experiments:

	EAF	AOD	Ladle
S	20-60% [14,15]	33-62% [16]	40-99% [18,19]
P	4-82% [14,15]	30-70% [17]	14-93% [20]

Carbon, low-
alloy steels



Stainless, high-
alloy steels



Overall removal

S: 48-99%

P: 18-99%

S: 68-99%

P: 57-99%

Derivation of S, P limits

Calculation procedure:

1. Final acceptable S, P in steel before casting

↓ $\div$ (fraction of impurity removal
during refining)

2. Final acceptable S, P in steel at charging in EAF

↓ - (typical impurity in scrap)

3. Acceptable S, P added by hydrochar

↓ $\div$ (typical addition amount of
hydrochar addition in EAF) $\cdot 100\%$

4. Acceptable %S, %P in hydrochar

Example: Carbon steels

0.5 kg-S/t-Steel (0.05 wt%)

↓ $\div$ (0.5)

1.0 kg-S/t-LS

↓ - (0.4 kg/t-LS)
*Scrap has 0.04 wt%S

0.6 kg-S/t-LS

↓ $\div$ (50~120 kg/t-LS) $\cdot 100$

0.47 ~ 1.12 wt%

Utilizing biocarbon in the metallurgical industry and its technical specifications

Konstantinos Rigas
Business Development
Envigas AB

HåBiMet
Nulägesseminarium
2025.01.30

COMPANY OVERVIEW

Towards a fossil free metallurgical industry

First large-scale producer of high-quality biocarbon

- Deliveries for 5+ years to the European steel industry.

Part of the green industrial transition in northern Sweden

- First planned large scale blueprint facility in Bureå, outside Skellefteå, Sweden, fully operational by 2027.

Driving change through smart technology and strategic collaboration

- Extensive research combined with in-depth expertise to maximize the value creation of biocarbon and its by-products.
- In 2023, Envigas entered into a strategic partnership with Outokumpu.

Solutions-thinking at the core

- Optimizing biocarbon and its by-products for high-value use to deliver customized high-quality solutions.

350 000

By 2030, the swedish market for fossil-free steel will require a minimum of 350 000 tons of biocarbon annually.

150 000

By 2030, Envigas aims to produce 150 000 tons of biocarbon annually.

50%

Outokumpu has secured 50% of our 1st scale up production volumes in a long-term supply agreement.

Our Mission

We will build, own and operate facilities, under our own or via joint-ownership, for the large-scale production and processing of high-quality, fossil free coal and gas products for the metallurgical industry in Europe.

With the help of our products, customers will be given the opportunity to significantly reduce their CO2 emissions.



envigas

**TECHNOLOGY
&
PRODUCTS**

• Feedstock Qualification & Preparation

Certified and traceable sources, low-level humidity is advantageous. Envigas uses only residuals from Nordic stemwood, pine and spruce.

• Pre-treatment (alternative by choice)

The level of humidity, particle size and shape defines the need for pre-treatment. Wood pellets can be used with a homogenous shape and particle size, humidity and traceability.

• Pyrolysis

The biomass is pyrolysed in an inert atmosphere at approximately 600°C. Important factors; temperature & residual time. Approximative yield of biomass to HQ BioCarbon is 20-25%.

• Selective Condensation

The approximate biomass-to-gas yield is 60-70%. A selective condensation can be made to output a mix of BioOil and pyrolysis gas. Several post-processing steps can be added to eventually produce e.g. BioMethane (CH₄) or Green Hydrogen (H₂).

• Post-treatment and Packaging

To reduce BioCarbon's high reactivity, there are various means to lower it and make it easier and safer to handle. Envigas has developed several solutions and special routines to secure **safe handling and transportation of BioCarbon.**



High fix-C level.

Low VM.

Low ash content, S, P.

Low moisture.

- Low ash, minimized sulfur content.
- Stem wood as primary choice for feedstock.

Selection of feedstock

Process parameters

- Optimization of residual time and temperature for increased carbon yield.
- $T > 500^{\circ}\text{C}$, ($< 100^{\circ}\text{C}/\text{min}$).

Low reactivity.

Increased density.

Appropriate PSD.

Adequate mechanical strength.

Safety & Handling

Post-processing

- Packaging.
- Transportation.
- Storage.

- Preparation of briquettes.
- Extruded/densified material.
- Control reactivity.

Coal	Brown	Bituminous	Anthracite	Graphite
Fix-C	65-70%	70-85%	85-95%	>95%
BioCoal	Torrified pellets	Biocarbon	HQ Biocarbon	Biographite

HQ BioCarbon for metallurgical applications

envigas

Fix-C: 90-95%

Heating value
33-35 MJ/kg

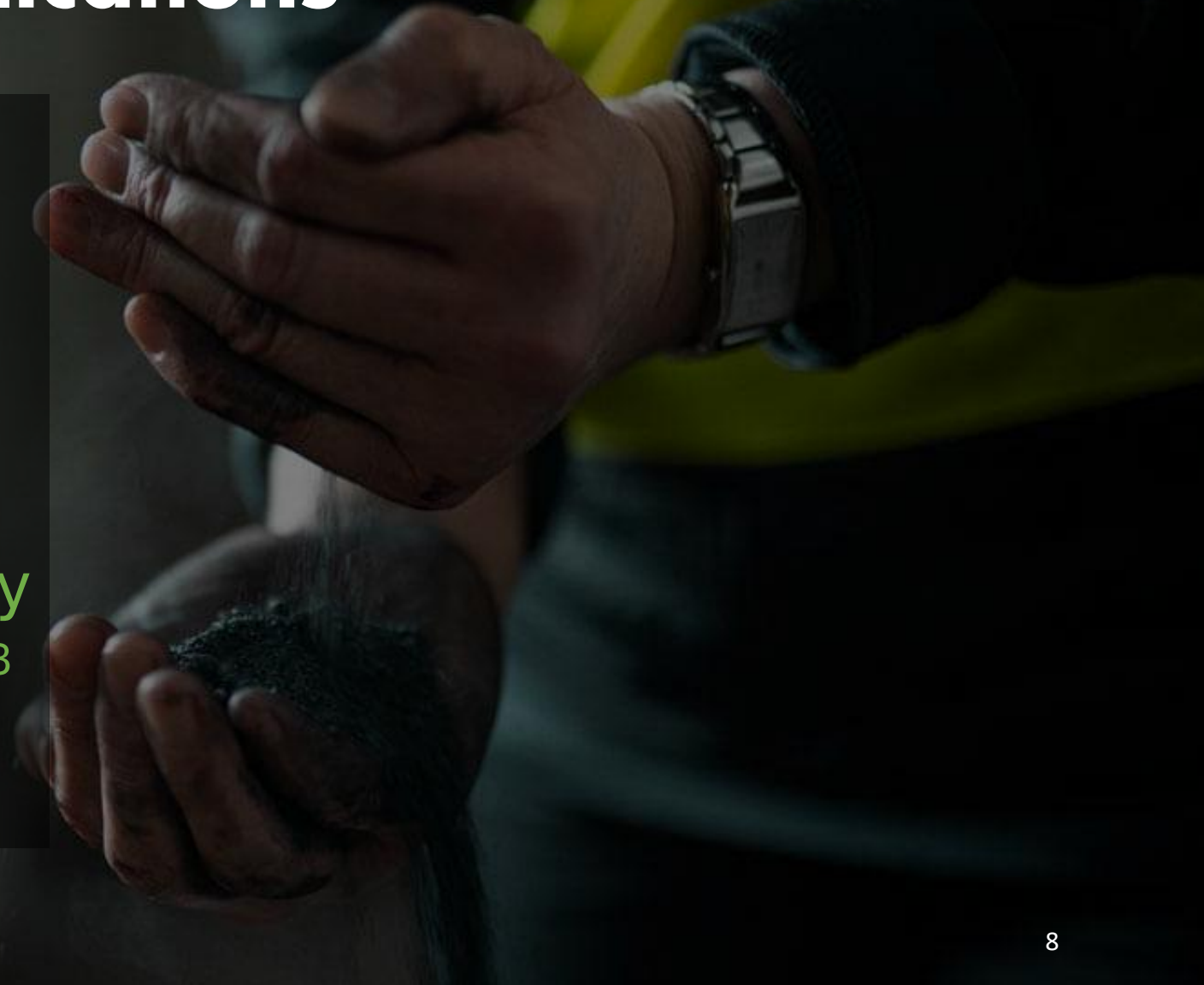
VM<3%

Ash content
<1.5%

S & P free

Moisture
<2%

Bulk density
~500 kg/m³



**USE IN THE
MET
INDUSTRY**

- ✓ Biocarbon is not a universal product, but its form and specifications should be aligned with the needs of the customer
- ✓ The majority of the customers implement EAF. Biocarbon can be used for charging, injection and recarburization.
- ✓ Need for customized solutions (e.g. briquettes, pellets etc.). Agglomeration might be needed according to specs.
- ✓ Differences among the same metallurgical process (e.g. EAF) depending on the procedure its company follows and the steel grade produced.
- ✓ The majority of the customers choose to start with a partial substitution of fossil carbon with biocarbon.
- ✓ Tests and trials are necessary.
- ✓ Safety and handling of biocarbon should be a priority.



Property	Range/Values
Fixed Carbon (Fix-C)	80% - 95%
Ash	1% - 10%
Volatile Matter (VM)	2% - 10%
Moisture	0.5% - 10%
Sulfur (S)	0.1% - 1%
Phosphorus (P)	0.015% - 0.05%
Particle Size	0.5mm-60mm
Density	> 500kg/m ³

Fossil coke properties

Property	Anthracite	Breeze coke	Pearl coke	Foundry coke
Fixed Carbon (Fix-C) (%)	85	>75	>85	>87
Ash (%)	11	16-18	<12.5	<12
Volatile Matter (VM) (%)	3.69	5	<1.5	<1.5
Moisture (%)	5.91	<10	<6	<5
Sulfur (S) (%)	0.48	0.6	<0.6	<0.5
Calorific Value (MJ/kg)	27.78	26-29	30-34	28-32
Density (kg/m ³)	1300-1800	920	1200-1500	850-900



envigas

PROJECTS WITH MET INDUSTRIES

Bio4SAF

- Development and implementation of biocarbon-chromite briquettes in full-scale production of FeCr

R-Carbon4EAF

- Pyrolysis of EOL tires for metallurgical applications mainly for EAF

M-Graphite

- Graphitization of biomass for use as electrodes in smelting processes

BioChargeEAF

- Development and implementation of biocarbon-chromite briquettes in full-scale production of FeCr

HåBiMet

- Technical requirements for biocarbon in metal industry. Social aspects of biocarbon. Policy and regulations

POLICY & REGULATIONS

GHG Protocol: Greenhouse Gas Protocol. Global standard for measuring emissions, categorizing them into **Scope 1, 2, and 3**.

- **Scope 1:** Direct emissions from processing biocarbon.
- **Scope 2:** Indirect emissions from purchased electricity.
- **Scope 3:** Upstream emissions from biomass sourcing & logistics.

Benefits:

- Lowers **Scope 1 emissions** by replacing fossil carbon.
- Supports **decarbonization** of metal production.
- Aligns with **carbon neutrality goals** & potential **carbon credits**.

CBAM: Carbon Border Adjustment Mechanism. Aims to prevent companies from relocating production to countries with weaker climate policies. Mainly for steel, Al, power, cement production.

- Biocarbon is not under the CBAM framework 2023-2026.
- No information if it will be included in the future

- Biomass and biocarbon are not currently taxed under CBAM, but their use in industrial processes will influence the carbon footprint of CBAM-covered imports.

EUDR: The EU Deforestation Regulation. New policy aimed at preventing deforestation linked to products entering the EU market.

- a wider range of raw materials, including wood, soy, palm oil, coffee, cocoa, and rubber.
- Non-compliant businesses face **fines of up to 4% of annual turnover**.
- Producers with FSC certification may gain a market advantage.
- Biomass from high-risk regions (e.g., parts of South America, Southeast Asia, Africa) may face import restrictions.

THANK YOU ☺

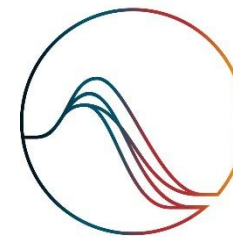
Q&A



Höganäs' experiences with biocarbon

Ryan Robinson, Höganäs AB
Process Development, Global Technology

Climate targets



SCIENCE
BASED
TARGETS

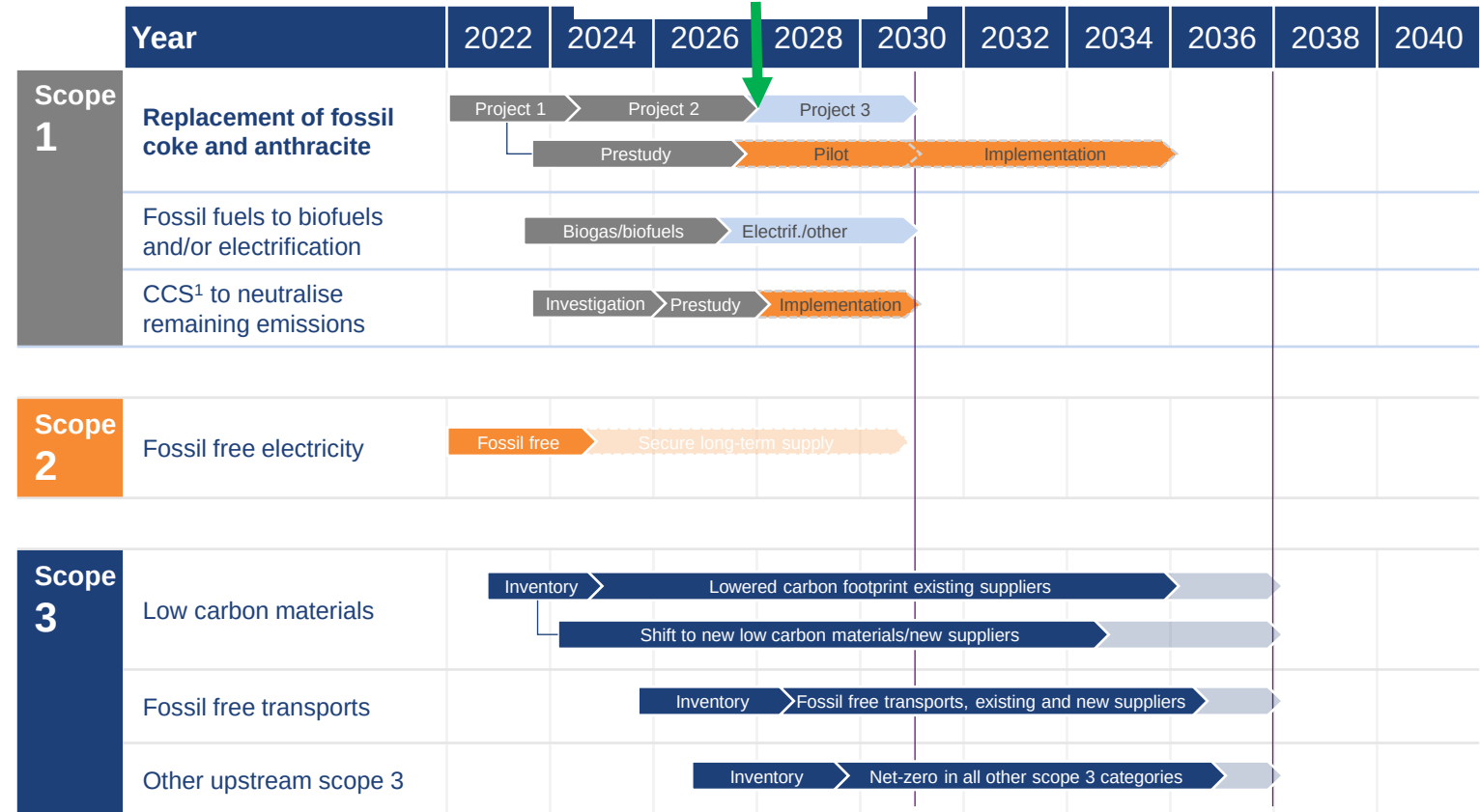
DRIVING AMBITIOUS CORPORATE CLIMATE ACTION

Biocarbon

THE NET
ZERO
STANDARD

APPROVED NET-ZERO TARGETS

- » Targets validated by the Science Based Targets initiative:
 - to reach net-zero* GHG emissions across the value chain by 2040 from a 2018 base year
- » Targets**
 - 2030: Net-zero in own operations (scope 1 and 2)
 - 2030: 30 percent reduction of scope 3 upstream, with focus on raw materials
 - 2037: Net-zero across the value chain (scope 1, 2 and 3 upstream)



Note 1: CCS, Carbon Capture and Storage, is a technology for permanent carbon removal.

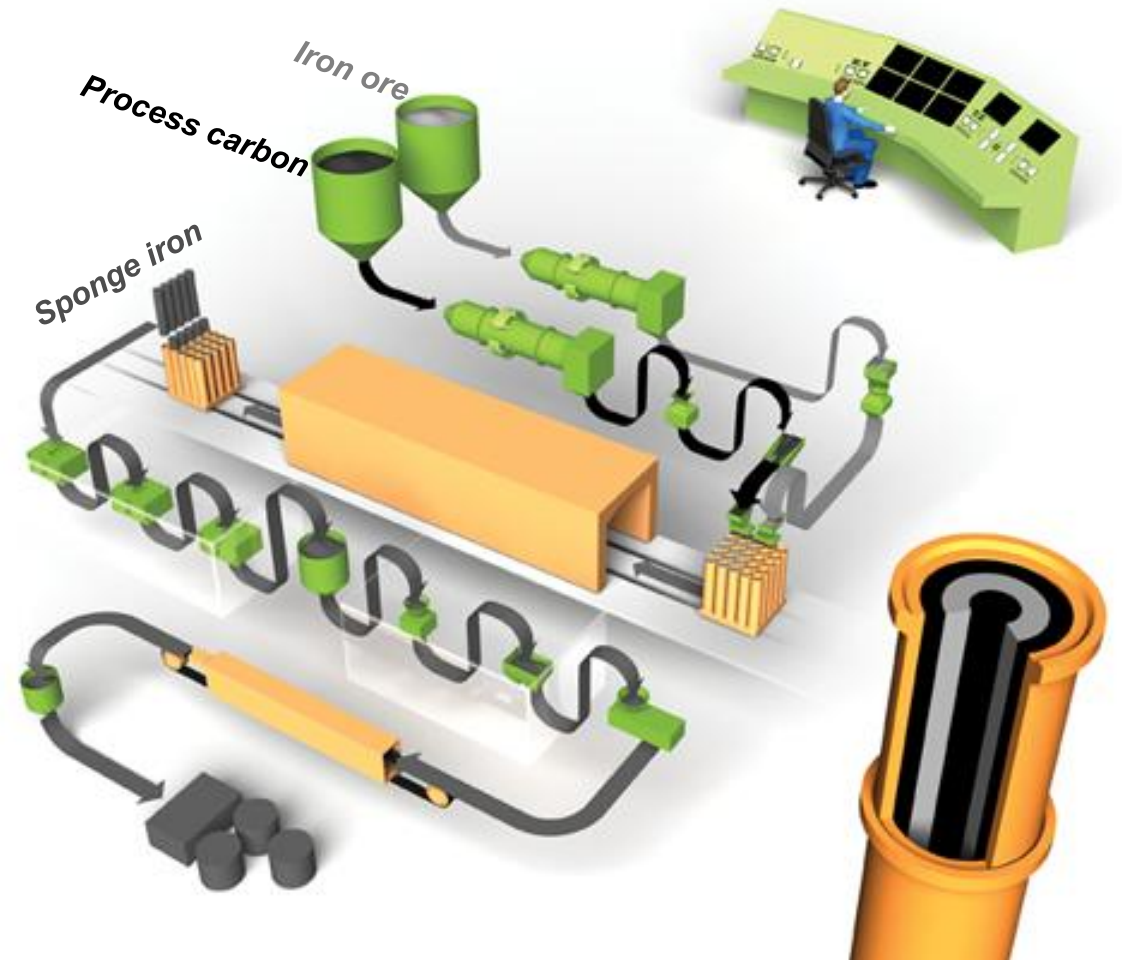
*Net-zero is to reduce greenhouse gas emissions and, when there is no possibility to eliminate more emissions, neutralise remaining emissions with permanent carbon removal technologies.

** Accelerated ambitions, not part of SBTi validation

Höganäs' carbon footprint in Sweden

» Sponge Iron Process, Höganäs

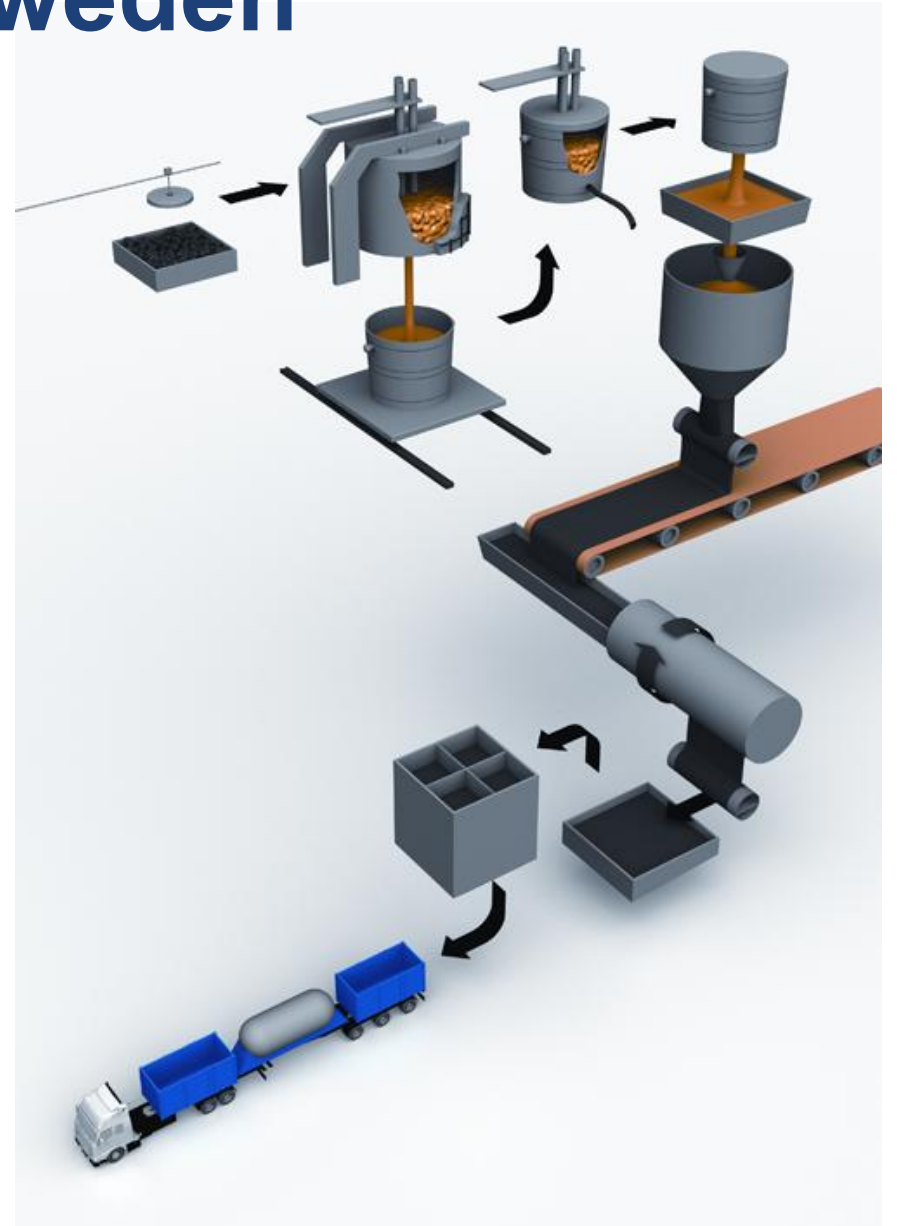
- Solid state reduction of iron ore to sponge iron using fossil coal/coke reduction mix.
- Carbon used as reduction agent and process heat
 - 45 000 fossil coal/coke tonnes/yr.
 - 55% of Höganäs' global direct emissions
 - >50% replaceable w/ biocarbon



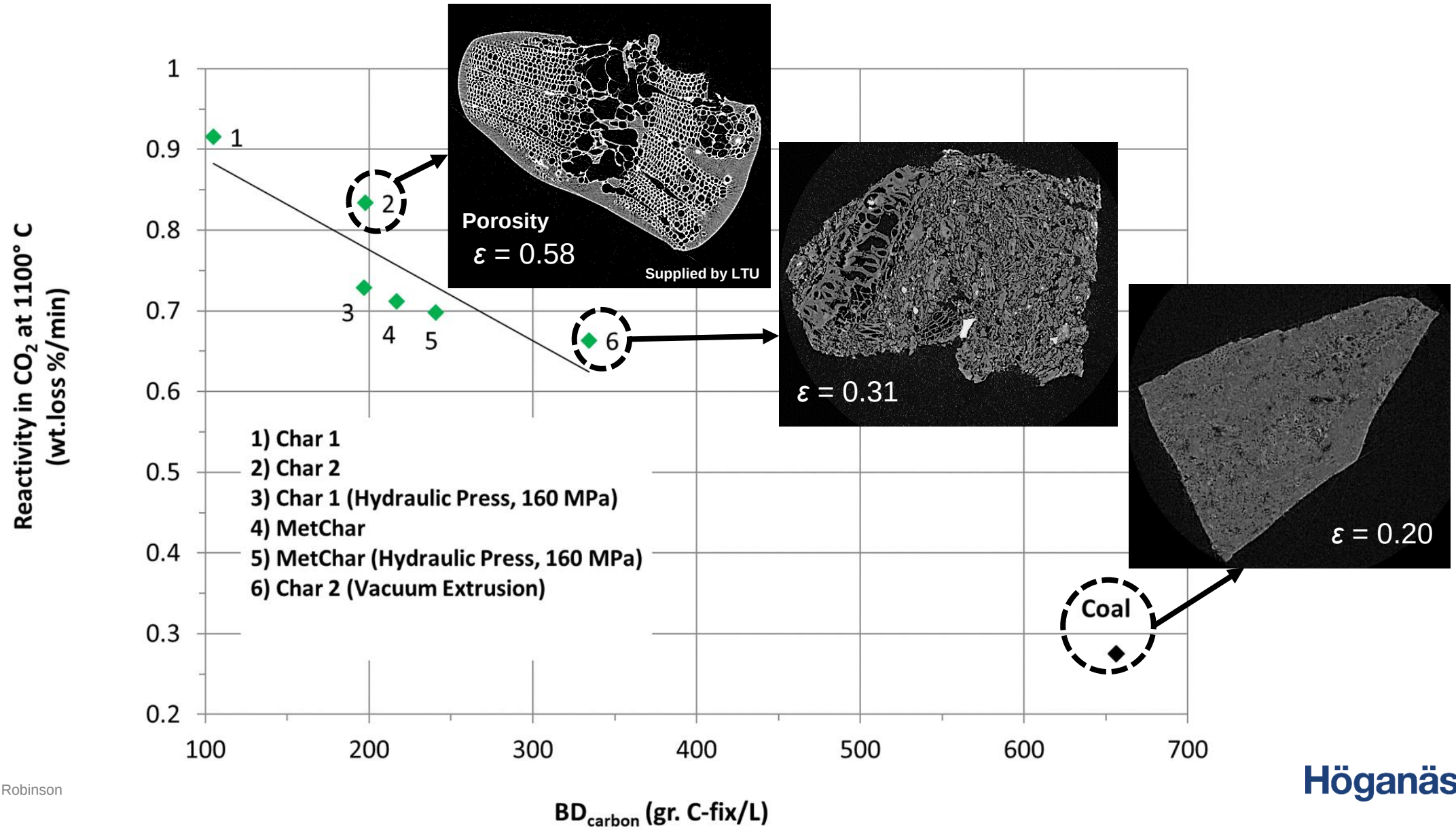
Höganäs' carbon footprint in Sweden

» Water Atomized Iron Process, Halmstad

- Steel scrap melted and refined in EAF/LF
- Molten steel atomized to powder via high pressure water spray
- Carbon used for slag foaming and alloying
 - 4000 fossil carbon tonnes/yr.
 - 8.5% of Höganäs' global direct emissions
 - 80-100% replaceable w/ biocarbon



Main Challenge: taming biochar reactivity



Biocarbon compaction

» Purpose: Adapt biochar to metallurgical processes

- Increases density, facilitating more effective feeding to processes
- Decreases reactivity, increasing carbon utilization degree.
- Increases durability, less losses to dust emissions.

» Purpose: Facilitate bulk transport & handling

- e.g. Charcoal is not allowed to be transported in bulk.
 - MHB-class 4.2 (self-heating)
- Compacted biocarbon (density > 0.7 g/cc, MC $< 10\%$)
 - Conforms to IMSBC code 4.1 & 4.2, not classified as dangerous goods
- Reduced risk of self-heating by lowering active surface area.
- Easier and less dusty to handle, transport and store.



Pilot trial using CO₂-neutral biocarbon in the Höganäs Sponge Iron Process

» 20% replacement of fossil coal with densified biocarbon in Sponge Iron Plant

August 2022 - March 2023

May - June 2023

Biochar Supply

450 tonnes biochar
Volume 2000 m³



Process tent, Pelletizing

450 tonnes biochar + additives, + water
25-30 weeks operation
7.5 tonnes wet pellets/day



Drying

Drying using residual hot air from Sponge Iron Plant
5 tonnes dry pellets/day

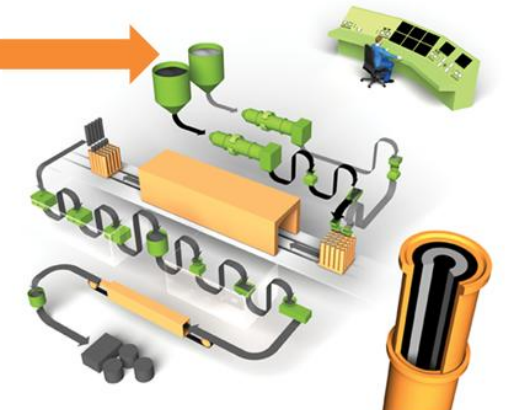
Storage tent

500 tonnes biochar pellets
Volume 1300 m³



Höganäs Sponge Iron Plant

6000 tonnes sponge iron
4 weeks operation,
Fossil CO₂ savings = 1500 tonnes



Investigate optimal production & storage conditions

Testing in EAF

» Lab-scale trials

- Compacted biochar has similar dissolution kinetics to Anthracite.
- Lower carbon crystallinity and higher porosity in biochar not necessarily negative.
- Biochar ash composition/fusion properties more important.

» EAF trials in Halmstad

- Charge carbon: 6 heats with 33% replacement of Anthracite, no deviation from normal operating conditions.
- Slag foaming: During trials with biocarbon the furnace operator deemed the slags as foamy, both by sound and when de-slagging.
- Alloying carbon: Trials replacing Petcoke (C-fix = 98%) with biocarbon (C-fix = 65%) during tapping. Avg. yield C-fix to steel melt:
Petcoke = 87%, biocarbon = 54%

An Empirical Comparative Study of Renewable Biochar and Fossil Carbon as Carburizer in Steelmaking

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1) Höganas AB, Höganas, 23683 Sweden.

2) Cortus Energy AB, Kista, 16440 Sweden.

(Received on March 10, 2020; accepted on May 18, 2020; J-STAGE Advance published date: August 27, 2020)

Approximately 60–70% of the direct greenhouse gas emissions in electric arc furnace (EAF) steelmaking originate from the use of fossil carbon charge during melting of steel scrap. Regarding short-term solutions to mitigate the climate impact of steelmaking, there is greater potential to replace fossil carbon charge with renewable carbon in the EAF than in integrated blast furnace steelmaking where mechanical strength requirements on carbon charge are too demanding. Therefore, the present study aims to provide an experimental and practical foundation for using renewable biochar in the EAF as a relatively simple step to decrease the climate impact of steelmaking.

In order to evaluate the inherent performance of biochar as a carburizing agent, lab-scale tests were completed using four different types of carbonaceous materials: synthetic graphite, anthracite coal and two types of biochar from woody biomass (BC1 and BC2). The first order dissolution rate constants from experiments ranged between 0.7 to 1.9×10^{-4} m/s, which agrees well with previously reported results. Furthermore, lab-scale results show that biochar properties commonly seen as detrimental, such as low carbon crystallinity and high porosity, do not necessarily constitute a disadvantage for biochar utilization as carburizer in steelmaking.

In order to further assess the results from lab-scale tests, an industrial trial including six consecutive heats was performed in a 50 t EAF at the Höganas Halmstad Plant. Results show that 33% substitution of standard Anthracite carbon charge with biochar BC2 gave no deviation from normal operating conditions in the EAF.

KEY WORDS: greenhouse gas emissions; renewable biochar; anthracite; carbon dissolution rate; liquid iron; EAF; carbon yield; ash content.



Biocarbon specifications for Höganäs' processes

	Unit	Sponge Iron Process	Electric Arc Furnace
Moisture	%	5 -10	< 5
Fixed Carbon	% db	≥ 75	≥ 85
Volatile matter	% db	≤ 15	≤ 5
Ash	% db	≤ 10	≤ 10
Phosphorous	% db	≤ 0.05	≤ 0.02
Sulfur	% db	≤ 0.5	≤ 0.4
K+Na	% db	≤ 0.3	-
Bulk density db	kg/m3	≥ 400	≥ 500
Particle density db	g/cm3	≥ 0.7	-
Tumbling index	%	≥ 95	-

Future needs

- » **More metallurgical quality biocarbon!**
 - Höganäs needs 15 000 tonnes/yr. 2026-2027
- » **New infrastructure for production and safe bulk transport of biocarbon**
- » **Global standards for metallurgical biocarbon quality specifications**
- » **Further development of biocarbon properties/process to optimize implementation**



Thank you!



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[@hoganasAB](https://twitter.com/hoganasAB)



www.linkedin.com/company/hoganas-ab/

Höganäs 

BIOCARBON FOR FERROCHROME

LUDVIG ÅNNHAGEN

7 February
2025



Vargön Alloys AB – Swedens only ferrochrome producer



1874: The company was founded

1912: Installation of the first ferroalloy furnace (SiMn)

1957: The first energy recovery system became operational

1972: Inauguration of the world's largest smelting furnace for ferroalloys

1987: Management buy-out (MBO) by four managers

2008: Vargön Alloys AB was acquired by Yildirim Group of Companies

2025: CoreX Holding established



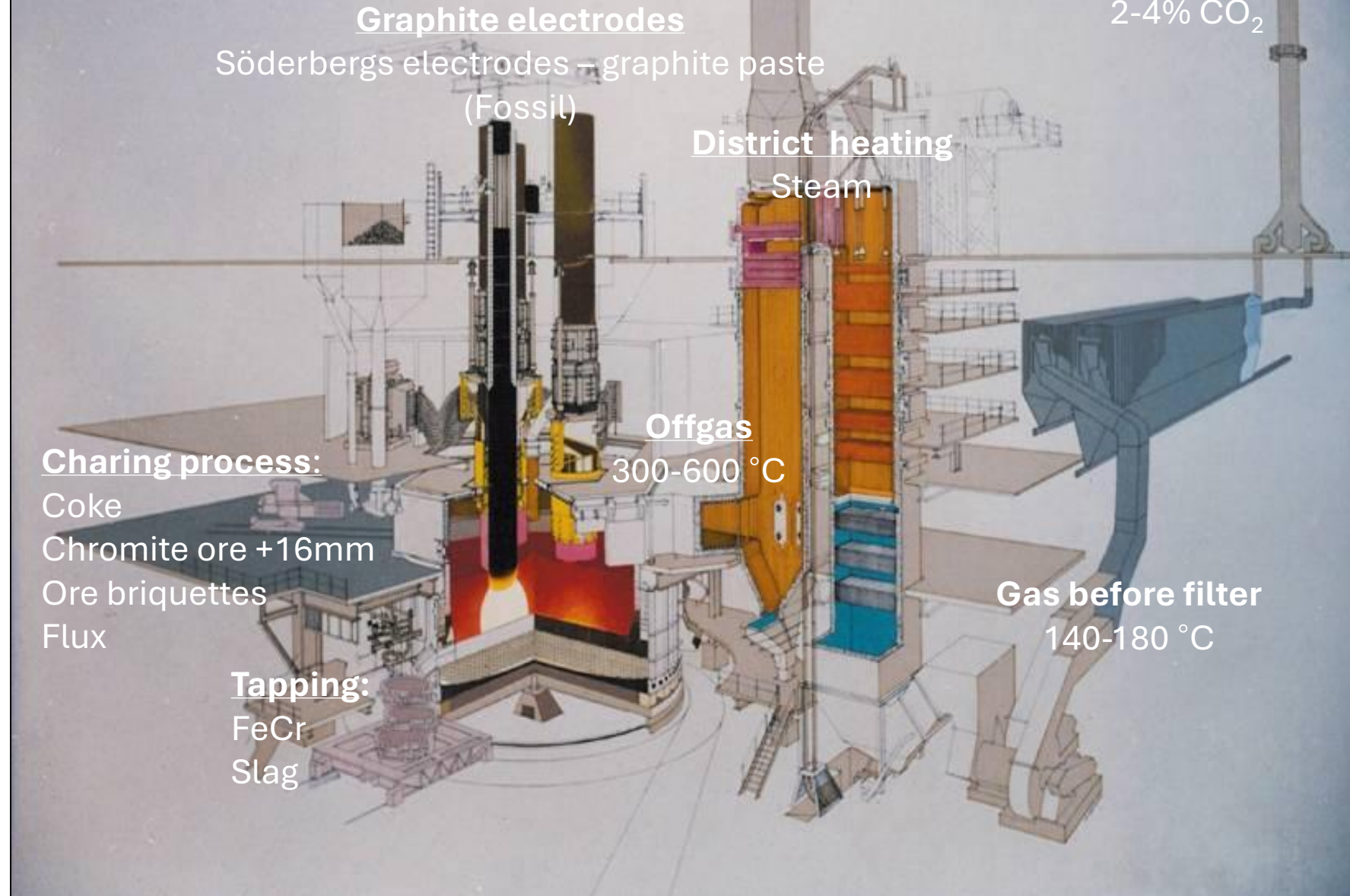
FeCr - production

Ferrochrome, shortened FeCr, is a ferroalloy consisting of 50-70% Cr.

- Low carbon = 0,01 – 0,5%
- Medium carbon = 0,5 – 4%
- High carbon = 4 – 9% C

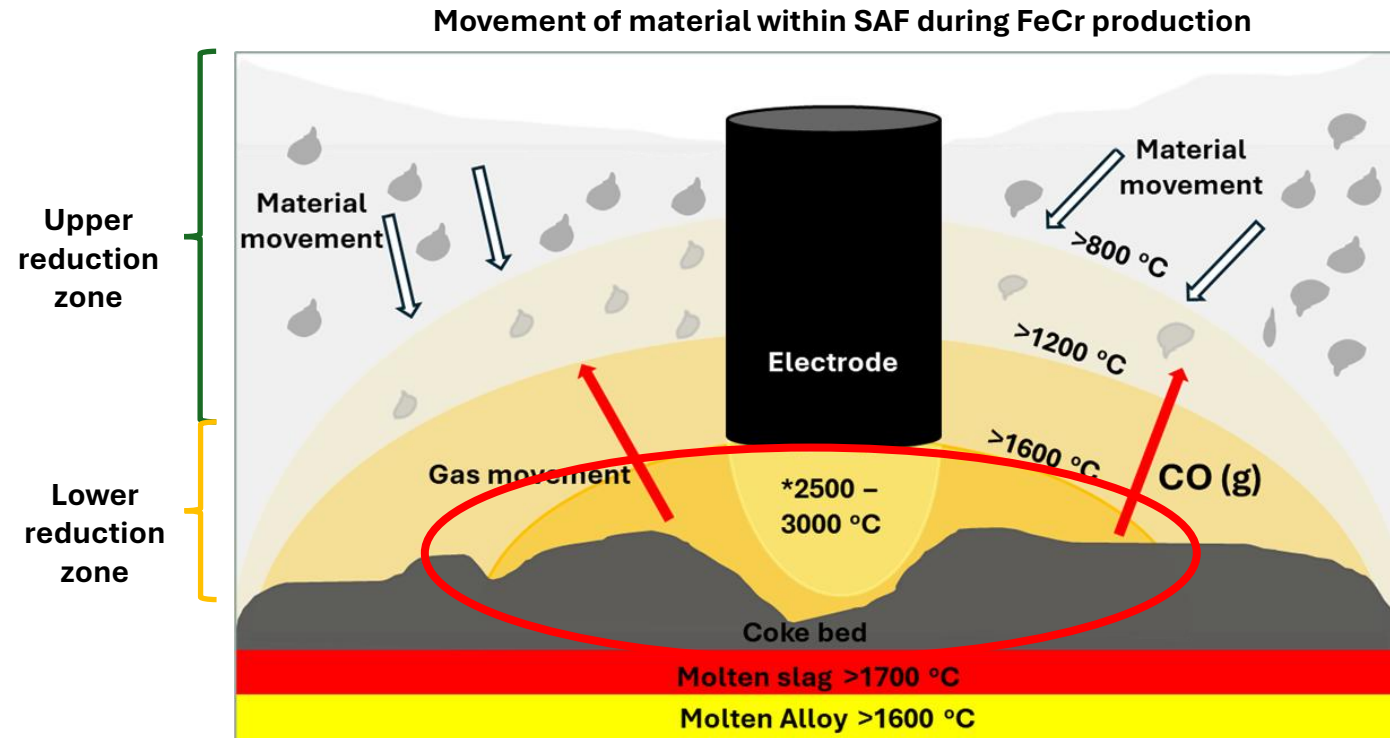


Semi-closed submerged arc furnace - SAF



Implementation of biocarbon for FeCr

- **Introducing biocarbon** to any metallurgical process requires understanding carbon's purpose and, most importantly, where the main reactions occur.
- The reduction of chromite occurs in two stages within a SAF.
 1. The upper part reduction zone, "loose charge zone," contributes most of the furnace volume but only approximately 20% of the reduction occurs here.
 2. The lower reduction zone is located beneath the electrodes. Here, the temperature is high enough for the reaction to occur
- **What are the requirements for biochar for FeCr production?**
 1. Low-reactivity: essential that carbon reaches the lower reduction zone
 2. High C-fix >85%,
 3. Low in impurities such as Sulfur and **especially low in phosphorus (P)**.
 - A. Due to the high process temperatures and the reducing atmosphere result in a high P-yield → reduced quality
 4. Low ash content: Refers to the percentage of inorganic materials or minerals that remain in the carbon source after it has been subjected to high-temperature carbonization processes.
 5. Low Volatile content: Portion of a carbon source that is driven off as gas during heating.



Vargöns experience and thoughts on biocarbon



I. Technical aspect

- I. How much biocarbon can replace fossil coke without influencing the quality
- II. Safety – Storage and handling of biocarbon

II. Request for green alloys – Green steel with fossil alloys?

- I. From only constituting 5% of the carbon footprint of steel, alloys will, in the future, make up 50% of steel's carbon footprint.

III. Current biocarbon market

- I. High prices compared to fossil coke – up to 4X the price of fossil coke
- II. Several producers who can produce 1-1.5 ton/year - not enough
- III. High P in the raw material → high P in biocarbon

IV. Carbon neutrality.....

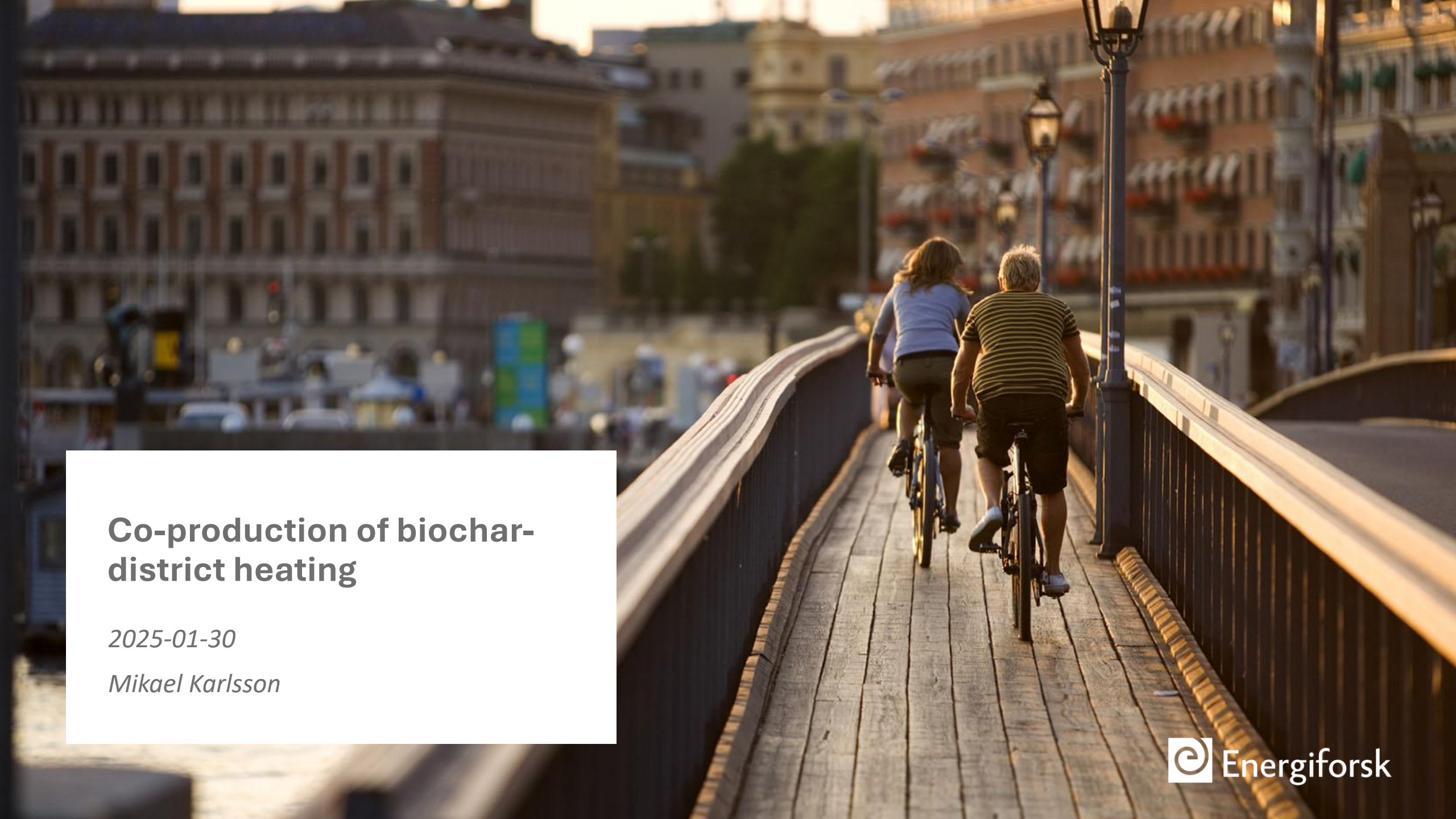
- I. Metallurgical process + heat recovery = win win!

TACK!

Ludvig.annhagen@vargonalloys.se



Block 3 – Möjligheter och policy

A photograph of two people cycling away from the camera on a wooden bridge. The bridge has a dark metal railing and is set against a backdrop of a city with historic buildings under a warm, golden sunset sky. The cyclists are a woman in a light blue shirt and a man in a striped shirt, both on dark bicycles.

Co-production of biochar- district heating

2025-01-30

Mikael Karlsson



Biochar + district heating = true

- Production facilities are available.
- Can new business be created for a pressured industry?
- Is it possible to produce the qualities that the metal industry needs?
- Or can the metal industry adapt its needs to what is technically possible with existing plants?

A tall, white industrial chimney or smokestack rises vertically against a clear, bright blue sky. The chimney has a dark, circular top section with some structural details. The perspective is from a low angle, looking up at the chimney.

What might a typical district heating production plant look like?

- Baseload boiler – A wood chip boiler that will handle most of the base load during the year
- Medium load boiler – Pellet boiler that handles summer operation and the increased load during the winter months
- Peak load / reserve – Bio-oil boiler that takes shorter power peaks as well as loss of base load or medium load.



Example from E.ON

- The following slides are from a presentation that Johan Wiman, E.ON did at Energiforsk's Värmekluster a while ago.
- I have been approved to show this during the workshop but I have not yet been told if it can be included in the "final report".
- Preliminary signals indicate that E.ON may be able to collaborate with the project.

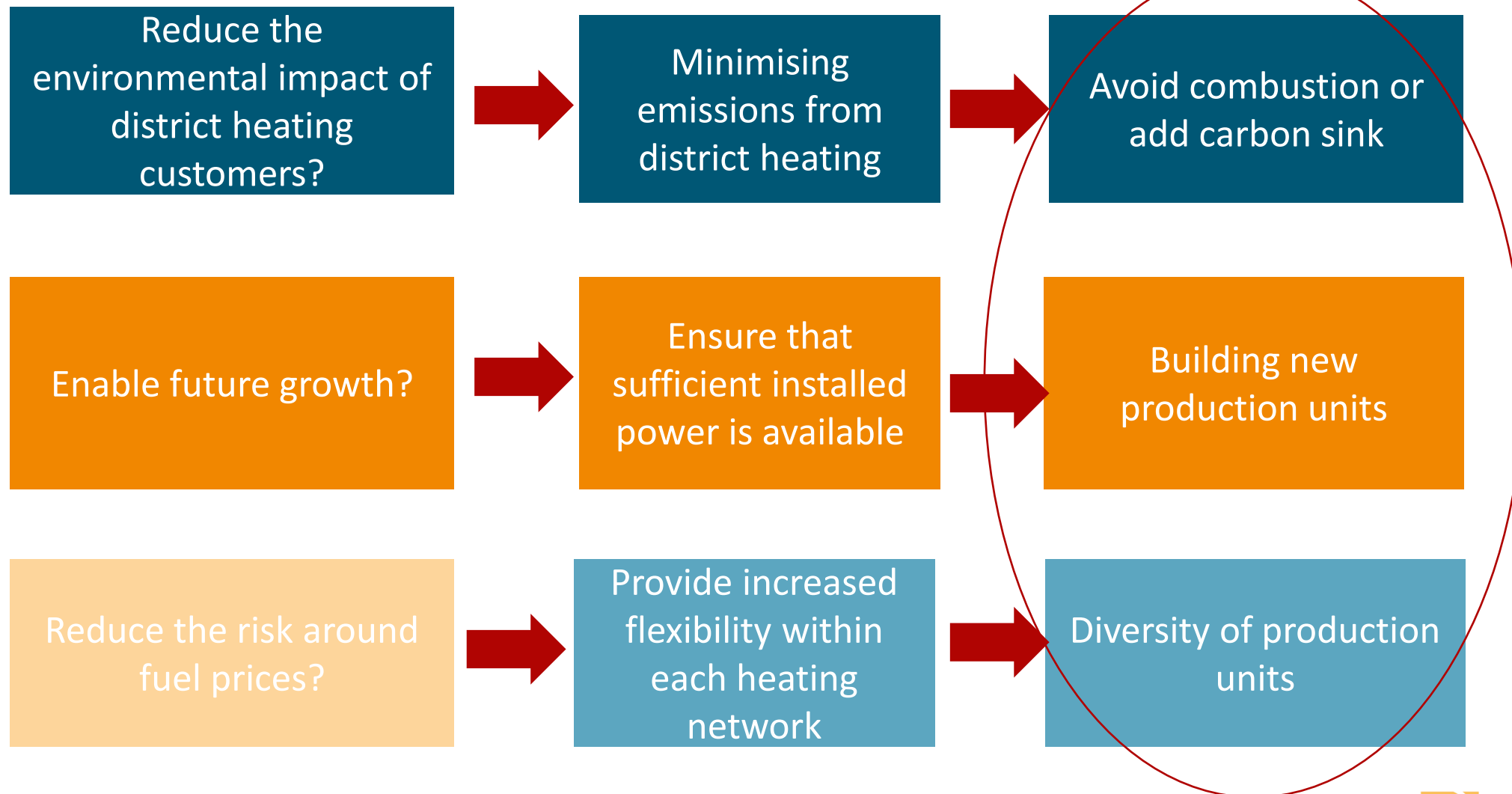
Challenges

Customers' wishes for
reduced climate impact
Current customers have a
high environmental focus

High potential new
connection
About 20% growth over the
next 15 years

Current energy market
High fuel costs and reduced
availability

Idéer till lösningar



Prof of Concept

Idéstudie

Performed test operation

Verified flexibility of heat production

Bio carbon – Quality not yet verified



Next steps

Doing longer test drives

Verifying results in another facility

Full year of operation with full flexibility
on medium-load boiler.

Examples of DHC companies that produce biochar



- SolörBioenergi
- >100 District heating plants
- Currently produces biochar in 4 plants.

Thanks and questions!



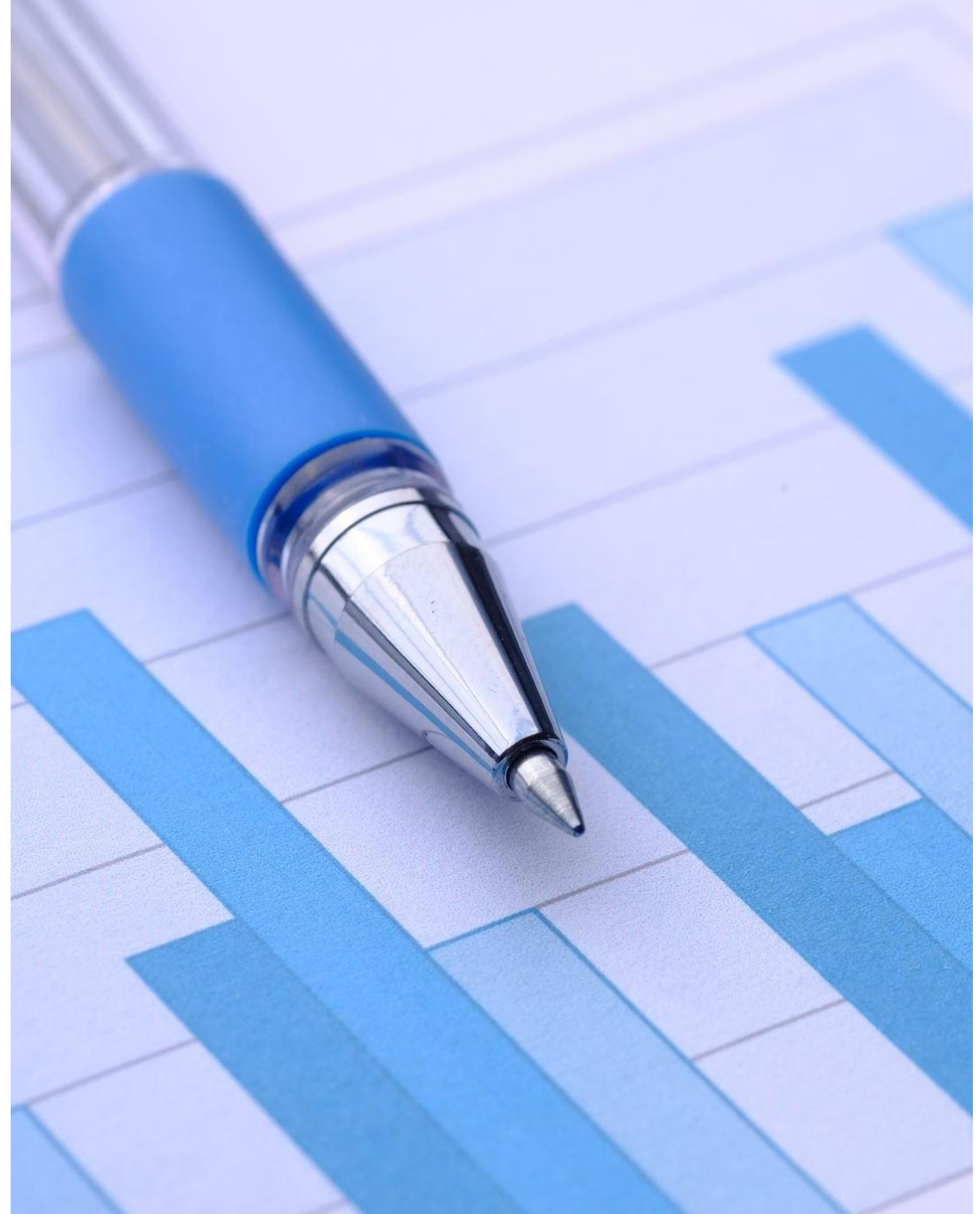
Policies, markets and prices

The conditions for a large-scale production of industrial grade biochar



The concept of a market

- An **economic market** is any structured system where buyers and sellers engage in the exchange of goods, services, or resources.
- Resources are **scarce**, there are not sufficient resources to ensure that **all activities** get **all the resources** they want.
- Scarce resources are distributed based on achieving the highest level of **welfare** possible based on the resources available.
- Market **delineation** along product and geographical dimensions.





System perspective on markets

- Highlights how changes in **interrelated market** can lead to resource strain, price adjustments, availability, and long-term sustainability.
- Market changes in one area can cause ripple effects across other sectors, requiring a systemic view to fully understand **cascading impacts**.

Criteria for market establishment

A clear, identifiable demand for the new product

Differentiate itself from existing alternatives

Economic viability with reasonable returns on investment

Regulatory frameworks should support or at least not hinder the market

The technology behind the product should be viable and scalable

Infrastructure for distribution, logistics, and supply chain management

Risk mitigation strategies

Understanding the competitive landscape

Biochar market development



Challenges remain that need to be addressed for biochar

- **Economic competitiveness:** Biochar is often more expensive than fossil fuels, requiring continued subsidies and support.
- **Market establishment:** Transaction costs and barriers must be reduced and include multiple market participants.
- **Technological development:** There is a significant need for research and development of more efficient biochar processes.
- **Regulatory adaptation:** Policies must remain flexible to support innovation without creating barriers.

Market barriers for biochar

Technological

- High-cost processing (e.g., advanced pyrolysis technology).
- Slow adoption rates (e.g., hesitations due to process uncertainties).
- Capital intensive production (e.g., significant investment, scaling limitations).
- Unclear process optimisation (e.g., biochar properties and quality)
- Competing decarbonization technologies (e.g., hydrogen-based or CCS/CCU)

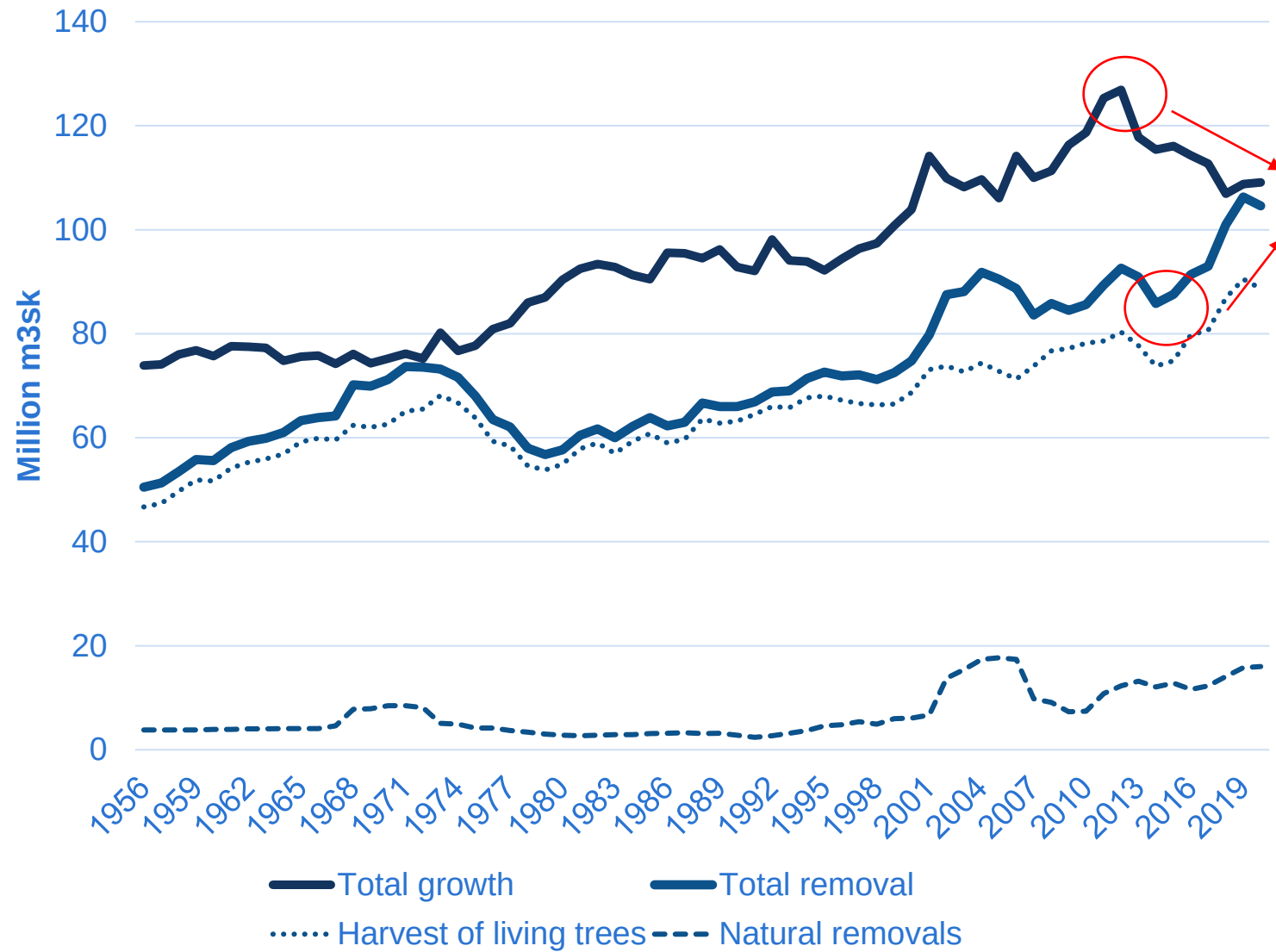
Economical

- Unclear policy frameworks (e.g., regulations and incentives are still developing).
- Unfamiliarity and lack of knowledge (e.g., about biochar's benefits and applications).
- Consistent biomass supply (e.g., leading to high costs).
- Biomass competition (e.g., limits the availability at competitive prices).
- Low-cost import alternatives (e.g., biochar production elsewhere).

Key factors for biochar market development

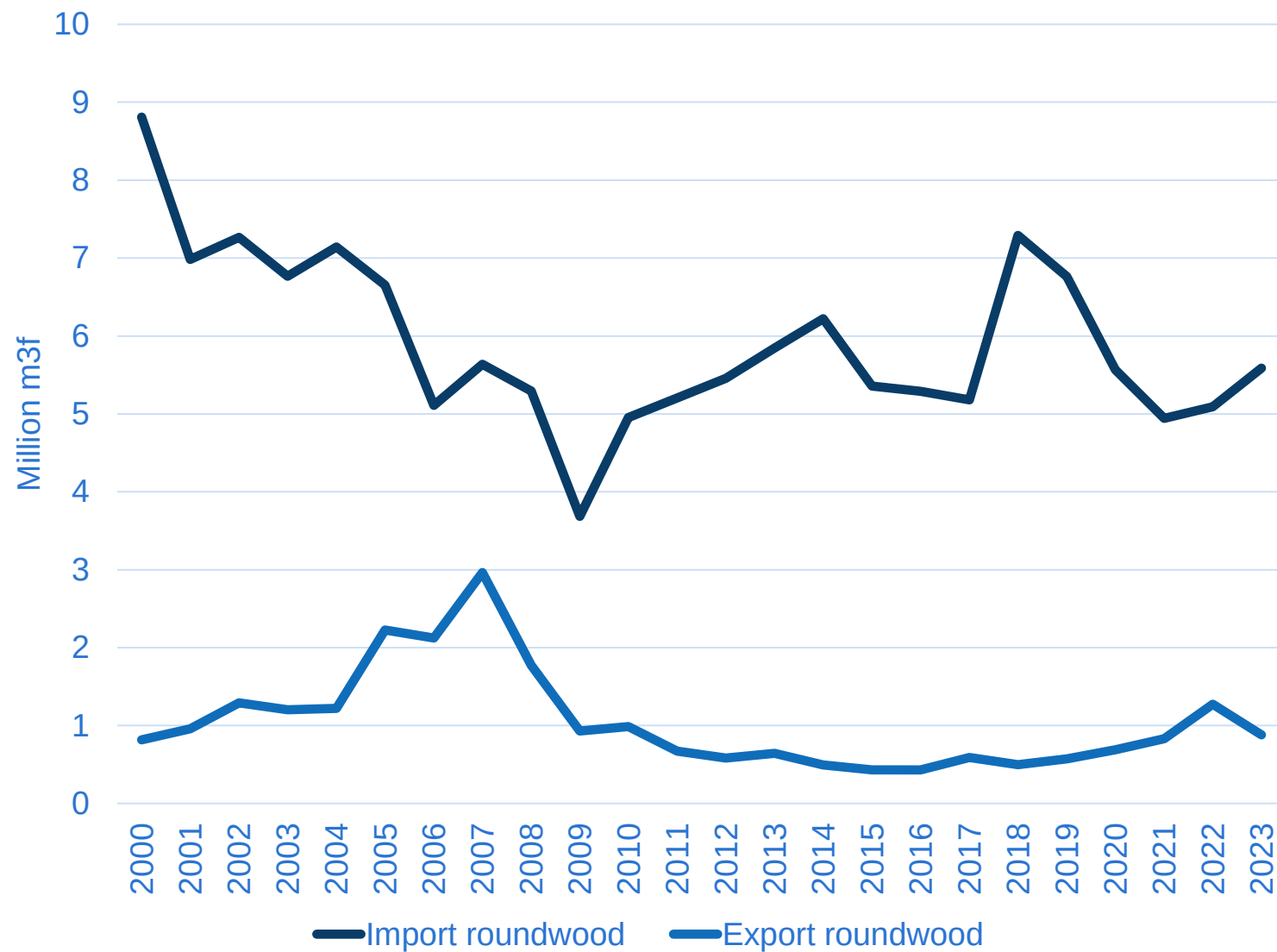


Biomass feedstock



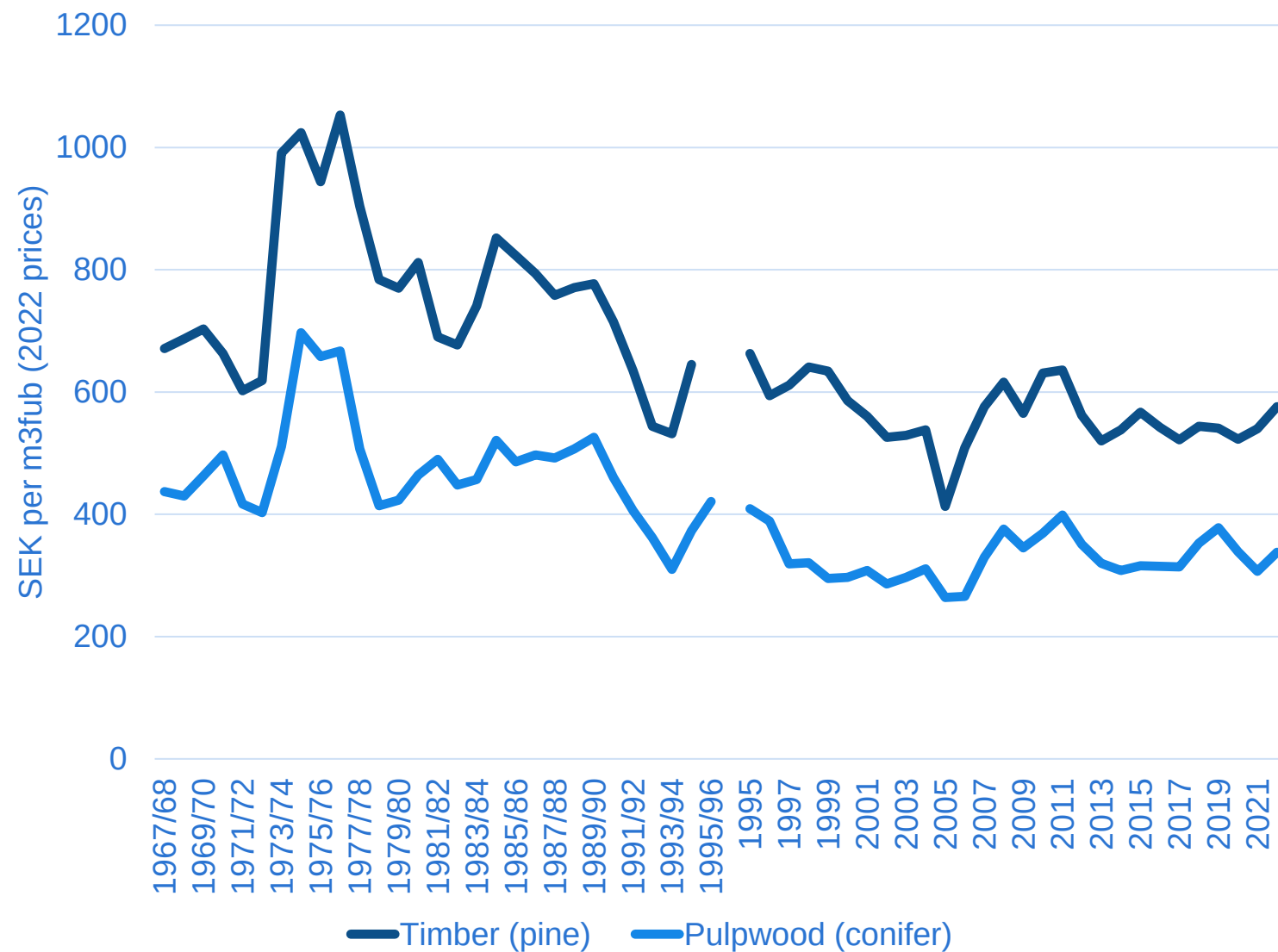
Annual growth and removals (Sweden)

Source: Riksskogstaxeringen (Table 3.30)



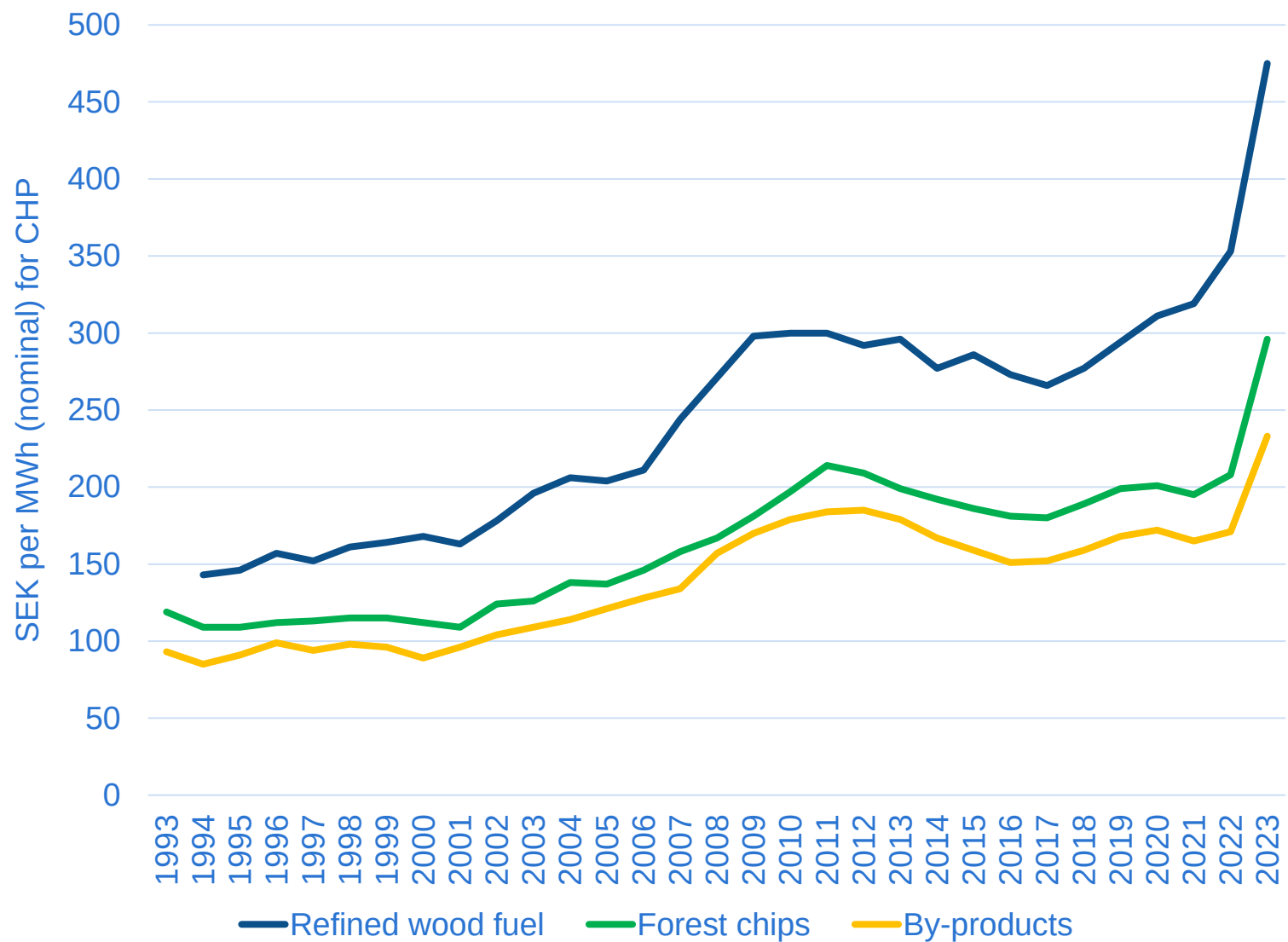
Trade with roundwood (Sweden)

Source: SCB (Kombinerade nomenklaturen, KN)



Roundwood prices

Source: Skogsstyrelsen



Wood fuel prices

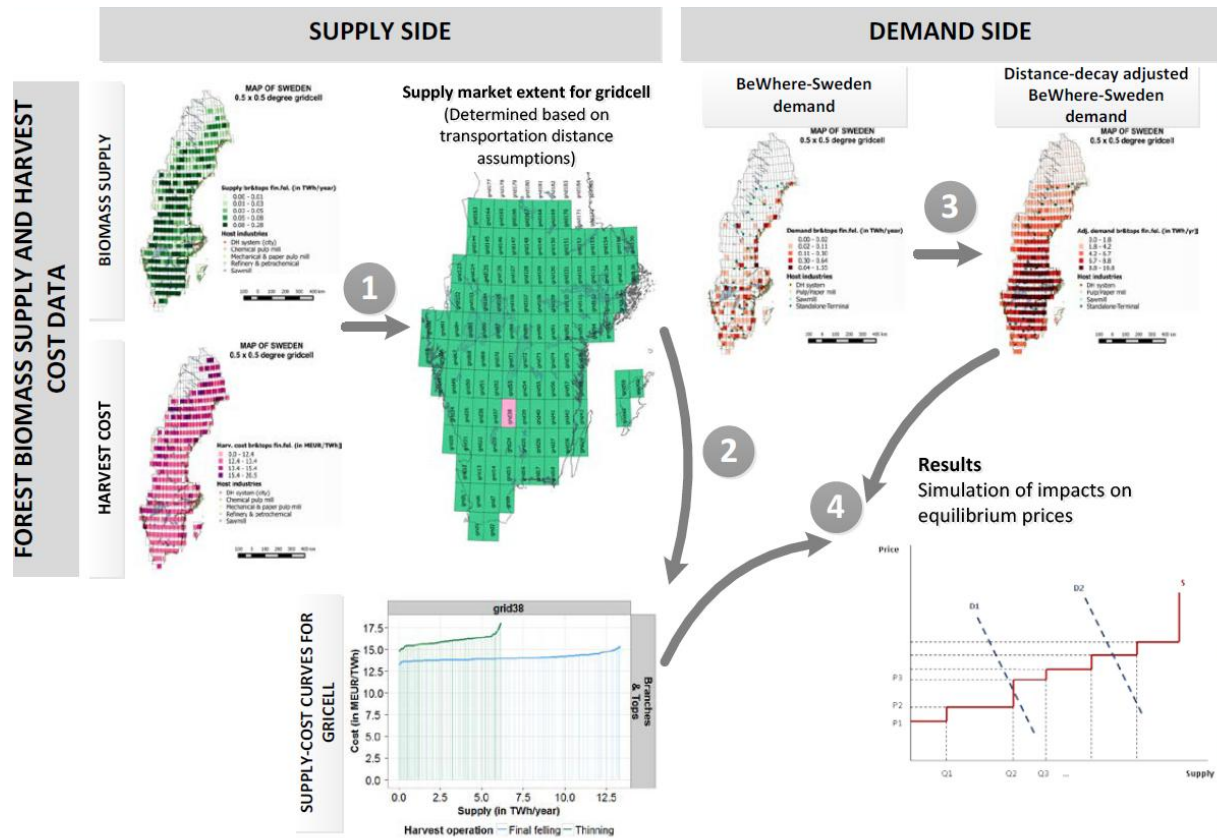
Source: Energimyndigheten

Modelling results

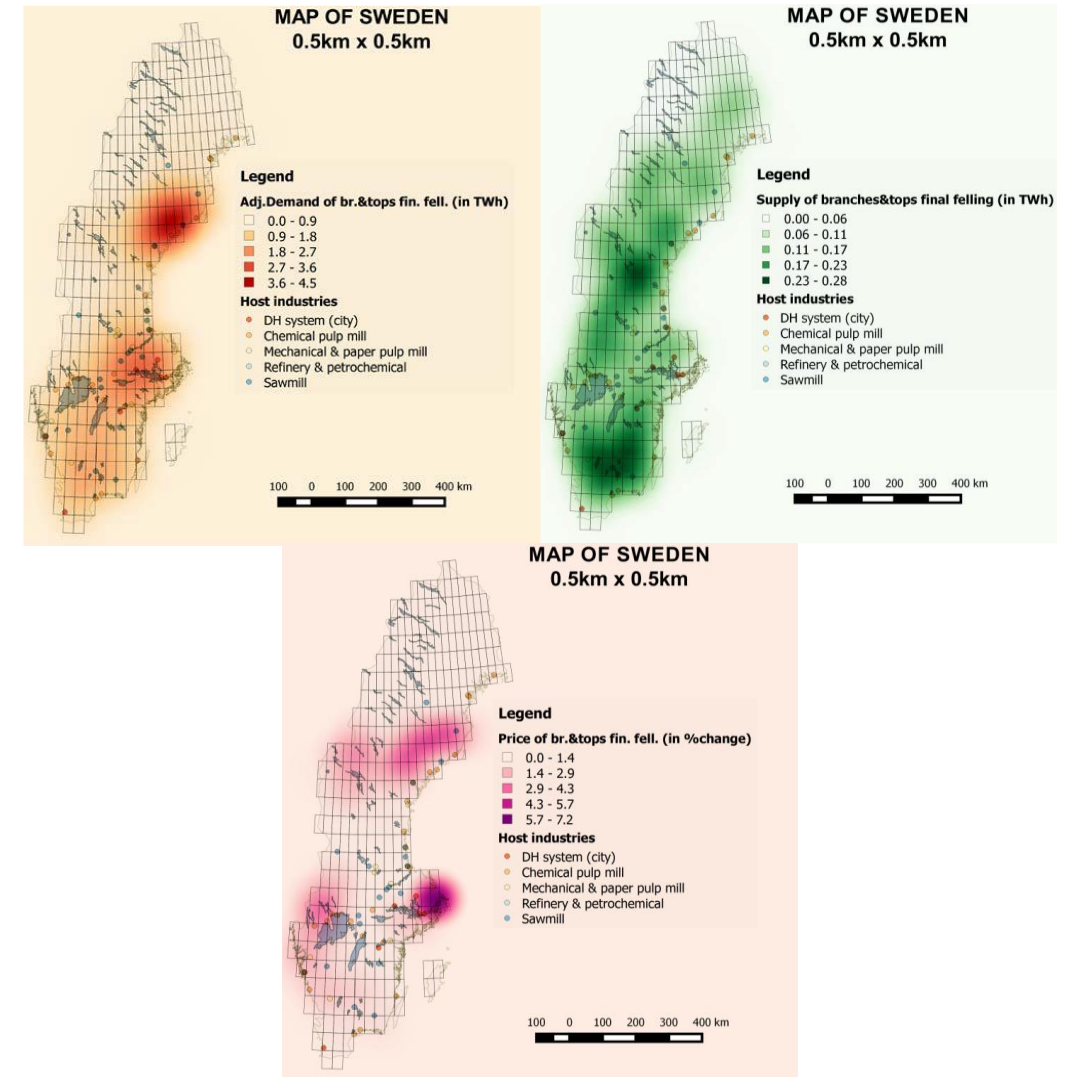
Examples from previous research projects

Spatial Price determination model

Spatial pricing of multi-market heterogeneously distributed resources

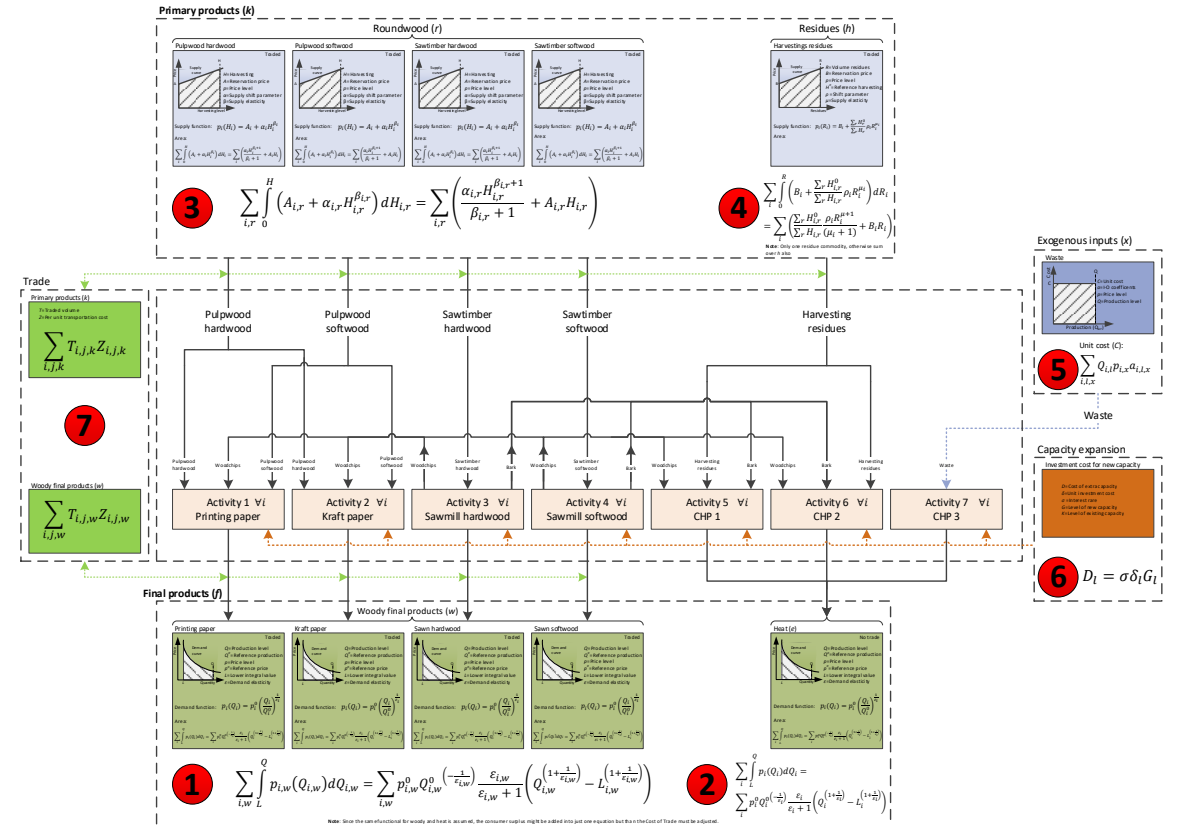


Branches & tops, final felling, 10 TWh



Regional price-determining market model for forest resources

Explicitly consider the conditions and the possibilities for a **transition of the mining and metals industry** towards increased biomass-based production and identify and quantify the **price-affecting local and regional market changes**.



... and the results

- Price effects varies, e.g., a 10% demand increase by the mining and metal industries will have a **17-24% price increase** effect on harvesting residues, bark and industrial by-products (Olofsson, 2019b).
- An efficient forestry sector (increased supply) can **reduce the price effect by up to 25%** (Lundmark, et al., 2020).
- Market forms (i.e., “level” of competition and price-settings behaviours) affect the price effect. The **price of timber (pulpwood) will be reduced by 12-28% (3%)** if the level competition is reduced (Olofsson, 2020).
- Carbon sequestration, recreation, biodiversity and cultural expressions, when accounted for, will also **have a price effect on woody biofuels**.
- Necessary to **increase the supply** of woody biofuels to reduce the price effect.
- Significant spatial variations in demand structures suggest that **decision-makers can affect regional prices**.



Uncertainty

- Types of uncertainties:
 - Parametric uncertainty.
 - Structural uncertainty.
- With increased ease of computations, it is now possible to include stochastic elements in the models.
- Uncertainty, especially about price variations, is important to policy-makers.
- Incompleteness of markets:
 - Availability of futures markets.
 - Availability of insurance markets.
 - Availability of contingent markets.



Appendix 2:

Presentation from concluding seminar

Hållbart Biokol för Metallurgisk användning (HåBiMet)

www.habimet.se

Swedish Metals
& Minerals

impact innovation

Swerims programråd
för metallurgi

FORMAS ::

 Energimyndigheten

VINNOVA
Sveriges innovationsmyndighet

Project och prestudies

HåBiMet – Technical perspective

HåBiMet – Social perspective

HåBiMet – Policy perspective



Project partners



Biocarbon – what is that?



Bild från Höganäs

Important to establish standardised terminology

Biocarbon

Biocoal

Circular
biocarbon

Biogenic
carbon

Renewable
carbon

Biocoke

Green
carbon

Charcoal

Carbonized
biomass

Hydrochar

Biographite

Char

How is biocarbon produced?

- Pyrolysis
- Torrefication
- Gasification
- Hydrothermal carbonization (HTC)



Biocarbon powder



Biochar



Torrefied material



Hydrochar

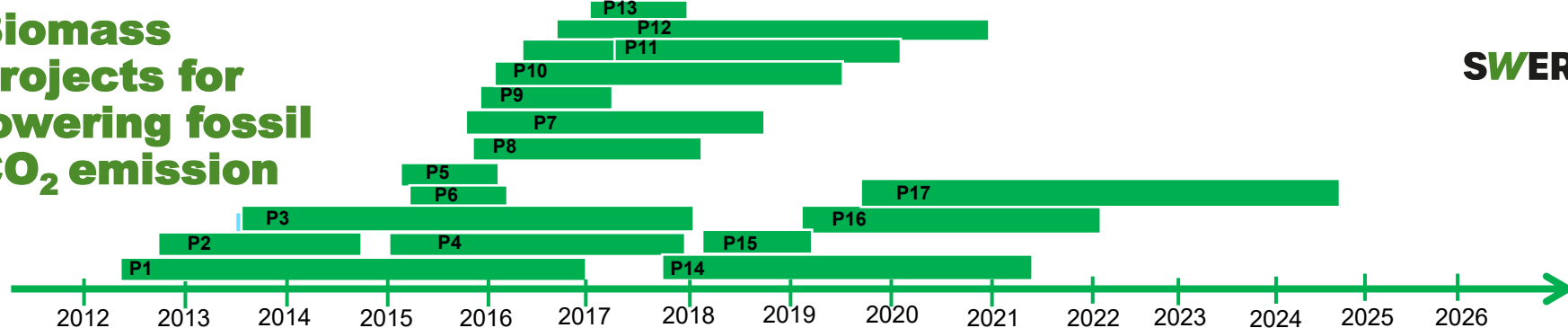
Biomass sources

- Wood
- Forest residues
- Garden waste
- Agricultural waste
- "Grot" (branches and tops)
- Sludges
- Orangepeel, lemonpeel
- Nut shell:
coconuts, hazelnuts...
- Algae
- ...

Previous biocarbon research at Swerim

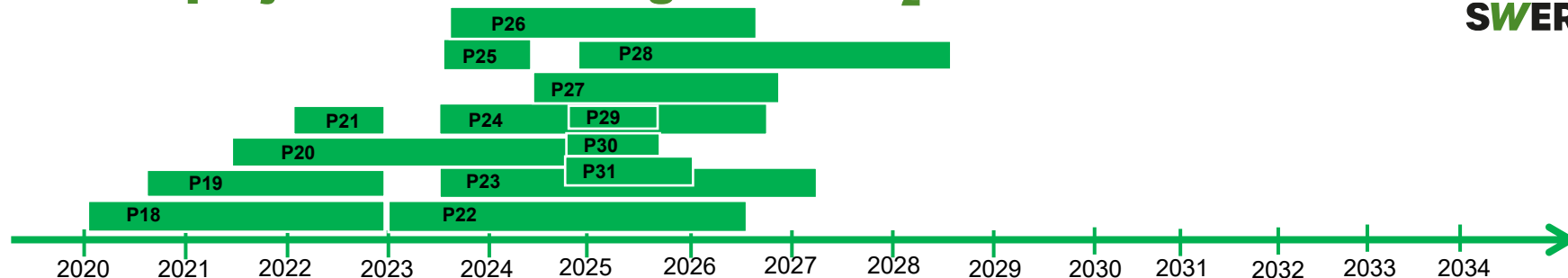


Biomass projects for lowering fossil CO₂ emission



	Title	Start date	End date
P1	Improved coal combustion under variable BF conditions (IMPCO)	2012-07-01	2016-12-31
P2	Preliminary investigation and evaluation of biomass utilization in the blast furnace	2012-10-01	2014-09-30
P3	Flexible production of coke using alternative coals—effects on coke properties under blast furnace conditions (FLEXCOKE)	2013-07-01	2017-12-31
P4	Bio-agglomerate	2015-01-01	2017-12-15
P5	Utilization of biomass lignin in the integrated steel plant briquettes	2015-02-01	2016-01-31
P6	Design of Biomass Products from Forest Products for Metallurgical Applications	2015-03	2016-02
P7	Renewable Energy Sources in Steel Plant Processes: Biomass-based Reductants, Fuels and Chemicals	2015-10-01	2018-09-30
P8	Injection of renewable and hydrogen rich reducing agents	2015-11-10	2018-01-10
P9	Green BF (Grön Masugn)	2015-12-09	2017-02-28
P10	Bio4Metals	2016-01-01	2019-04-30
P11	Utilization of organic sludge in metal industry (OSMet S1, S2, S2+ & S3.0)	2016-04-18	2023-04-01
P12	Forest biomass in metal industry – future possibilities and consequences (BioMetInd)	2016-09-01	2020-12-31
P13	Green BF- Focus Biomass (Grön Masugn-Fokus biomassa)	2016-12-01	2017-11-30
P14	Bio4BF	2017-09-01	2021-03-31
P15	Investigation of behaviour of bio-carbon briquettes at elevated temperatures	2018-02-01	2019-02-01
P16	Bio-coal as raw material in coke for lower CO2-emission in metal production	2019-01-01	2021-12-31
P17	Reduced CO2 emission through designed bio-coal in the residue briquette for the blast furnace (MICO)	2019-07-01	2024-11-30

Biomass projects for lowering fossil CO₂ emission



	Title	Start date	End date
P18	Future Feedstock Flexible Carbon Upgrading to Bio Energy Dispatchable carriers (F-CUBED)	2020-01-01	2022-12-31
P19	Developing Biocarbon Briquettes for Sustainable Cupola Furnace - Bio4Cupola	2020-09-01	2022-12-31
P20	BioChargeEAF	2021-06-01	2024-11-30
P21	Bio4SAF	2022-03-01	2023-06-30
P22	GreenHeatEAF	2023-01-01	2026-06-30
P23	Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling - BioReSteel	2023-10-01	2027-03-31
P24	Vätgas och cirkuläret i Västerbottens metallindustri, AP4 Biobaserat legeringsmedel till gjuteriindustrin i Västerbotten	2023-10-01	2026-09-30
P25	ANGELUS	2023-10-02	2024-05-31
P26	FEMOST	2023-10-23	2026-10-22
P27	Maximizing carbon-rich product yield from bioresources via an innovative two-stage pyrolysis	2024-06-03	2026-11-15
P28	CROSSCUT	2025-01-01	2028-06-30
P29	HåBiMet – Tekniskt perspektiv	2024-11-01	2025-06-30
P30	HåBiMet – Socialt perspektiv	2024-11-01	2025-06-30
P31	HåBiMet - Policyperspektiv	2024-11-01	2025-12-31

Background HåBiMet



Background for the HåBiMet projects

-  Why is there not large-scale market for metallurgical biocarbon in Sweden?
-  What hinders a **sustainable market** for metallurgical biocarbon from developing in Sweden?
-  What kind of initiatives would support it. The three projects adress challenges from different perspectives: **technical, social and policy**.
-  How can the many **stakeholders for biomass, biocarbon and bioenergy in Sweden coordinate**?
-  Need for a better understanding of the **social, environmental and economic potential of biocarbon in Sweden**.

What is new with HåBiMet?

- In order to credibly assess the **potential and barriers** for biocarbon supply, other industries with an interest in biocarbon and biomass must be taken into account.
- **System perspective**: Assembling a **broad consortium** of actors from biomass production to final use of biocarbon, including forestry, energy, chemical and agricultural sectors.
- Identifying challenges to **social acceptance** for the use of metallurgical biocarbon, and proposing possible ways of improving that acceptance.
- Identifying opportunities to strengthen the **attractiveness as an employer** of the developing metallurgical biocarbon industry.

Need and demand inventory

Scale of demand

- How much biocarbon is needed?
- How large is the uncertainty?

From litterature

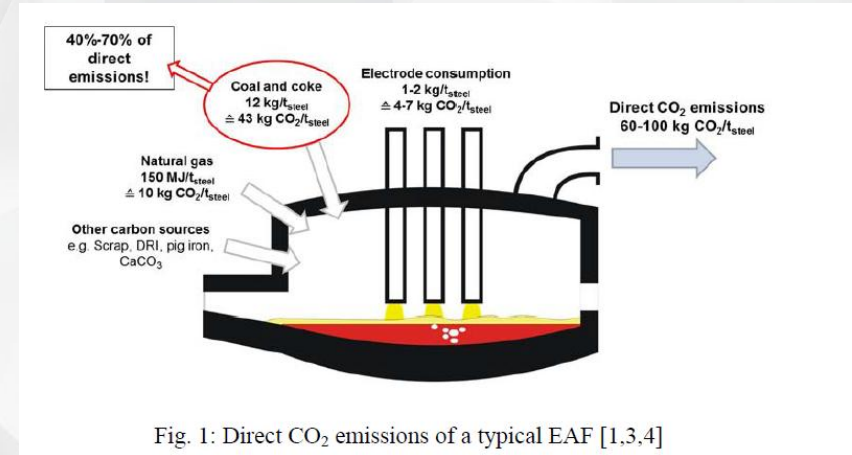
- Fossil free Sweden – steel industry
 - 1-1.5 TWh biocarbon (current production) → ~127-190 kton, 28-40 kg/t
 - 2.3 – 3 TWh biocarbon (including Stegra) → 296 – 380 kton, 31-40 kg/t

Other figures in the litterature

~~150 kg/tonne steel?~~

~~3 kg/tonne steel?~~

- 12 kg/tonne steel?



Factors impacting biocarbon demand estimates

Easier to account for

- Biocarbon properties
 - fixed carbon
 - total carbon
 - Volatiles
- Slag amount
- FeO content of slag
- Steel grade, target C content

Difficult to account for

- Hydrocarbons in scrap
- Other reducible oxides in slag
- Biocarbon yield
- Produced gas volume



DRI use and
availability

Model for estimating demand Sweden

Contributors to C need

- C proportional to FeO content of slag
- C proportional to total slag volume
- C for alloying

Key assumptions

- Total steel production 2030: 9.5 Mton
- DRI fraction of feedstock: 65%
- Average metallization DRI: 95%
- 80% yield in EAF

Results

- Total C demand 230-300 kton/year
- With 58% Cfix (gasification byproduct biochar) → 400-515 kton/year
- SSAB + Stegra 75-80% of demand

Uncertainty analysis (1) – 2 scenarios

High DRI

70% DRI
30 % scrap
190 kg slag/t

Low DRI

30% DRI
70 % scrap
139 kg slag/t

1. Woody → 28.8 kg/t steel

2. Agri. Residue → 34.8 kg/t steel

3. HTC → 143.8 kg/t steel

4. Fossil ref. → 13.7 kg/t steel

1. Woody → 12 kg/t steel

2. Agri. Residue → 14.5 kg/t steel

3. HTC → 59.9 kg/t steel

4. Fossil ref. → 5.7 kg/t steel

Carbon products

1. Woody
2. Agri. Residue
3. HTC
4. Fossil ref.

Cfix parity

Uncertainty analysis (2) – key assumptions

- Stegra Phase 2: 2.5 Mton capacity, ca **135 kton, 26%**
- 95% metallization → 98% metallization: **63 kton, -12%**
- C content at tapping:

Tapping C [w%]	Total biocarbon need [kton]
1%	422
1.50%	524
2%	626



+/- 19%

Not the whole pictures

- A few more metal industries could be taken into account
 - Syngas-DRI (Ferrosilva)
 - Casting industries including Volvo and Scania
 - Copper and Zinc (Boliden)



Conclusions

Stegra and SSAB will dominate demand

- ~80% of demand from SSAB+Stegra

Carburisation of DRI using NG or syngas could have considerable impact

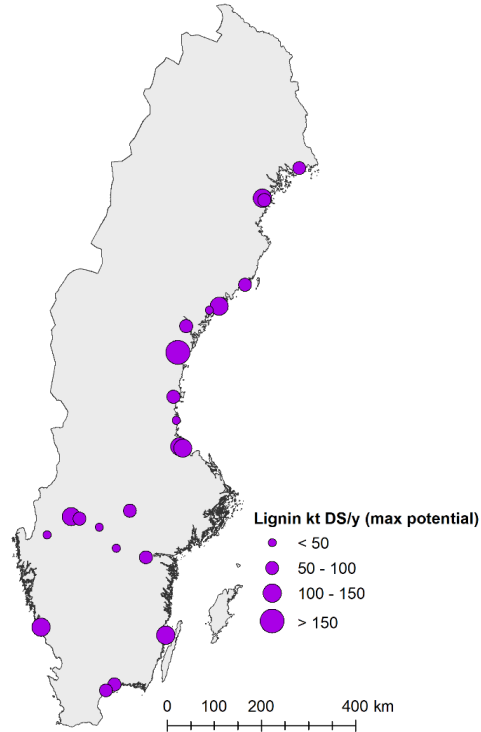
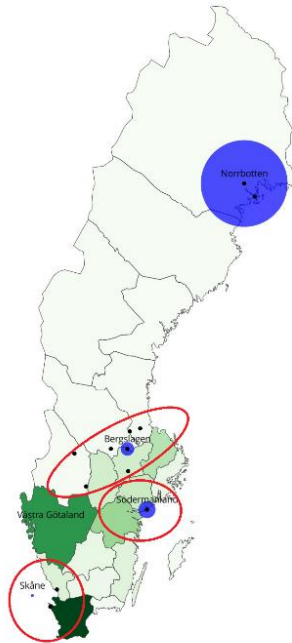
Total C demand in the range of 230 – 300 kton/year

- Estimate: 400 – 515 kton biocarbon/year
- 3-4 TWh biocarbon

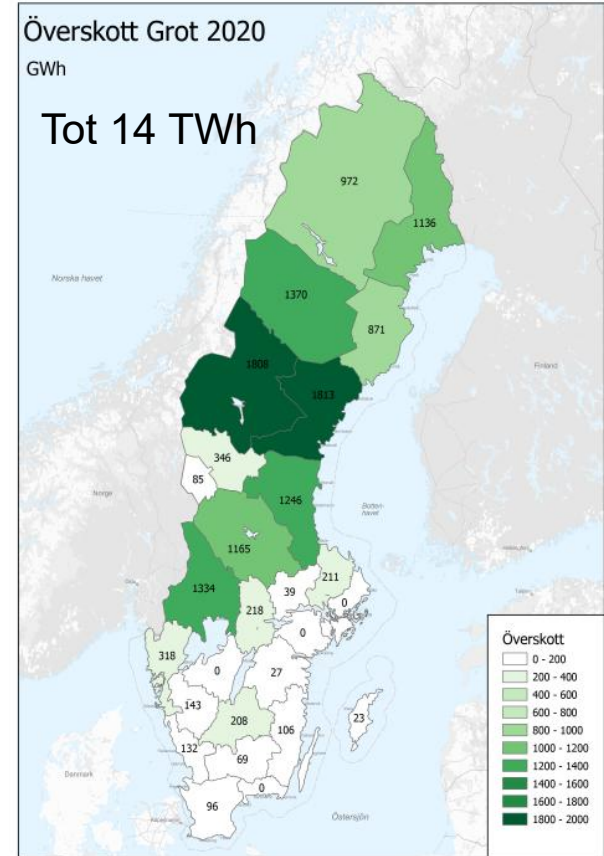
6 to 40 TWh woody biomass (depending on prod. route)

- Total biofuel use in Sweden 2022: 154 TWh, district heating ~40 TWh

Short notes on supply



(Wetterlund 2025)



Sustainable biocarbon for metallurgical use

Saga Grevarp

Material Science and Engineering - KTH Royal Institute of Technology

Supervisors: Yu-Chiao Lu, Tova Jarnerud Örell, Erland Nylund

Background

- 2023, the metal industry accounts for 17% of Sweden's total carbon dioxide emissions
- Metal industry is transitioning towards **fossil-free** manufacturing
- Biocarbon is a fossil-free carbon source
- 68% Forest land of which 84% is productive forest land
- Biochar is often used in Sweden for soil improvement

Purpose

Draw conclusions on whether the availability and properties of biocarbon produced from woody biomass can satisfy the demand of the metal industry and the difference to soil improvement application.

Research questions

- Can residual biomass from the Swedish forestry and sawmill industry meet the requirements for biocarbon in metallurgical applications?
- What technical properties of fossil coal used in today's metallurgical processes in Sweden?
- What are the properties of biocarbon that can be produced today in Sweden, and how they compare with requirements of metallurgical processes and soil improvement?

Methodology



Literature review

Main topics:

- Biomass and resources
- Biomass conversion processes
- State-of-the-art application of biochar in metallurgical industry



Interview

21 Interviews

Interviewees cover:

- Forest industry (3)
- Biochar producers (6)
- Biomass (1)
- Fossile carbon (2)
- Steel producing companies (5)
- Ferroalloy producer (1)
- Soil improvement (2)
- Consultant (1)

Analysis:

- Transcription of interviews
- Analysis of interviews

“No biomass is grown for biocarbon, it is taken from waste streams to make it”

- Scientists biocarbon/biomass

Types of biomass from forest

Forest

- Thinning residues
- Thin wood
- Stem wood
- “Grot”
- Storm damaged
- Bark beetle infested
- Fungal infested

Sawmill industry

- Sawdust (pellets)
- Wood chips

Biocarbon production

Raw material:

Wood pellets

Wood chips

Wood type

Pine

Spruce

Deciduous tree

Density

Pine 550 kg/m³

Spruce 430 kg/m³

Alder 535 kg/m³

Birch 610 kg/m³

Biocarbon production

- Yield from processes:

Biocarbon 20-35%

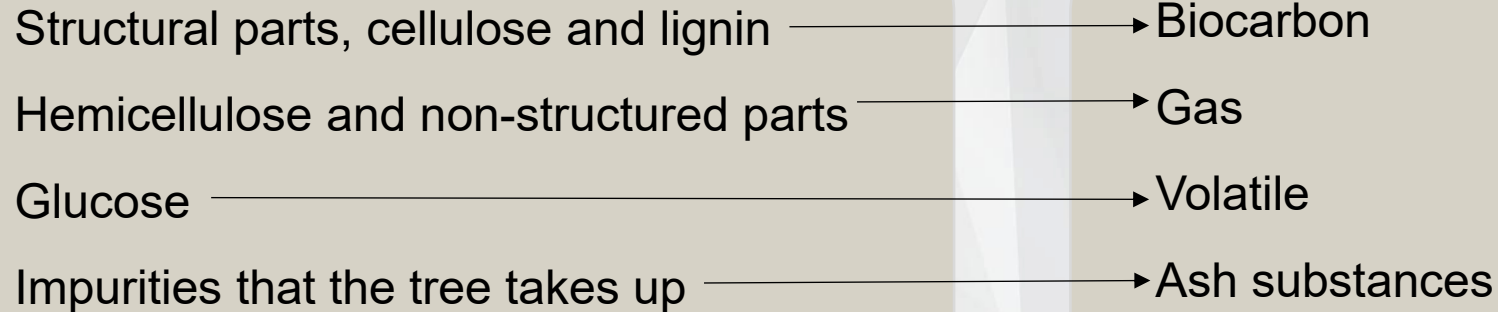
Gas

Oil

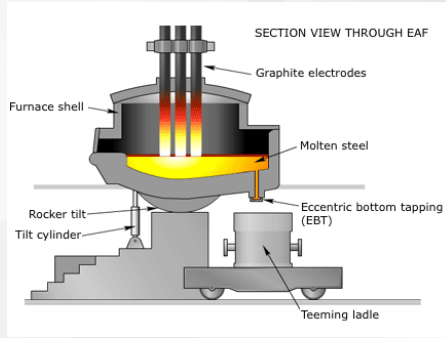
Heat

Biocarbon production

- Quality comes from the components of the biomass

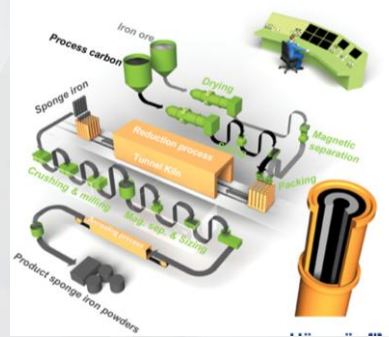


Results and discussion



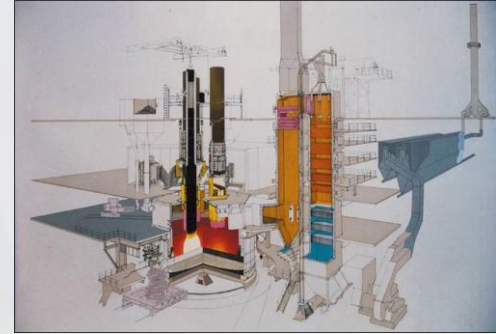
Electric arc furnace

- Charging
- Injection



Tunnel oven

- Reducing agent



Submerged arc furnace

- Reducing agent

Quality requirements in metallurgical processes

Metal producer	Process	Steel type	Application	C fix (%)	Ash (wt%)	Vol (wt%)	S (wt%)	P (wt%)	Particle size (mm)
A	EAF 1	Stainless steel	Charge coal	>90	≤8	6 – 9	< 0.7	0.015 – 0.025	10-30
			Injection coal	>95	≤ 8	6 - 9	< 1.2	0.015 – 0.025	2-3
B	EAF 2	Low alloy	Charge coal	>80	< 8	< 8	< 0.9	< 0.05	10-40
			Injection coal	>85	< 8	< 8	< 0.9	< 0.05	3-8
C	EAF 3	Stainless steel	Injection coal	97.5-100	< 1.1	< 1	≤1.8	0.0015 – 0.0045	1mm, 50% = 0.15-0,45
D	TO	Low-alloyed	Reduction	>75	< 10	< 15	< 0.5	0.05 Historic	~ 10
E	SAF	Ferrochrome	Reduction	>85	< 2	< 10	< 0.1	< 0.02 – 0.03	-

Available coal products

Carbon	Production	Density (kg/m ³)	C fix (%)	Ash (wt%)	Vol (wt%)	S (wt%)	P (wt%)	Particle size (mm)
Anthracite	Fossil	0.9 – 1.1	93 – 94	1 – 12	3 – 8	0.2 - 1	0.05	-
Charging	Fossil	-	80 – 95	0.1 – 8	0.1 – 8	0.016 – 0.9	0.05 – 0.65	-
Biocarbon A	Pyrolysis	-	90 – 95	< 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	~340	>90	2 – 4	12 – 15	0.018	0.023	60
Biocarbon D	Pyrolysis	420 - 450	70 - 92	< 2	5 - 18	0.055	0.045	0 - 10

Matching requirements vs available

	Biocarbon A	Biocarbon B	Biocarbon C	Biocarbon D
Metal Producer A				
Metal Producer B				
Metal Producer C				
Metal Producer D				
Metal Producer E				

- X criteria fulfilled

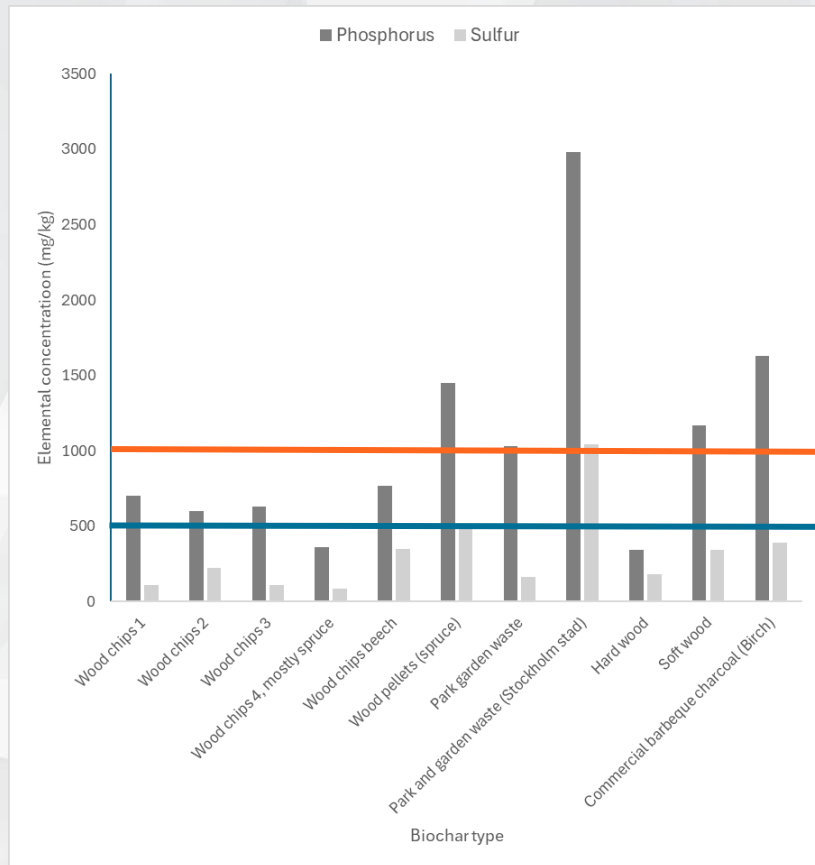
5-6

4

3

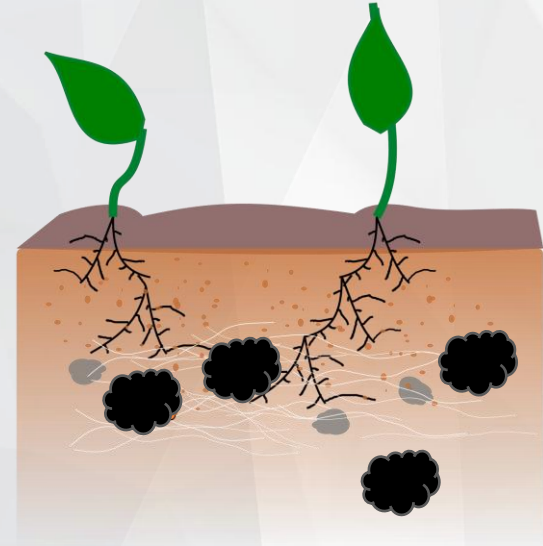
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Use in metallurgical processes



Biocarbon for soil improvement

- What effect:
 - Moisture keeper/Bind water
 - Surface for microlife and heavy metals
 - Keep nutrition
 - Carbon sink



Biocarbon for soil improvement

- Main properties required by soil improvement:
 - Lower density
 - High sulfur content
 - High phosphorous content
 - Just the right high C fix

Contrast - Contrary to what the steel industry wants

Conclusions



1. Residual biomass from the forest and sawmill industry has the potential to be used for biomass for metallurgical biochar by improving the sorting of bark and seasonal biomasses with mainly high phosphorus contents.
2. 4 out of 5 metal producers interviewed have the ability to find biochar at a relatively good match
3. Main technical limitations of biochar are: Particle size > P (especially for stainless steel producers) > C fix > Volatiles > Ash > S
4. In terms of quality, biochar for the metal industry and for soil improvement should not be huge competitors, except in some cases of high C fixed contents. As they mostly have the opposite of the required specifications.



Future work

- Maximize the value of use of biomass in different sectors (metal, soil improvement, energy, chemistry...etc.)
- Investigate biochar production from biomass other than products from forest industry, such as sludge, roadside residues...etc.
- Investigate the influence of biochar ash on metal production processes and its potential positive impact (e.g. replacing lime and flux).



Technological Innovation System Analysis and the impact of Dynamic Capabilities of System Actors

Development of Swedish biocarbon for metallurgy

By John Pettersson and William Di Francesco

Industrial Engineering and Management, Innovation and Strategic Business Development, Luleå University of Technology

Supervisors: Patricia Carolina Garcia Martin (LTU), Tova Jarnerud Örell and Erland Nylund (Swerim)

FORMAS

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& Minerals
impact innovation



Energimyndigheten

Swerims programråd
för metallurgi

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Sveriges innovationsmyndighet

Background

Theoretical

- Innovations can create disruptions and emergence of new markets
- "Green" innovations are usually disadvantaged against linear business models
- Common challenges are financing, developing reliable technology and a lack of urgency, leading to ill-functioning markets

Case

- Biocarbon can replace fossil coal in steelmaking and production of other alloys
- New interactions between industries
- Lack of market formation
- Lack of institutions
- Successful pilot projects

Overview



Background

Theoretical background
Case background



Technological innovation system analysis

Defining the system
System mechanisms
Functional assessment



Results

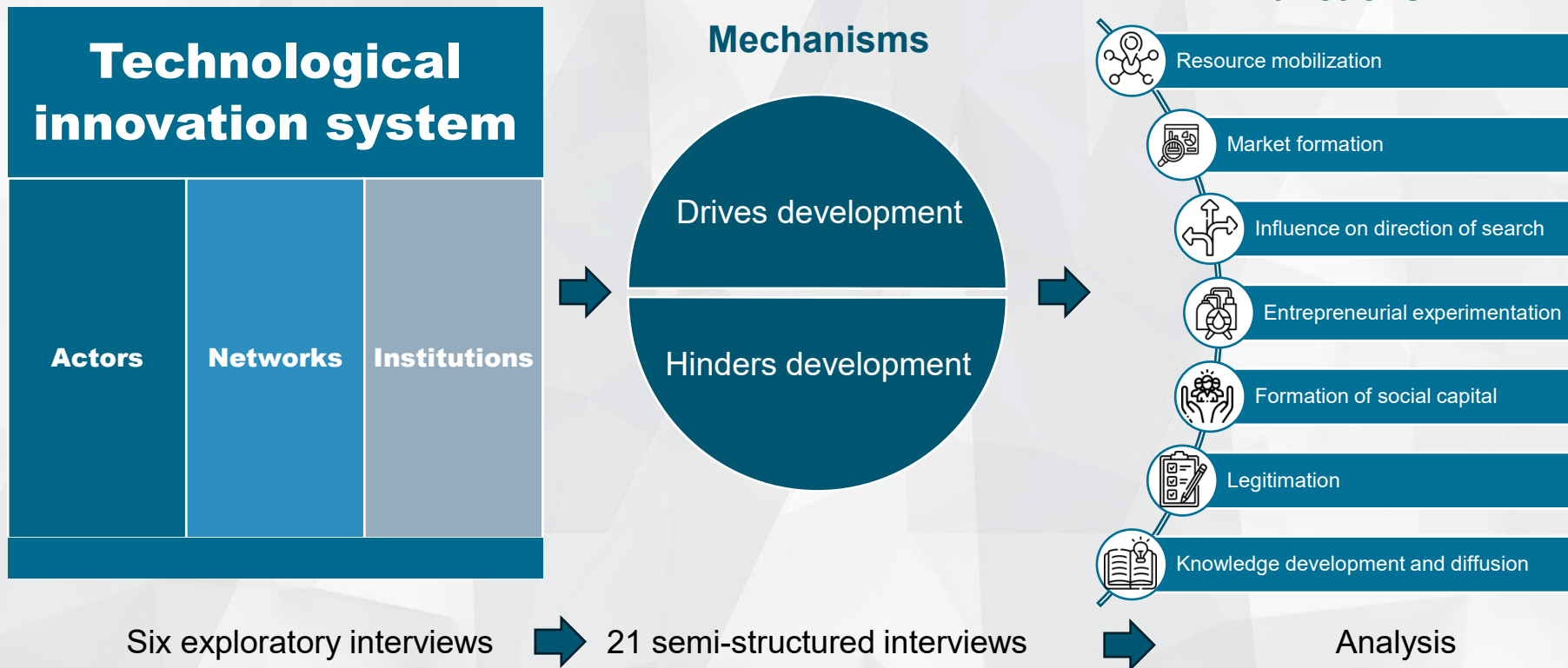
System mechanisms
System functions
What is needed to improve
weak functions?



Discussion

System-level implications
Firm-level implications

Technological innovation system analysis



Results – System mechanisms

Internal

Drives development

Hinders development

Strong competence development

Cross industry knowledge/perception alignment

Recognized importance of partnerships

Immature market

Pilot plants for biocarbon production

Low and uncoordinated investment initiatives

Cooperation and transparency among smaller actors

Reluctance to share sensitive information

Strong research infrastructure

Uncertain material availability

Several potentially complementary value chains

Logistics knowledge

Sustainability trends drives development

Lack of formal institutions

Global

Results – System mechanisms

Hindering mechanisms

Cross industry
knowledge/
perception
alignment

Immature
market

Low and
uncoordinated
investment
initiatives

Reluctance to
share sensitive
information

Uncertain
material
availability

Logistics
knowledge

Lack of formal
institutions

Internal TIS

National / Internal TIS

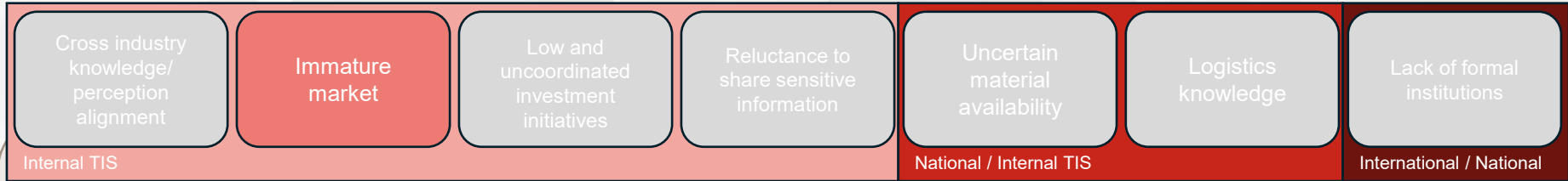
International / National

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

– Process development engineer, Metal producer 1

Results – System mechanisms

Hindering mechanisms

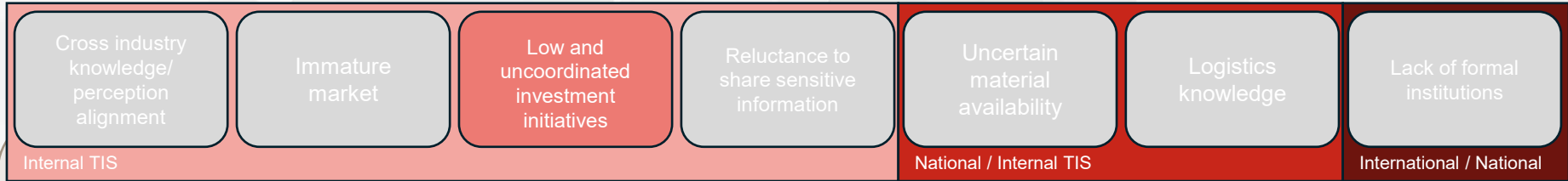


” ...when we started this, there was almost no [biocarbon] to be found. Now there are maybe, not a hundred manufacturers, but probably 50 different manufacturers of biocarbon. However, most of them are very small. We are still talking about lab or pilot scale for a lot of them.”

– Research engineer, Metal producer 3

Results – System mechanisms

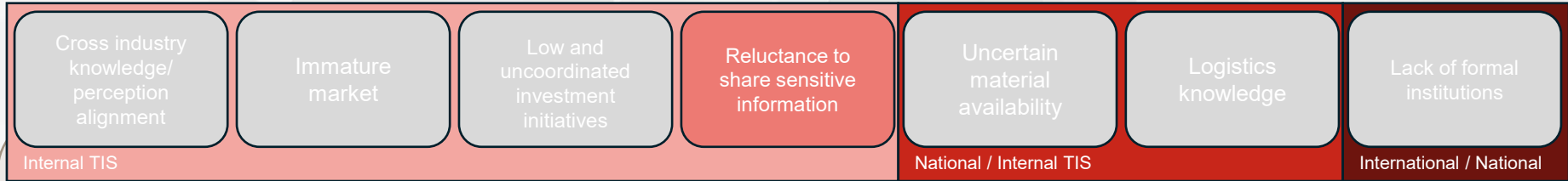
Hindering mechanisms



"Now I've started looking a lot more at who's producing biocarbon and so on, it feels like there are hundreds of projects underway. But no one has really scaled up production, for example, who dares, because it's a big investment."

Results – System mechanisms

Hindering mechanisms



"It's a bit slower with the cooperation in the steel industry now. Some are very secretive and do things completely by themselves. And that may apply to the larger steel manufacturers. We are quite small then and there are some other smaller ones too who may be more inclined to cooperate..."

Results – System mechanisms

Hindering mechanisms

Cross industry
knowledge/
perception
alignment

Immature
market

Low and
uncoordinated
investment
initiatives

Reluctance to
share sensitive
information

Uncertain
material
availability

Logistics
knowledge

Lack of formal
institutions

Internal TIS

National / Internal TIS

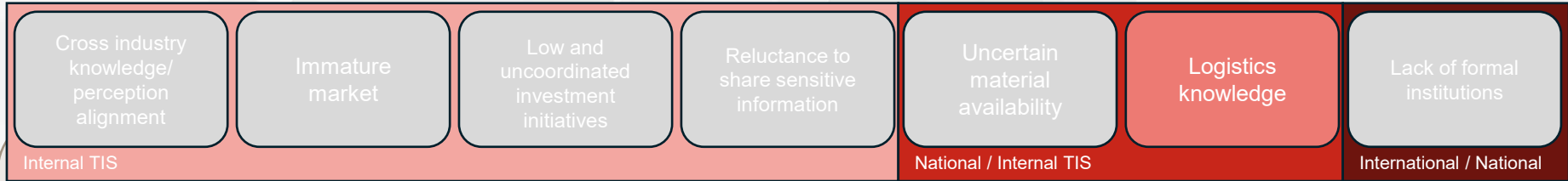
International / National

"There haven't been the quantities I was really looking for. At the same time, I understand that you don't want to come here as a biocarbon producer unless you can guarantee sales."

– Senior process engineer, Metal producer 4

Results – System mechanisms

Hindering mechanisms

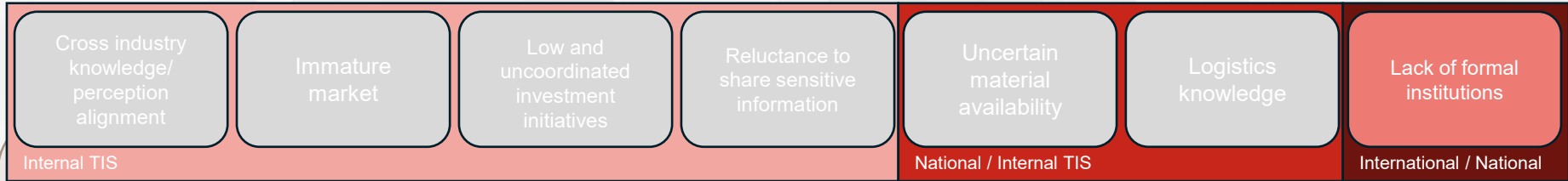


"The safety aspects of storage and things like that. Handling, there's also a gap. It's been a long time since the steel industry handled charcoal. And it's not the same as coal. It's alive."

– Process engineer, Metal producer 1

Results – System mechanisms

Hindering mechanisms



” ...the user of biocarbon actually, depending on which domain they belong to, they have to make sure that the biocarbon has a particular certificate.”

– Technical business specialist, Biocarbon producer 1

Results – System functions

Functions



Results – System functions

Weak functions

Resource
mobilization

Market formation

Intermediate functions

Formation of
social capital

Legitimation

Knowledge
development and
diffusion

Strong functions

Influence on
direction of
search

Entrepreneurial
experimentation

What is needed to overcome the weak functions of the system?

Results – Framework for firms



System level analysis

We analyzed the system, identified key drivers and barriers, assessed functions, and developed a framework to address weak functions at the firm level.

System weaknesses

Weak market formation and resource mobilization are expected at this stage and should not be discouraging for a developing innovation system.

Policy implications

Policy efforts should support market formation and resource mobilization. This could be through investment support, tax breaks, standards, and certifications.

Firm-level implications

Biocarbon producers lack investment to scale up, our framework supports strategic decisions of system actors to adapt to biocarbon and help build the market.

Conflicts of interest

"Where the biomass is most beneficial is subjective, so it is important that policy makers set clear rules and have a long-term perspective"

Conflicts of interest

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

Competence requirements

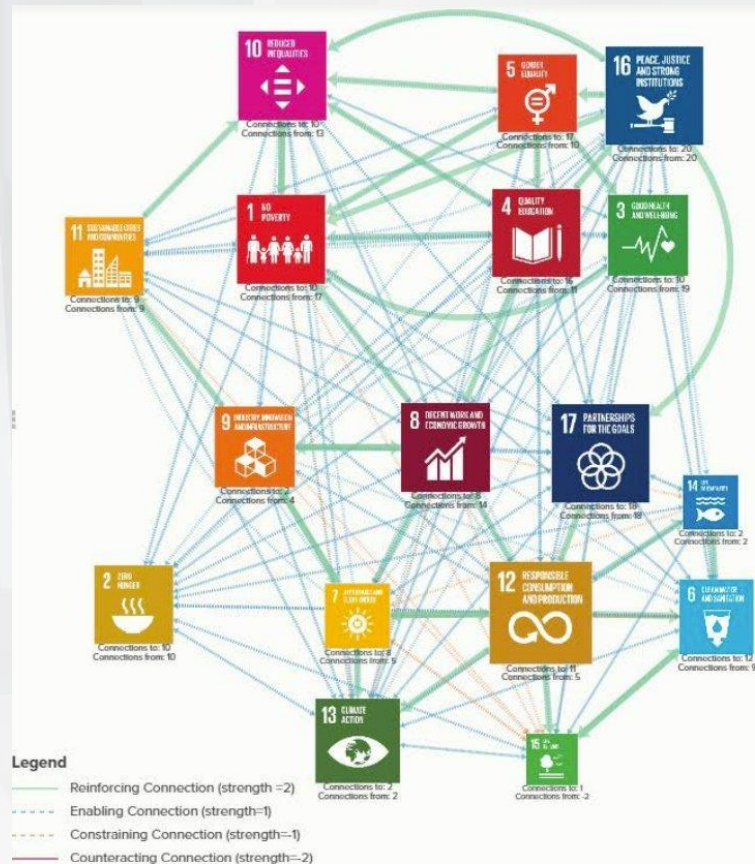
- In general, a **high level of competence** is recognized and knowledge and experiences are shared
- Competence on **security risks** and how to manage them has been built and shared but needs to be continuously updated and adapted to new technologies, policies and management
- Knowledge is lacking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

Competence requirements

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

Competence requirements

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



Sustainability compass

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

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

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

Sustainability compass

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

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

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

These virtuous circles would benefit from cooperation with:

SINTEF (LTU)

RISE, IVL, SWERIM, Energiforsk

Karolinska (physicians)

Politicians in relevant regions and committees

The academy in relevant fields: SLU, LTU, KTH, ..

Unions

Svenskt näringsliv/industry associations

Steel- and forestry company leadership

The chemical industry

Foundries

Permitting agencies

Technical areas within Jernkontoret

State/regional financiers of pilot projects

Raw material actors – forestry, agriculture, ore, energy

Companies of interest along the entire value chain

Biocarbon fraction stakeholders of all kinds



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

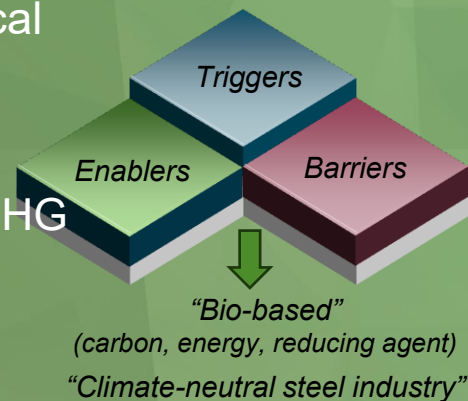
What actors could take part in risk mitigation initiatives to manage challenges in the biocarbon value chain:



HåBiMet - Policyperspektiv fortsättning

Three main tasks:

1. To summarize policies, regulations and standards/certificates relevant to metallurgic biochar market development in Sweden (*due June, a draft report*)
 - EU & national levels
 - Biochar production & usage
2. To identify in what ways they can potentially influence metallurgical biochar system transition (*due June, the draft report*)
 - Biochar production: biomass feedstock, green finance, ESR, etc.
 - Biochar use in metallurgy: economic and regulatory incentives, GHG emissions, sustainability reporting, etc.
3. To propose a vision for metallurgic biochar in Sweden (upcoming workshops in *Autumn*)



Relevant policies, regulations and standards/certificates

Forest biomass feedstock

- EU Bioeconomy Strategy
- RED II & III
- LULUCF (Land Use, Land Use Change and Forestry)
- EUDR (Deforestation-Free Supply Chains)
- EUTR (EU Timber Regulation)
- New EU Forest Strategy for 2030
- Sweden: Bio-strategy
- Sweden: The Forestry Act
- etc.

Biochar production

- Effort Sharing Regulation (ESR)
- Circular Economy Action Plan
- EU Taxonomy (incl. DNSH principles)
- IED 2.0
- Energy Efficiency Directive
- EU Carbon Removals and Carbon Farming Certification (CRCF) Regulation
- European Biochar Certificate (EBC)
- Corporate Sustainability Reporting Directive (CSRD)
- etc.

Relevant policies, regulations and standards/certificates

Biochar use (non-metallurgical)

- EU ETS2
- EU CRCF Regulation
- EU Fertilising Products Regulation
- Common Agricultural Policy (CAP)
- ReFuel EU Aviation Regulation
- FuelEU Maritime Regulation
- Revision of the Energy Taxation Directive
- Urban Tree Biochar Initiative (Sweden)
- Sweden's carbon tax
- Climate Leap
- etc.

Biochar use (metallurgical industry)

- EU ETS1
- EU Taxonomy
- Ecodesign for Sustainable Products Regulation (ESPR), incl. DPP
- EU Industrial Carbon Management Strategy
- EU Net-Zero Industry Act
- EU Hydrogen Strategy
- Carbon Border Adjustment Mechanism
- Green Claims Directive
- Just Transition Fund, InvestEU, Industrial Leap
- etc.

Seeing the forest for the trees: Swedish metallurgical biocarbon & EU bioeconomy and climate targets

European Climate Law (all sectors)

-55% reduced net emissions by 2030, compared to 1990

EU Emission Trading System (EU ETS)



Energy, industry, aviation and shipping

Effort Sharing Regulation (ESR)



Agriculture, transport and other

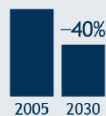
Regulation on Land Use, Land Use Change and Forestry (LULUCF)



Land use and forestry



Reduced emissions by 2030, compared to 2005

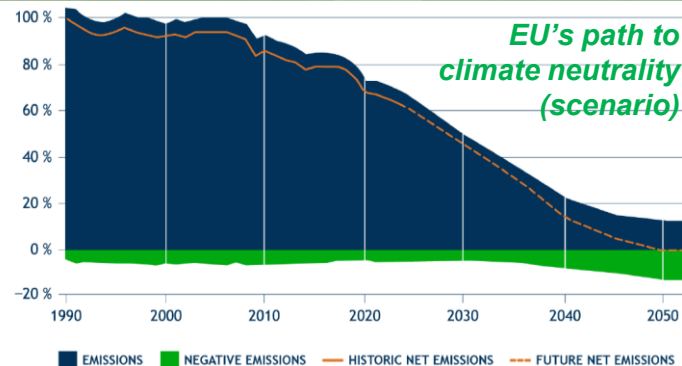


Reduced emissions by 2030, compared to 2005



Increased carbon sink by 2030, compared to 2016-2018

Source: European Commission³⁷.



Source: European Commission³⁷.



KÄLLA: NATURVÄRDSVERKET

Next steps on the HåBiMet journey

- Technical challenges in production rather than use – scaling up and cost efficiency
- Project incorporating multiple sectors – energy, agriculture, forestry
- What is the optimal use of biomass?

Identified needs



Collaboration across a broader value chain



Deeper understanding of possible supply chains



Market developing initiatives



Practical understanding of logistical solutions



Reinforce understanding and acceptance

Technical-social-policy

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

Social goals of Metals and Minerals

Outside of the typical research scope

Socio-technical:

- Safe handling

Social impact:

- Social symbiosis
- Regional development

Policy impacts

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

Formation of technical continuation project

- Focus on needs of forestry, agriculture, district heating → productification of residues
- Time horizon?
- Leadership and coordination: flexible

Identified needs

Safe
handling

Technical
project

Social
project

Policy
project



Collaboration across a broader value chain



Deeper understanding of possible supply chains



Market developing initiatives



Practical understanding of logistical solutions



Reinforce understanding and acceptance



Main directions of research

- Safe handling of biocarbon
- Metallurgical biocarbon from district heating
- Policy impact – best use of available resources

Appendix 3:

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

MSc thesis by Saga Grevarp



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

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2025-08-22
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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.

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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]

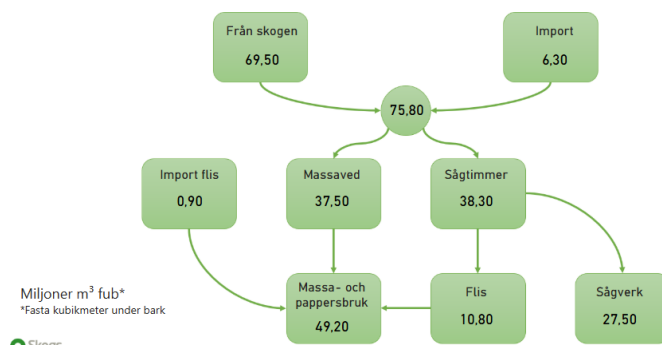


Figure 2: Schematic picture of the forest industry's timber supply 2022 [37]

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]

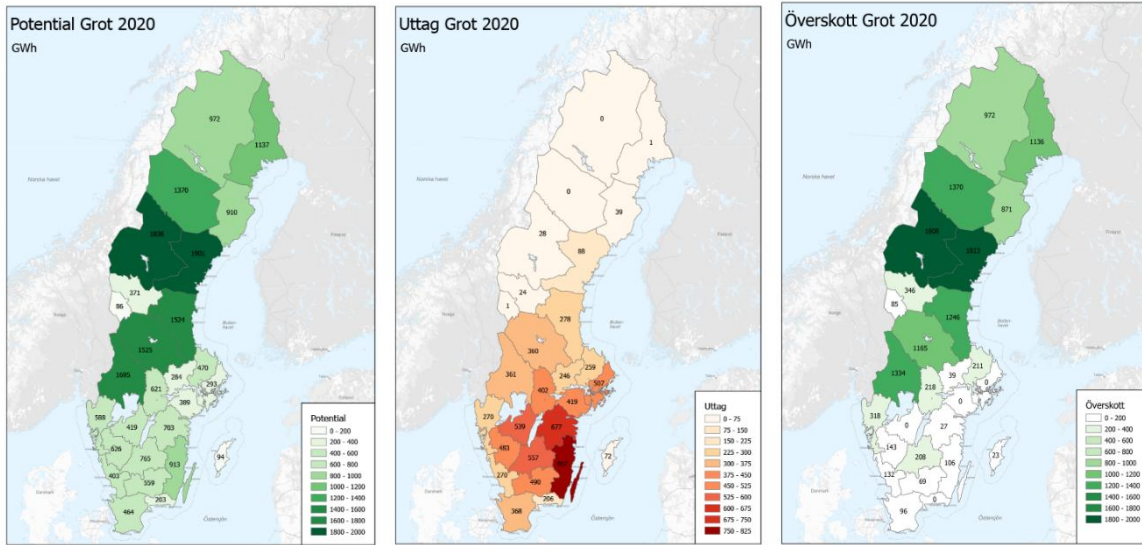


Figure 3 (a): Total GROT Potential in Sweden 2020 [39]

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.

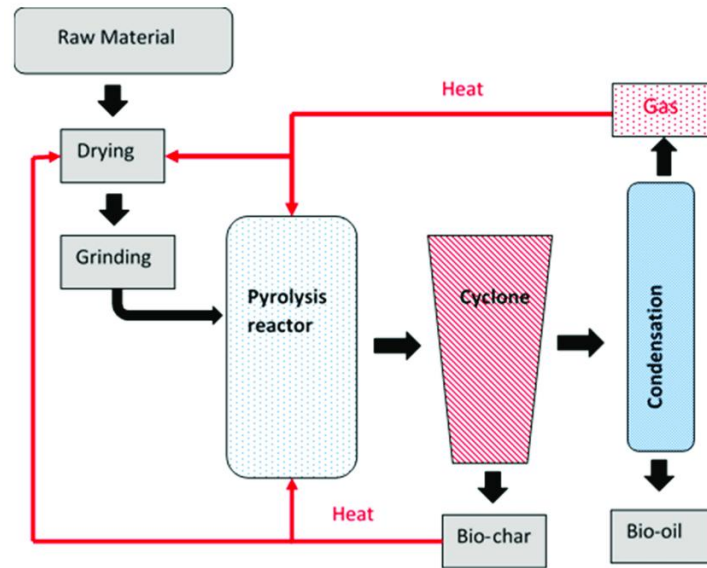


Figure 6: Process flow diagram for pyrolysis[49]

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.

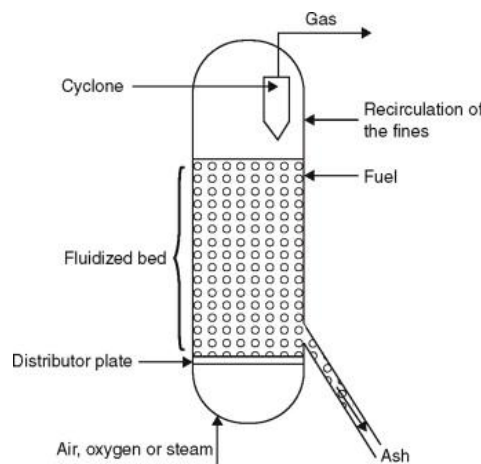


Figure 7: Cross-section of a gasification process[50]

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)

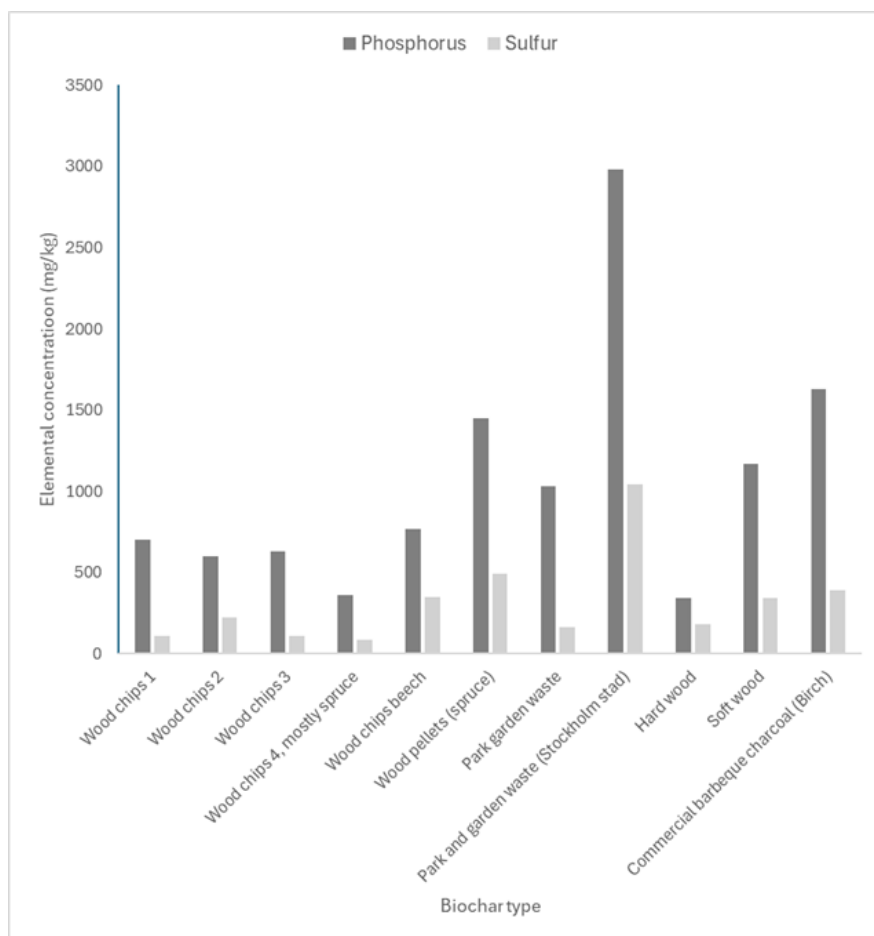


Figure 8: Amount of phosphorus and sulfur in different biocarbon's with different biomass inputs[79]

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.

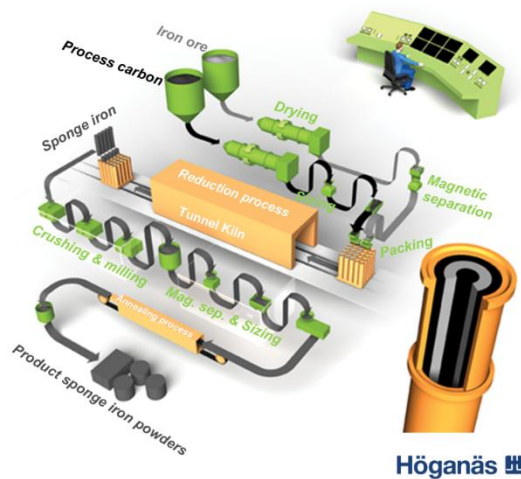


Figure 9: Process flow chart for a tunnel oven (R9, R10)

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)

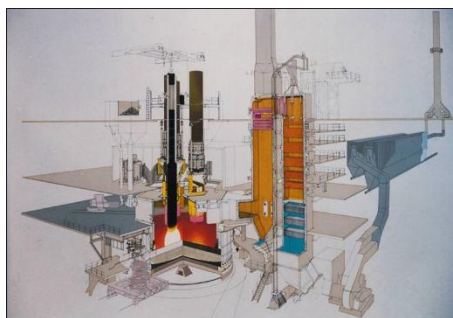


Figure 10: A picture of a submerged arc furnace (R12)

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)

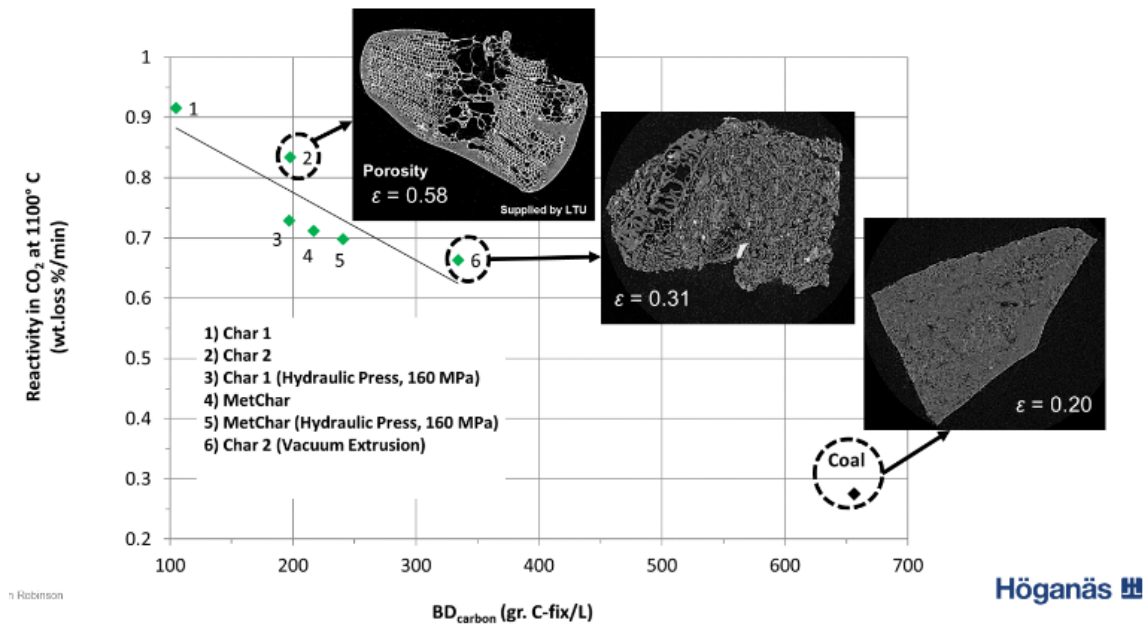


Figure 11: The relationship between reactivity, carbon and porosity (R9, R10)

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).

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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

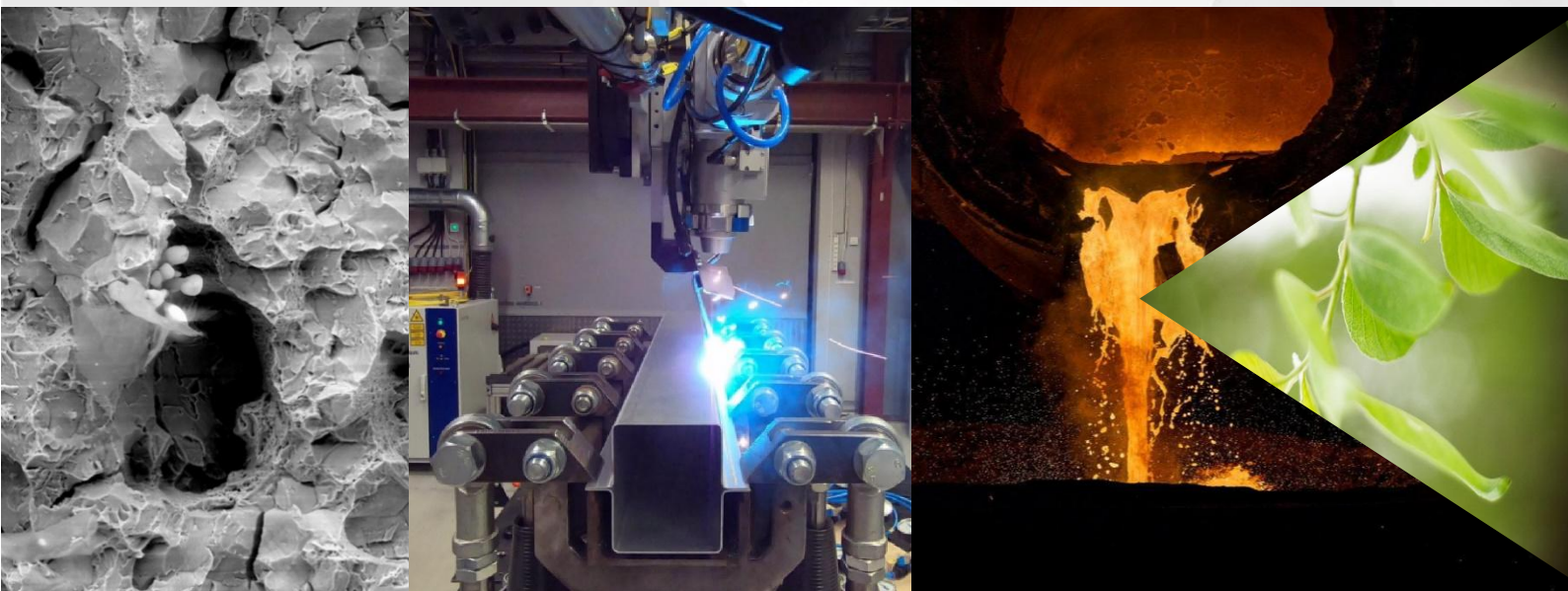
-Ash

-Price

-Calorific value

Appendix 4:

Comparing methods for estimating biocarbon demand in EAF processes



Comparing methods for estimating biocarbon demand in EAF processes

Erland Nylund

Report number. Swerim-2025-229

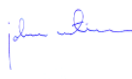
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Johan Martinsson, Group Manager

Comparing methods for estimating biocarbon demand in EAF processes

Erland Nylund

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Customer value

The report evaluates methods for calculating the Swedish biocarbon demand, and prescribes the main factors that should be included to achieve accurate forecasting.

- Many estimations in the literature are derived from old or unclear sources
- Estimations must take into account carbon alloying content, DRI share of iron carriers in the Swedish market, metallization of DRI, and total slag volumes.
- When comparing gross demand of biocarbon products, C_{fix} or C_{tot} parity should be used.

Abstract

In order to facilitate future system modelling and scenario analysis, a literature review was conducted to identify methods of estimating carbon demand in EAF steelmaking. The identified methods were evaluated for plausibility and suitability when forecasting Swedish biocarbon demand. A number of estimation methods were evaluated using two rough future scenarios for Swedish steelmaking – with higher and lower proportion of DRI in input materials.

Approaches assigning a fixed carbon demand per tonne steel, or relying on historic carbon demand statistics were judged unsuitable for accurate forecasting.

The most promising method identified was a mass balance approach taking into account slag volume and iron oxide content in slag. Furthermore, carbon content of all input materials, fixed and total carbon of carbonaceous materials and average carbon content in tapped hot metal should be included in forecasting estimations.

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1 Introduction

Swedish steelmaking is in the middle of a transition away from fossil-based Blast Furnace (BF) steelmaking, toward a value chain combining hydrogen direct reduction of iron (H-DRI), and Electric Arc Furnace (EAF) smelting [1], [2], [3]. In this new production system, there will be vastly lower emissions of greenhouse gases as coking plants and blast furnaces are eliminated. However, the EAF process still utilizes some amounts of metallurgical coal as a process input, improving energy efficiency, achieving a foaming slag, and acting as an alloying element in steel.

Currently, fossil coal materials such as anthracite are used, and in the future electrified steel industry, this carbon will represent a large proportion of fossil CO₂ emissions. In order to facilitate a full de-fossilisation, considerable research has gone into investigating options for replacing fossil carbon with biogenic carbon materials (“biocarbon”) [4], [5]. Replacing fossil carbon with biocarbon will require a biomass supply of a large enough volume and consistent enough quality to satisfy steel industry needs. When investigating the feasibility of a particular supply scenario, it is vital to understand the scale of biocarbon demand so that the demand for biomass can be properly understood.

There are a number of estimations of biocarbon demand in steel production, either per unit of steel or for entire markets, and there is considerable range between them. Some studies [6] use carbon need figures of just a few kilograms per tonne steel, others estimate needs in the range of 20-55 kg biocarbon per tonne steel [7]. A common figure is 12kg per tonne (e.g [5], [8], [9], [10], [11], [12], [13], [14], [15]), and reading the World Steel pamphlet “Raw materials”, you find that “*The electric arc furnace (EAF) route uses primarily recycled steels and direct reduced iron (DRI) or hot metal, and electricity. On average, the recycled steel-EAF route uses 710 kg of recycled steel, 586 kg of iron ore, **150 kg of coal** [sic], 88 kg of limestone and 2.3 GJ of electricity, to produce 1,000 kg of crude steel*” [16].

Since the production of one mass unit of biocarbon requires 2-5 times as much biomass, a difference in factor 5-10 between lowest and highest demand projection creates a huge uncertainty envelope when estimating biomass needs.

In some cases where academic publications mention an estimated carbon need, the method for creating that estimation is outlined. However, in many cases the values are given without in-depth explanation, and or with explicit caveats stating that it is simplified and not complete. There are many well-known factors that can impact the specific carbon need for a certain furnace or a certain heat, such as handling methods, slag amounts, slag composition, steel grade, and much more.

Swerim currently participates in several research projects, such as *Hållbart Biokol för Metallurgisk användning* (HåBiMet) [17] and *Forskning och Innovation i Norrbotten för Avancerad grön Stålframställning och Tillverkning* (FINAST)[18], with an ambition to investigate the future supply of biocarbon to steel and metal industries. In order to construct meaningful estimations of steel industry demand for biocarbon in these projects, reasonable estimations of EAF biocarbon consumption will have to be made.

This study will approach the problem of estimating biocarbon demand in an Electric Arc Furnace in a systematic fashion, looking at literature to identify different methods for estimation, and comparing them to each other. The comparison will evaluate the simplicity, the verifiability and the theoretical rigour of different methods. The stated goal is to find a method or combination of methods that are suitable for estimating the total biocarbon

demands of the future Swedish steel market under different scenarios, and the corresponding biomass requirements.

2 Method

- Literature overview to catalogue different estimates, and see where they reference.
- Identifying underlying methods of estimation
- Identify characteristics of steel production (furnace type, input material composition, product types) that may influence total carbon need
- Use estimations on two scenarios for Swedish steel industry in 2030: low DRI, high DRI

2.1 Literature overview

A limited structured literature review was performed, using a keyword search in the Scopus database, combined with a “snowballing” procedure adding publications cited by the initial article selection.

The initial search was the Boolean {“EAF” AND “biocarbon” OR “biochar”} applied to publication titles, abstracts or keywords. This query which yielded 32 results. These were screened using the following criteria:

1. Whether the article treated the use of biocarbon or carbon in an EAF (14 publications excluded).
2. Whether the full-text article was accessible (3 publications excluded).
3. Whether there was a reference to specific carbon demand in the process. (36 publications excluded)

In order to expand the literature list and identify original sources “snowballing” of cited sources [18] (p.121) was used, including any articles referenced by the initial selection that also fulfilled the inclusion criteria. This added 47 publications.

These publications were investigated more closely, to determine what methods they used to determine carbon need in the EAF, and what specific carbon need (per unit steel or per unit slag) they arrived at. Many of the publications simply cited another publication as the source for their estimations, without explaining the underlying method, making the snowballing strategy crucial, as it can enable the tracking of commonly used figures and assumptions to their origin. A visualisation of the selection process is shown in Figure 1.



Figure 1: Overview of literature review selection process

A total of 62 publications were investigated in more detail, out of which 26 were both accessible, and contained values for the carbon consumption of EAFs. Four publications [20], [21], [22], [23] were identified that were directly quoted as sources of C-consumption figures, but have not been made available to the author at the time of writing.

In addition to this, a few publications previously known to the author were selected, and their sources investigated: [24], [25], [26].

2.2 Biocarbon demand estimations

Based on the different estimation methods identified in the literature review, estimations were made for the total biocarbon demands of Swedish steel industry in 2030. In the coming years, a number of new DRI-plants and EAFs will be built in Sweden, so the product mix will change considerably. A 2030 scenario was established, based on the planned start-of-production dates for projects by LKAB, SSAB, Stegra and Ferrosilva. Within this scenario, there is a maximum possible fraction of DRI-supply (ca 70% of iron feedstock), and a minimum (almost pure scrap). Two scenarios were developed, one with 70% DRI / 30% scrap, the other with 30% DRI and 70% scrap.

The estimations required assumptions about material properties, such as DRI composition and biocarbon composition. Reference values for biocarbon were chosen from among those presented in the reviewed publications – one woody biocarbon, one HTC, one biocarbon material made from agricultural residues, and one reference fossil petroleum coke material. The materials selected were chosen for expedience, not taking into account the representative

3 Results

In reviewing the literature, a number of recurring values for carbon demand were identified, as well as a remarkable breadth of estimates. Among the literature examples are many experimental works relating the conditions used in laboratory, pilot or industrial trials, but also many references to industry “averages” or typical values. Not all of the experimental studies motivate their choice of carbon additions, and even though several use varying proportions of biogenic and fossil carbon sources, few of them actually systematically vary the amount of carbon-per-tonne-steel. However, remarkably, there are no studies among the evaluated publications presenting a broad industrial overview of carbon demand, though several make references to other publications that supposedly have done so.

A detailed description of the different kinds of carbon demand figures and their underlying method (or lack thereof) is presented in section 3.1. The findings will be presented in a few broad categories of estimation methodology: industrial averages, specific steel plant practices, lab- or pilot trial values, mass balance methodologies, and flow-based methodologies.

Even the industry roadmap estimations of biocarbon needs [25], [26] are unspecific about the assumptions made when calculating the Swedish biocarbon demand, but at least they seem to rely on direct information and estimations made by the steel producers themselves. However, unless the estimates can be somewhat closely reproduced using more general principles, they are difficult to modify for alternative industrial development scenarios. Therefore, the roadmap figures are compared to different estimation methods in section 3.2.

3.1 Literature overview

Table 1 lists the publications identified in the survey that contain some form of values for carbon demand in EAF processes. Note that this list contains four publications that were referenced as the source for specific values, but were not obtainable as of writing this draft.

Table 1: List of publications with specific values for carbon use in Electric Arc Furnaces.

Actual ref. no (in this report)	Publication title	Reference
[27]	Biochar for a sustainable EAF steel production (GREENEAF2)	Directorate-General for Research and Innovation (European Commission), Marcos, M., Bianco, L., Cirilli, F., Reichel, T., Baracchini, G., Echterhof, T., Rekersdrees, T., Mirabile, D., Griessacher, T., & Sommerauer, H. (2018). <i>Biochar for a sustainable EAF steel production (GREENEAF2)</i> . https://doi.org/https://data.europa.eu/doi/10.2777/708674
[28]	Sustainable EAF steel production (GREENEAF)	European Commission and Directorate-General for Research and Innovation, Echterhof, T., Baracchini, G., Pfeifer, H., Griessacher, T., Demus, T., Moriconi, E., Bianco, L., Marcos, M., Beiler, C., Cirilli, F., & Moriconi, A. (2013). <i>Sustainable EAF steel production (GREENEAF)</i> . https://doi.org/https://data.europa.eu/doi/10.2777/44502
[8]	Progress Toward Biocarbon Utilization in Electric Arc Furnace Steelmaking: Current Status and Future Prospects	DiGiovanni, C., & Echterhof, T. (2024). Progress Toward Biocarbon Utilization in Electric Arc Furnace Steelmaking: Current Status and Future Prospects. <i>Journal of Sustainable Metallurgy</i> , 10(4), 2047–2067. https://doi.org/10.1007/S40831-024-00940-0/TABLES/4
[29]	Utilization of Renewable Carbon in Electric Arc Furnace-Based Steel Production: Comparative Evaluation of Properties of Conventional and Non-Conventional Carbon-Bearing Sources	Kieush, L., Schenk, J., Koveria, A., Rantitsch, G., Hrubia, A., & Hopfinger, H. (2023). Utilization of Renewable Carbon in Electric Arc Furnace-Based Steel Production: Comparative Evaluation of Properties of Conventional and Non-Conventional Carbon-Bearing Sources. <i>Metals</i> 2023, Vol. 13, Page 722, 13(4), 722. https://doi.org/10.3390/MET13040722
[30]	An Empirical Comparative Study of Renewable Biochar and Fossil Carbon as Carburizer in Steelmaking	ROBINSON, R., BRABIE, L., PETTERSSON, M., AMOVIC, M., & LJUNGGREN, R. (2022). An Empirical Comparative Study of Renewable Biochar and Fossil Carbon as Carburizer in Steelmaking. <i>ISIJ International</i> , 62(12), 2522–2528. https://doi.org/10.2355/ISIJINTERNATIONAL.ISIJINT-2020-135
[31]	Biocarbon materials in EAF Steelmaking	Ng, K. W., Huang, X., Giroux, L., & Li, D. (2019). <i>Biocarbon Materials in EAF Steelmaking</i> .
[32]	EAF long term industrial trials of utilization of char from biomass as fossil coal substitute	Cirilli, F., Baracchini, G., & Bianco, L. (2017). EAF long term industrial trials of utilization of char from biomass as fossil coal substitute. <i>Metallurgia Italiana</i> , 109(2), 13–17.
[5]	Increasing the sustainability of steel production in the electric arc furnace by substituting fossil coal with biochar agglomerates	Reichel, T., Demus, T., & Pfeifer, H. (2014). Increasing the sustainability of the steel production in the electric arc furnace by substituting fossil coal with biochar agglomerates. <i>4th Central European Biomass Conference</i> . www.iob.rwth-aachen.de
[23]	Energy use in the steel industry	Cairns, C. J. (1998). <i>Energy use in the steel industry</i> . Committee on Technology of the International Iron and Steel Institute.
[33]	Developing Benchmarking Criteria for CO2 Emissions	Neelis, M., Worrell, E., Mueller, N., Angelini, T., Cremer, C., Schleich, J., & Eichhammer, W. (2009). <i>Developing Benchmarking Criteria for CO2 Emissions</i> .
[9]	Review on the Use of Alternative Carbon Sources in EAF Steelmaking	Echterhof, T. (2021). Review on the Use of Alternative Carbon Sources in EAF Steelmaking. <i>Metals</i> 2021, Vol. 11, Page 222, 11(2), 222. https://doi.org/10.3390/MET11020222
[10]	Biomass as a Source of Renewable Carbon for Iron and Steelmaking	Norgate, T., Haque, N., Somerville, M., & Jahanshahi, S. (2012). Biomass as a Source of Renewable Carbon for Iron and Steelmaking. <i>ISIJ International</i> , 52(8), 1472–1481. https://doi.org/10.2355/ISIJINTERNATIONAL.52.1472
[11]	Investigations on the use of biogenic residues as a substitute for fossil coal in the EAF steelmaking process	Demus, T., Echterhof, T., Pfeifer, H., & Schulten, M. (2012). Investigations on the use of biogenic residues as a substitute for fossil coal in the EAF steelmaking process. <i>Conference: 10 Th European Electric Steelmaking Conference Vol.10</i> , 2. https://www.researchgate.net/publication/231367477
[12]	Determining the reactivity of biochar agglomerates to replace fossil coal in EAF steelmaking	Kalde, A., Demus, T., Echterhof, T., & Pfeifer, H. (2015). Determining the Reactivity of Biochar-Agglomerates to Replace Fossil Coal in Electric Arc Furnace Steelmaking. <i>European Biomass Conference and Exhibition Proceedings</i> , 497–507. https://doi.org/10.5071/23RDEUBCE2015-2A0.8.3
[13]	Potential of biomass usage in electric steelmaking	Echterhof, T., & Pfeifer, H. (2011). Potential of biomass usage in electric steelmaking Contact Data. <i>EECRSteel 2011, 1st International Conference on Energy Efficiency and CO2 Reduction in the Steel Industry</i> .
[34]	Replacement of fossil carbon with biogenic residues in the electric steelmaking process	Demus, T., Thomas Echterhof, I., & Pfeifer, I. H. (2012, March). Replacement of fossil carbon with biogenic residues in the electric steelmaking process. <i>International Workshop EAF Perspectives on Automation, Materials, Energy & Environment</i> .
[35]	Potential for the use of biomass in the iron and steel industry	Mathieson, J., Ridgeway, P., Somerville, M. A., Jahanshahi, S., & Rogers, H. (2011). Potential for the use of biomass in the iron and steel industry. <i>METEC InSteelCon 2011 Conf</i> . https://www.researchgate.net/publication/267246501
[36]	Recycling of industrial and municipal waste as slag foaming agent in EAF (RIMFOAM). Final report	Alexis, J., Heintz, I., Björkvall, J., Cederholm, F., Russo, P., Antoine, P., Faraci, E., Fritella, P., & Filippini, S. (2020). <i>Recycling of industrial and municipal waste as slag foaming agent in EAF (RIMFOAM)</i> . https://doi.org/10.2777/533760
[15]	Verwendung von biogenen Karbonisaten im Elektrostahlverfahren	Demus, T., Echterhof, T., Pfeifer, H., & Reichel, Ti. (2014, May). Verwendung von biogenen Karbonisaten im Elektrostahlverfahren. <i>Konversion von Biomassen</i> . https://www.researchgate.net/publication/262387690
[7]	Influence of direct reduced iron on the energy balance of the electric arc furnace in steel industry	Kirschen, M., Badr, K., & Pfeifer, H. (2011). Influence of direct reduced iron on the energy balance of the electric arc furnace in steel industry. <i>Energy</i> , 36(10), 6146–6155. https://doi.org/10.1016/J.ENERGY.2011.07.050
[22]	High Productivity With Low Emissions - Challenge for Tomorrow	Rummler, T., Apfel, J., Belous, J., Doninger, T., & Knoth, V. (2008, November). High productivity with low emissions - Challenge for tomorrow. <i>AISTech 2008 Conference Proceed-ings</i> .

		https://www.researchgate.net/publication/288296934_High_productivity_with_low_emissions_-_Challenge_for_tomorrow
[37]	Industrieller Einsatz von Biomasse in der Elektrostahlerzeugung	Wilms, T., Kalde, A., Demus, T., Echterhof, T., & Pfeifer, H. (2016, May). Industrieller Einsatz von Biomasse in der Elektrostahlerzeugung. <i>Konversion von Biomassen Und Kohlen. Vol: DGMK-Tagungsbericht 2016-2</i> . https://www.researchgate.net/publication/304246197_Industrieller_Einsatz_von_Biomasse_in_der_Elektrostahlerzeugung
[38]	Evaluation of Biochar and Coke Blends for Slag Foaming Applications in Electric Arc Furnace Steelmaking	DiGiovanni, C., Li, D., Ng, K. W., & Huang, X. (2025). Evaluation of Biochar and Coke Blends for Slag Foaming Applications in Electric Arc Furnace Steelmaking. <i>Steel Research International</i> , 96(1), 2400518. https://doi.org/10.1002/SRIN.202400518
[39]	The Slag Foaming Practice in EAF and Its Influence on the Steelmaking Shop Productivity	Morales, R. D., Romero, J. A., Rubén, L. G., López, F., & Camacho, J. (1995). The Slag Foaming Practice in EAF and Its Influence on the Steelmaking Shop Productivity. <i>ISIJ International</i> , 35(9), 1054–1062. https://doi.org/10.2355/ISIJINTERNATIONAL.35.1054
[40]	Biochar as a slag foaming agent in EAF – A novel experimental setup	Hoikkaniemi, E., Sulasalmi, P., Visuri, V.-V., & Fabritius, T. (2024). Biochar as a slag foaming agent in EAF – A novel experimental setup. <i>IOP Conference Series: Materials Science and Engineering</i> , 1309(1), 012010. https://doi.org/10.1088/1757-899X/1309/1/012010
[41]	Control of greenhouse gas emissions from electric arc furnace steelmaking: evaluation methodology with case studies	Thomson, M. J., Evenson, E. J., Kempe, M. J., & Goodfellow, H. D. (2000). Control of greenhouse gas emissions from electric arc furnace steelmaking: evaluation methodology with case studies. <i>Ironmaking and Steelmaking</i> , 27(4), 273–279. https://doi.org/10.1179/030192300677552
[42]	Hydrothermal bio-char as a foaming agent for electric arc furnace steelmaking: Performance and mechanism	Wei, R., Zheng, X., Zhu, Y., Feng, S., Long, H., & Xu, C. C. (2024). Hydrothermal bio-char as a foaming agent for electric arc furnace steelmaking: Performance and mechanism. <i>Applied Energy</i> , 353, 122084. https://doi.org/10.1016/J.APENERGY.2023.122084
[43]	Ranking of Injection Biochar for Slag Foaming Applications in Steelmaking	Wei, R., Zheng, X., Zhu, Y., Feng, S., Long, H., & Xu, C. C. (2024). Hydrothermal bio-char as a foaming agent for electric arc furnace steelmaking: Performance and mechanism. <i>Applied Energy</i> , 353, 122084. https://doi.org/10.1016/J.APENERGY.2023.122084

Each of these publications were read and analysed, and the values for carbon demand extracted. Some of these were references as being industrial averages, some were values used at specific steel plants. Those that explicitly list a method for calculating C demand can be categorised into two categories: mass balance methods and flow based methodologies. Table 2 presents an overview of what methodologies were used or referenced in different publications, as well as the carbon demand values quoted. As can be seen, a large number of publications reference “average” industrial values that seem to originate from a handful of sources, though many of them also present the values used in their own experiments. The experimental proportions can be quite different from the stated industrial average, with no explicit motivation – for instance [5].

Table 2: Carbon estimation, including which publications used the particular method.

Method	Description	Used/quoted in
Industrial average		[5], [7], [8], [9], [10], [11], [12], [13], [14], [15], [27], [28], [33], [34], [35], [40]
Specific steel plant		[7], [30], [32], [36], [37], [39], [41]
Proportion used in lab or demonstration trials		[5], [15], [31], [36], [43]
Mass balance methods		[38], [42], [43]
Flow-based methods		[40], [42], [43]

3.1.1 Industrial averages

These are values that are referenced as being average or typical for steel industry. In total five different figures, with a remarkable range, were presented. Vallues will each be discussed in turn.

Table 3: Carbon need estimations from industrial average methods, including sources and apparent origin of each estimation

Method	C-values	Used/quoted in	“Original” sources
Industrial average	12 kg/t steel	[5], [8], [9], [10], [11], [12], [13], [14], [15], [27], [28], [30], [34]	Possibly [20] or [23] Corroborated by [27], [28]
	12 kg/t in charge, 5kg/t injected, additional 1.4kg/t for carb. added to charge	[35]	“private communications”
	20-55kg/t steel. Seems to be total carbon values, not just injected/charged, includes DRI content.	[7]	[22] (no access)
	13.7 kg/t steel. This includes 2.7kg/t for slag formation, and 11kg/t from electrodes and scrap. Supposed to be “most efficient” EAF technology in 1998	[33]	[23] (no access)
	5-10kg/t steel injected	[9], [40]	[44] (no access), [60][41] cited – but does not match
	3-12kg/t steel	[30]	[45] (no access)

12 kg/t and 13.7 kg/t

The most common figure quoted is “12 kg per tonne liquid steel”. Most, but not all, of the publications quoting this figure have a connection to, or a co-author previously involved with, the EU-financed GreenEAF and GreenEAF2 projects. Most of the references to this figure seem to originate to a conference proceeding paper related to the EU-funded GreenEAF EU project [13], which states “*The average amount of coal/coke used in the EAF is about 12 kg/tsteel*”(p. 1), directly referencing [20]. A separate publication related to the GreenEAF project with some of the same authors [11] contains a schematic overview of EAF energy consumption and CO₂-production (Figure 1), which has been reproduced in several subsequent publications (e.g. [5], [9], [12]).

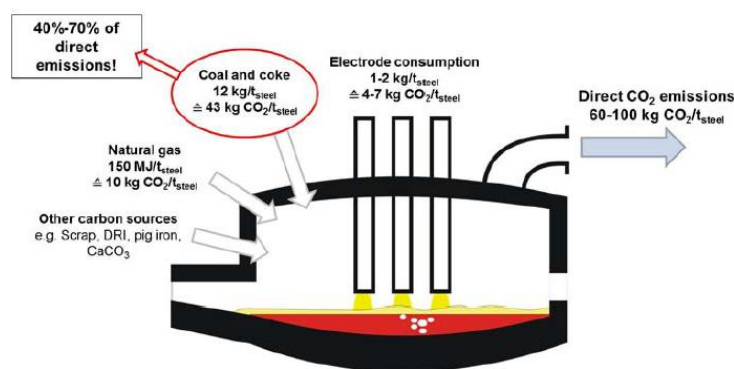


Fig. 1: Direct CO₂ emissions of a typical EAF [1,3,4]

Figure 2: EAF schematic from Demus et. al [11]. The original citations refer to: 1) - [13], 3) - [33], 4) - [20].

The three references in the original version of this schematic are the previously mentioned [20], the previous GreenEAF paper [13] and Neelis et. al. (2009) [33]. The Neelis paper is a report working toward benchmarking criteria for CO₂ emissions from different heavy industries, including steel industry. This paper in turn contains a table attributed to Cairns et al. [23], listing “Most efficient electric arc furnace technology” with “Carbon from electrodes and scrap 11kg / tonne crude steel” and “Carbon for slag formation 2,7 kg / tonne crude steel” –summing up to 13.7 kg/t steel. The Cairns et al. publication was not accessible for this survey, so the methodology behind this estimation is unclear.

It would seem that the 12kg value in Figure 2 comes from [20], another source not accessible to the author as of the writing of this report. However, perhaps coincidentally, the GreenEAF project involved three EAF plants that all reported a standard practice where injection carbon and charged carbon summed up to ca 12kg per tonne liquid steel (see Fig. 2).

	Charge weight (tLS)	Num. buckets /heat	Electrical energy input [kWh/tLS]	CH ₄ [Nm ³ /tLS]	O ₂ [Nm ³ /tLS]	Coal lump [kg/tLS]	Injected Coal [kg/tLS]	Power on [min]	Tap to tap [min]
FENO	140	3	341	6	42	4	8	38	45
DEW	130	2	417,2	0	21,8	10.7	1,53	54	69
MH	40	3	375	7	45	0	12	31	45

FENO: Ferriere Nord

DEW: Deutsche Edelstahlwerke GmbH

MH: Marienhütte Ges. m.b.h.

Main characteristics of the electric furnaces of the industrial partners participating to the project

Figure 3: GreenEAF overview of EAF operating conditions for participating EAF plants [28]

To conclude, the GreenEAF publications seem to have made the 12kg figure recurring, and it seems to be based on a publication whose methodology and reliability cannot be evaluated in this report. No matter its reliability, the other reference values used in this project seem to corroborate that many EAFs come close to the 12kg/t figure. However, there is an obvious contradiction in the fact that the schematic in [11] has two references, one seemingly presenting 12kg/t as an average, and the other listing 13.7 kg/t as the “most efficient electric arc furnace technology”.

As can be seen by the other “Industrial average” type estimates in Table 2, the 12kg figure is by far the most specific one, all other examples (including the report from the GreenEAF2-project [27]) are ranges.

3-12 kg/t

This range was cited by Robinson et al. 2022 [30], “Typically, carbon consumption is in the range of 3 to 12 kg per tonne liquid steel with a recovery rate in the range of 30–80% depending on the particle size and method of addition” (p. 2523), with [45] given as a source. This publication from 2005 was not available at the time writing this report. It is unclear whether this is a peer-reviewed publication.

5-10 kg/t injected carbon

Two studies - [9], [40] state a typical injection carbon use in EAFs as being 5-10kg. Echterhof [9] attributes this figure to Zulhan 2006 [44], a thesis publication not available during this literature review. Hoikkaniemi et al. [40] writes “The typical amount of injected carbon for slag foaming purposes is 5–10 kg/ton of steel, which results in CO₂ emissions of 24.2 kg/ton of steel, on average” directly followed by a reference to Thomson et al. 2000 [41]. The Thomson et al. study does not in fact contain a direct value for injected carbon, but lists values for the CO₂-emissions per tonne steel directly related to it, one for a US plant, one for a UK plant. A simple mass balance extracting the ~27% of CO₂ molar weight that is carbon yields 4 kg/t in the US plant, and 6.6kg/t in the UK plant. The 24.2 kg CO₂/t figure quoted by Hoikkaniemi et al. is the value from the UK plant in the study, and seemingly not an average at all. Furthermore, the primary data in the Thomson et al. comes from these two sites, so the claim of it being “typical” has to be attributed to Hoikkaniemi et al.

20-55kg total carbon /t steel

The seemingly most deviant estimation of total carbon content comes from Kirschen et. al [7], a study doing an energy analysis of the EAF using different amounts of DRI. When discussing CO₂-emission figures, they state “Recent carbon mass balances of industrial EAF processes in Germany with 100% scrap charges showed values in the range from 20 kgC/tSteel to 55 kgC/tSteel i.e. direct CO₂ emissions from 70 to 200 kgCO₂/tSteel in agreement with an independent benchmark from a plant supplier”, citing Rummler et. al 2008 [22]. This mass balance checks out, but the source from 2008 was not available. Even so, the value might be reasonable, as it refers to the total amount of carbon among all input materials, including DRI, scrap etc., and as such is not a direct benchmark for injected or charged carbon.

In summary, although several values are cited in ways indicating they should represent averages or industrial standards, none of the publications reviewed actually presented the methodology or underlying data backing these assumptions up. Most of the cited studies that may contain broader datasets of industrial data are published in the 90’s and early 2000’s.

3.1.2 Specific steel plant practices

In this category is data detailing the consumption of carbon in specific steel plants either studied in research projects, or participating in trials. Some of the data include total values of carbon, but most break it down into injected- and charge carbon. Some only include one of the carbon categories. The different values given are summarized in Table 4.

Table 4: Carbon need estimations from specific steel plants, including sources and apparent origin of each estimation

Method	C-values	Used/quoted in	“Original” sources
Specific steel plant	5kg/t steel injected	[7]	[7]
	14kg/t injected		
	17-24kg/t steel in total.	[39]	[7]
	10.8kg/t for foaming.		
	6.8-13.6 kg/t for reduction of FeO (IMEXSA, DRI based production)		
	20-25kg/t (Ferriere Nord)	[32]	[32]
	12kg/t steel (Höganäs)	[30], [37]	[30], [37]
	7.6kg/t (Feralpi)	[36]	[36]
	17.5 kg/t (Höganäs)		
	4 kg/t injected	[41]	[41]
	6.6 kg/t injected		

3.1.3 Lab- or pilot trial values

In the lab- and pilot scale trials included among the publications, there were either specific values of carbon per tonne steel included, or possible to calculate them. Table 5 lists the specific consumption of carbon in these trials.

Table 5: Specific carbon consumption in lab- and pilot scale trials

Method	C-values	Used/quoted in
Proportion used in lab or demonstration trials	20kg/t steel	[5], [15], [31]
	1.9-3.0kg/t steel (MEFOS)	[36]
	2.4 kg/t steel in slag foaming experiments	[43]

3.1.4 Mass balance methodologies

The mass balance approach uses information about the input materials to establish a carbon need with reference to the desired product. The most common approach was to have a stoichiometric approach, where the molarity of carbon should correspond to for instance FeO molarity in input materials [7]. However, the stoichiometric balance was used primarily to estimate the difference in consumption between fossil and biogenic carbon, since both total carbon (C_{tot}) and fixed carbon (C_{fix}) values are often lower for biocarbon than for fossil products. Some studies aimed for a C_{fix} parity between different trial runs, other aimed at a C_{tot} parity.

Since most of the experimental studies aimed to vary as few parameters as possible, this meant that slag and steel amounts and composition were typically fixed, but in some cases a principle for carbon ratios were presented, typically relating to FeO content of slag, or as a percentage of the total slag mass – e.g. [38] used a C amount equal to 5% of the slag total. Digiovanni et al. [43] propose a method for slag foaming evaluation, with specific proportions

between melt, slag and carbon addition, ca 53 kg carbon per tonne slag. Even many of the pilot and industrial trials not explicitly using this method seem to arrive at a carbon-to-slag proportion of roughly 5%.

In addition to this, there is a required carbon content in each of the steel grades produced, and as such there is a minimum total carbon content that must be met, which is also part of a mass balance approach.

Method	C-values	Used/quoted in	“Original” sources
Proportion used in lab or demonstration trials	5 w% of slag / 50kg/t of slag	[57], [7]	[57], [7]
	Ca 53 kg/tonne slag	[9]	[9]

3.1.5 Flow-based methodologies

Much of the carbon applied in EAFs to achieve slag foaming is added through injection directly into the slag. When replacing fossil injection carbon with biogenic alternatives, there are specific requirements on both density and agglomeration size, in order to use the same injection equipment. The RIMFOAM project [36] evaluated several different municipal wastes with slag forming potential, in pilot and industrial scales. Several of the injection setups used in the project were limited to a particular flow rate, or could change flow rate but not dynamically. This meant that the amount of injected carbon was in practice decided by the number of injection lances added, and the flow rate of said lances. This is a reminder that in the end, final carbon consumption will actually be determined by the practices of operators at the steel plant, and the degree to which carbon usage can be optimized is limited by the operators’ range of choice. Thus, flow rate and heat length are important parameters. Hoikkaniemi et al. [40] designed an experimental setup where slag foaming can be visually inspected over time, with a constant carbon injection rate being applied for two periods of two minutes. Certain carbon materials will need a higher mass flow to achieve the same slag foaming performance, and this setup can allow for a meaningful comparison of such performance. MEFOS trials in RIMFOAM investigated injectability of different materials, and found that some of the chosen residues could only be injected at high flow rates.

Hoikkaniemi et al. [40] and Morales et al. [39] contain flow rate values for laboratory setups and industrial scale injection respectively, but did not provide any theoretical principles for calculating a priori the required mass flow to achieve foaming.

Flow rate examples from the literature are presented in Table 6.

Table 6: Flow rate methodologies

Method	C-values	Used/quoted in	“Original” sources
Flow of carbon-per-minute	Injection carbon: 0.39g/min - 1.46 g/min rates were used for a slag bath of 300 or 400g, ca	[40]	[40]
	Injection carbon: 25 kg/min flowrate, in 220t furnace, 90 min heats.	[39]	[39]
	10t/h, 150t furnace (AMMR), 66kg/h/t or 1.1 kg/t/min. 100kg slag/t steel		

The RIMFOAM project also contained an interesting method to estimate the replacement factors for conventional carbon feedstock when replaced with various residues. Since the purpose was slag foaming through gas production in the slag, the total stoichiometric amount of gas-forming carbon in hydrogen in the fossil product was replaced by a stoichiometrically equal amount of gas formers in the replacement product – including hydrogen, carbon and zinc. Thus this method focuses on gas flow parity, rather than a pure mass balance.

4 Biocarbon demand estimations

In the following sections, the usefulness of the identified estimation methods are evaluated for use in forecasting future national demand in Sweden, and for plausibility. A few selected methods are then applied to a constructed scenario for Swedish steel production in

4.1 Identified factors impacting carbon consumption

Here is a concise list of factors impacting carbon consumption in EAFs discussed so far:

- Carbon content of DRI and scrap
- Fraction of DRI and scrap in input materials
- Slag amounts
- Steel grade being produced and target C content
- Carbon material properties
 - Fixed carbon
 - Total carbon
 - Heating value
 - Molar gas production

4.2 Evaluating estimation methods

The overarching purpose of this paper is to understand how future demand for carbon feedstocks to EAF steelmaking in Sweden can be estimated. The Swedish EAF fleet is not only growing in total capacity, but is changing its feedstocks to H-DRI, and may be using new biogenic carbon carriers with new properties. A useful estimation method should ideally take one or all of these changing factors into account.

The industrial and steel plant-specific values presented in the literature are useful as a benchmark to compare any estimates to. However, they can only be useful for predicting future demand if they are based on data from a population of EAFs similar to that of the studied Swedish steel sector. None of the estimates claiming to be some sort of industrial average can be verified. They are also typically quite old (at best from the late 90s and early 00s), and have a very wide range. Furthermore, among the specific steel plants with reported carbon demand values there is none operating on H-DRI feedstocks, which have different carbon contents compared to conventional DRI.

The mass flow approach has an important conceptual value when estimating carbon need for slag foaming, but it is unclear how it should be applied to carbon added for carburisation. Additionally, the values found in literature were strictly empirical, and did not come with an established benchmark for a specific gas flow or carbon mass per tonne slag to be met.

On the other hand, the stoichiometric methods have the virtue that they do take feedstock parameters into account, and allows for easier evaluation of changes to slag formers, carbon inputs as well as iron carriers. The drawback of stoichiometric methods is that they may disregard losses and low yields of certain materials, and do not naturally differentiate between

the functions of injection- and charge carbon. To address this, the choice of carbon equivalent – C_{fix} , C_{tot} or the Heating Value of carbon matters.

Heating Value seem almost exclusively useful when conducting pure energy analyses, as volatile components of a material may have the same HV as fixed carbon, but contribute far less to carburisation or foaming. Between C_{fix} and C_{tot} there may be some argument, but C_{fix} will be the more conservative estimation. In either case however, it is important to consider the carbon content of all feedstocks, not just injection- and charge carbon products.

As for the differentiation between charge- and injection carbon, they both contribute to heating, foaming and carburisation, but may have very different efficiencies. However, in a holistic perspective, there will be a certain amount of carbon needed to fill all these functions in a steelmaking process, and there does not seem to be an obvious discrepancy in total carbon consumption between plants with a high fraction injected and those charging most of their added carbon.

Therefore, in the next session, two kinds of mass balance approaches will be used – a flat proportion of total slag amounts, and a stoichiometric proportion between iron oxides in input materials and carbon. Both C_{fix} and C_{tot} parity will be evaluated.

4.3 Applying estimation methods

In order to evaluate these methods, a scenario for Sweden's steel production system 2020 was developed, and certain assumptions about total production, share of DRI etc. had to be made. These assumptions are presented in Table 7. The reference composition of DRI is based on the LKAB KPRS pellets, using a mass balance where 95% of iron oxides were reduced, and 0% carbon content. The total slag amount was calculated as 100kg/t steel plus the gangue fraction of charged DRI. A low-DRI and a high-DRI scenario were evaluated.

Table 7: Assumptions for Sweden 2030 scenario

	Scrap [w%]	DRI [w%]	Total prod [Mton]	DRI [Mton]	Slag [kg/t steel]	Slag tot [Mton]	Fe_m in DRI [%]	FeO in DRI [w%]	DRI metallization [%]
High DRI	30%	70%	9.76	6.8	190	1.86	87.1%	6.5%	95%
Low DRI	70%	30%	9.76	2.9	139	1.35	87.1%	6.5%	95%

Four carbon products – one fossil and three biogenic – with different C_{fix} and C_{tot} values were chosen, presented in Table 8.

Table 8: Reference carbon material properties

	Woody biocarbon [5]	Agricultural residue biocarbon [5]	HTC [42]	Fossil reference [28]
C_{fix}	58.30%	54%	15.18%	89.50%
C_{tot}	64.70%	57.80%	49.76%	88.40%

Demand in kg/t, as well as total demand in Mton and kton are presented in Table 9. For comparison, the demand under the same conditions assuming a fixed amount of carbon per tonne steel and per tonne slag, are presented in Table 10.

Table 9: Carbon demand using stoichiometric proportion between FeO in feedstock and carbon input. Presented for four carbon products and one

		FeO stoichiometric					
		Cfix parity [kg/t]	Cfix parity [Mton]	Cfix parity [kton]	Ctot parity [kg/t]	Ctot parity [Mton]	Ctot parity [kton]
High DRI scenarios	Woody biocarbon	28.8	0.37	197	16.8	0.11	115
	Agri. residue biocarbon	34.8	0.44	238	18.8	0.13	128
	HTC	143.8	1.82	983	21.8	0.15	149
	Fossil ref.	13.7	0.17	94	12.3	0.08	84
Low DRI scenarios	Woody biocarbon	12.0	0.15		7.0		
	Agri. residue biocarbon	14.5	0.18	84	7.8	0.05	49
	HTC	59.9	0.76	102	9.1	0.06	55
	Fossil ref.	5.7	0.07	421	5.1	0.06	64

Table 10: Carbon demand assuming specific carbon need per tonne of steel and per tonne of slag. Specific demand of different feedstocks calculated according to C_{fix} parity.

		Fixed kg per tonne steel			Fixed amount per tonne slag
		5kg/t [kton]	15kg/t [kton]	12kg/t [kton]	5w% of total slag weight [kton]
High DRI scenarios	Woody biocarbon	84	84	201	159
	Agri. residue biocarbon	90	271	217	172
	HTC	321	964	772	612
	Fossil ref.	55	164	131	104
Low DRI scenarios	Woody biocarbon	84	251	201	116
	Agri. residue biocarbon	90	271	217	125
	HTC	321	964	772	446
	Fossil ref.	55	164	131	76

4.4 Comparison to previous market-level estimations

In this section, the calculated estimates will be discussed in relation to generalized estimates published by Swedish steel industry organisation Jernkontoret, with a brief note for the WorldSteel figure mentioned in the introduction.

First, the World Steel estimation of 150 kg coal per tonne steel in the EAF route [16] is wildly divergent from all other estimates discussed in this paper. It does not take a lot of scrutiny, however, to identify the reason. This is not a value for the average consumption of carbon in an EAF, but rather the total coal demand of global EAF-based steel production, divided by the output. This would include the production of coal-DRI, a practice which is dominant in India, but few other regions. The figure of 150kg/t therefore seems to be misleading in two respects. First, it should not be taken as representative for scrap-based steel production in EAF, which does use considerable amounts of coal, but way less than 150kg/t. Second, as a global average, it should be lower than the lifecycle demand of coal for coal-DRI steel production. Thus, for one process it grossly overstates the carbon demand, and for the other it is likely to be a considerable underestimation of carbon consumption.

When it comes to the Swedish steel industry, the Swedish iron and steel producer's association Jernkontoret, has made a roadmap for carbon neutrality [26]. This roadmap delineates a series of measures that will de-fossilize the Swedish steel industry, including the transition away from Blast Furnaces to H-DRI and EAF production, and the use of biofuels. In this roadmap, there is an estimation that the steel industry (excluding for instance alloy producers such as Vargön) will require 1-1.5 TWh of biocarbon to maintain the current production volumes in the future production system. This estimate was made before most announcements of steel industry newcomer Stegra, that will more than double the total Swedish steel output when its plant in Boden is fully established [46].

Let us first discuss how the Jernkontoret estimate might have been constructed, before assessing the impact of Stegra. The roadmap does not present a methodology for the estimates, but since Jernkontoret is the author, they may simply have asked its members for their future estimates. The figure 1-1.5 TWh/year translates to 127-190 kton/year (unit conversion using a Lower Heating Value of coal of 28.4 MJ/kg).

Using a scenario of 4.5 Mton steel production (roughly representative of Swedish steel production capacity excluding Stegra in 2030), this would mean ca 28-42 kg of biocarbon per tonne steel. This value is higher than the calculated stoichiometric estimates for the fossil reference coal product, but in a similar range to the woody biochar and agricultural residue biochars, assuming. The C_{tot} parity calculations yields lower biocarbon demands (12-22kg/t in the high DRI-scenario), and the 5w% of slag yields even lower estimates (25-80 kton at C_{fix} parity, excluding the HTC).

The presented calculations do not take into account the desired carbon content in steel. Assuming the Jernkontoret estimate was produced using a similar method, the average C-content that would explain the discrepancy in the high-DRI scenario is 0.8-2.2 w% (woody biochar) or 0.4-1.8w% (agricultural biochar). This is not outrageously high for a steel grade, but the higher end seems excessive as an average, since not all products are high-carbon grades.

For the low-DRI scenario, the corresponding C-concentrations would be 2.0-3.4w% (woody) and 1.8-3.2w% (agri). This is definitely above what be expected, and indicates that the Jernkontoret estimate likely assumes a higher DRI scenario.

Overall, the Jernkontoret estimate is somewhat higher than the proposed estimation methods, but taking into account a lower yield of biocarbon and an average carbon content of ca 1-1.5w%, they are in the same order of magnitude, assuming a high DRI usage.

In section 4.3, calculations for 2030 included a fully expanded Stegra Boden plant, not included in the Jernkontoret projection from 2018. However, Fossil Free Sweden published a biomass roadmap in 2021, which included an updated value taking Stegra into account [25]. This figure is 7-9 TWh in total, including all biofuels. Assuming the same split between

biogas needs and biocarbon demand in this projection as in the Jernkontoret projection, this should equate 2.3-3 TWh or 296-380 kton of biocarbon per year, also considerably higher than the calculated estimations in 4.3.

If one makes the same correction for carbon content in the steel for these figures, the required carbon is 1.0 – 1.9w% (woody) and 0.6-1.5w% (agri) in the high DRI scenario, and 2.0-3.0w% (woody) and 2.0-2.8w% (agri) in the low-DRI scenarios. Thus, the stoichiometric model balancing carbon with FeO content in slag seem to underestimate the carbon demand compared to the industrial estimations, but combined with assumptions of average carbon content of steel products and a lower-than-100%-yield for biocarbon, they seem to be in the same ballpark.

4.5 Analysis

As can be seen by the estimations, the total biocarbon need varies greatly with different assumptions. The lowest estimates are the fixed amount of 5kg carbon per tonne steel, using fossil coal – landing at 55kton total need. The highest estimation is for the high-DRI scenario with HTC, at 983 kton. This illustrates the impact of different C_{fix} values in this kind of calculation, and the fact that this particular HTC material seems an unlikely candidate for wide adoption.

We can see that the 12 kg/t estimate is in a similar order of magnitude to the High DRI, C_{fix} parity estimation, and higher than the corresponding C_{tot} estimation. Disregarding the HTC, most of the mass balance estimates are in the range of 5-22kg/t steel. But the limitation of the carbon-per-tonne-steel approach is also illustrated by the considerable difference in projected demand between Low DRI and High DRI scenarios. The mass balance approach projects much lower carbon need for this scenario, but the other mention does not differentiate in demand. The “5w% of slag” method however, appears to be a more middle-of-the-road approach, where projected demand is lower than the C_{fix} parity estimation in the High DRI scenario, but higher in the Low DRI-scenario.

These calculations do not take into account the carbon content of scrap, and assumes DRI has virtually no carbon content. If DRI producers include processes to carburise their products, the total balance will change, as more carbon enters the EAF from other sources. Estimations should also include at least an average raw steel C content, to include the alloying need of steel industry.

It seems clear however, that both slag amount, iron oxide content in feedstock, and carbon content should be included in an estimation intended to project future carbon demands in Sweden. Combining these factors, it is possible to arrive at the estimations used in Jernkontoret’s roadmap, and therefore it should also be possible to investigate the effects of changing some of those assumptions, giving a more nuanced idea of how biocarbon need can be quantified, mitigated and met.

5 Conclusions

When projecting future biocarbon demand in Sweden, relying on historical data is not sufficient as process inputs are rapidly changing. There are generalised estimations of typical carbon consumption circulating in the literature, but their validity is unclear.

Overall, slag composition and volumes are so significant for carbon demand that flat estimations of a certain amount of carbon per tonne steel should be avoided.

When looking at a specific future scenario for Sweden, an estimation model should take into account the following:

- Total slag volumes
- Iron oxide content in feedstock
- Fraction of DRI in feedstock
- Gangue content in DRI
- Carbon content in DRI and scrap
- C_{fix} and/or C_{tot} of carbonaceous materials
- Average carbon content of tapped hot metal from EAFs

6 Suggested continued work

Further analysis of experimental studies and industrial trials should be made to establish a more refined estimation model. The literature review in this work was quite limited, and could be refined to investigate older works, and more publications not directly related to biocarbon. Other publication databases should also be used.

Future studies should also investigate how decisions on carbon use is actually made by operators, and to what extent carbon consumption is pre-determined by choice of equipment. Finally, there seems to be a gap in the literature concerning contemporaneous broad averages regarding the use of charge- and injection carbon in EAF:s. LCA databases and steel product EPDs might be of help to establish such averages.

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