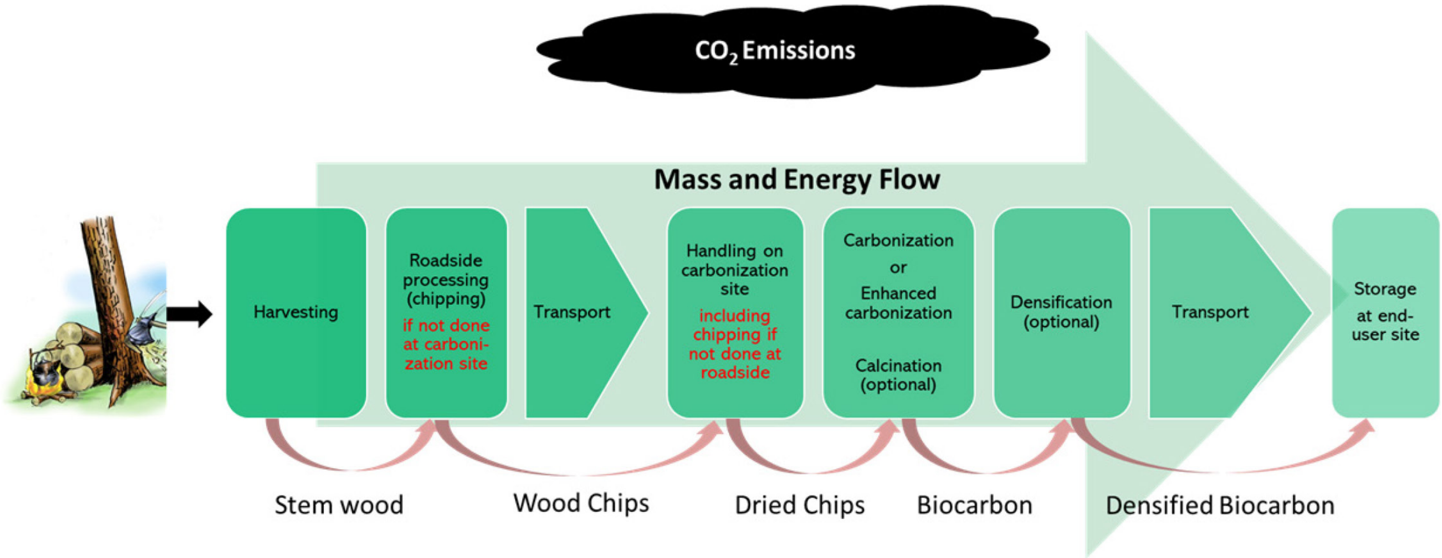
BioCarbUp

Optimising the biocarbon value chain for sustainable metallurgical industry

SINTEF
NTNU
NIBIO
NORWEGIAN INSTITUTE OF BIOECONOMY RESEARCH



BioCarbUp

Optimising the biocarbon value chain for sustainable metallurgical industry

ISBN 978-82-594-3795-2

Editorial staff at SINTEF Energi AS (SINTEF Energy Research):
Øyvind Skreiberg (BioCarbUp project manager)
Liang Wang (BioCarbUp sub-project manager)

Editorial staff at SINTEF Industri (SINTEF Industry):
Gøril Jahrsengene (BioCarbUp sub-project manager)

Editorial staff at NTNU (Norwegian University of Science and Technology):
Tian Li (Grate BioCarbUp CFD sub-project manager)

Editorial staff at NIBIO (Norwegian Institute of Bioeconomy Research):
Simen Gjølsjø (BioCarbUp sub-project manager)

Cover: SINTEF, Gry Karin Karlsen
Illustrations: SINTEF

Dr. Øyvind Skreiberg
Chief Scientist at SINTEF
and BioCarbUp project manager
Oyvind.Skreiberg@sintef.no

Background

This handbook is prepared by **SINTEF Energy Research** with contributions from the BioCarbUp partners, with the purpose to provide both partners in the BioCarbUp project, relevant research projects and centres, policy makers and others with a simple and easy to read guide on optimising the biocarbon value chain for sustainable metallurgical industry.

The information in this handbook is based on studies performed throughout a 4-year period in the knowledge building project entitled "**BioCarbUp – Optimising the biocarbon value chain for sustainable metallurgical industry**".

BioCarbUp has run from 2019 to 2022 with a total cash budget of 25 million NOK, whereof 80% financed by **the Research Council of Norway** through the ENERGIX program and 20% financed by the industrial partners Elkem, Eramet Norway, Hydro Aluminium, Alcoa Norway and Norsk Biobrensel. In addition, NTNU contributed with in-kind.

The **overall objective** of BioCarbUp has been to optimise the biocarbon value chain for the metallurgical industry through:

- **Production of biocarbon with sufficient quality** satisfying the end user quality requirements while ensuring optimum utilisation of the by-products,
- **Optimised sourcing of Norwegian forest resources** for biocarbon production towards the specific metallurgical processes, and
- **Maximising the energy and cost efficiency** of the biocarbon value chain for metallurgical industry

The sub-objectives were:

- Identifying optimum forest resources for the specific metallurgical processes
- Identifying and optimizing carbonisation processes and conditions to produce optimum yields and qualities
- Developing methods for upgrading and tuning biocarbon quality to increase its suitability for the specific metallurgical processes, and methods for upgrading the by-product tar to higher value products
- Developing fundamental knowledge of biocarbon behaviour in and influence on the specific metallurgical processes and biocarbon impact on product quality
- Increasing expertise throughout the biocarbon value chain for the metallurgical industry
- Educating highly skilled candidates within this area and training of industry partners
- Monitoring activities and state-of-the-art practice within this area and disseminating knowledge to industry partners, and other interested parties where applicable

Main anticipated results of the project were reduced harvesting and logistics costs for woody biomass resources, maximised BC yield and quality directly in the BC production process or via secondary upgrading and maximised utilisation in BC end-use applications, i.e. the metallurgical industry. Additionally, by-products utilisation and higher value products from tar are complementary foci.

Introduction

Knowledge needs - pre-BioCarbUp

The ENERGIX program plan clearly states the importance of sustainability and sustainable value chains, including biomass based, contributing to reduced CO_2 emissions and a carbon neutral Norwegian society in 2050. For biomass, there is an expectation of total biomass feedstock utilisation.

Four central documents were at that time defining the national bioenergy strategy: Klimameldingen, Energi21, Skog22 and Strategy for increased expansion of bioenergy - 2008. The latter states that the Norwegian energy policy shall work towards producing 14 new TWh of bioenergy by 2020. However, today the Norwegian bioenergy production is well behind the 2020 target. Concurrently, the metallurgical industry in Norway sought to substitute large amounts of biocarbon for fossil reductants in their processes. The Norwegian Process Industry Roadmap - Combining growth and zero emissions by 2050, and Industrimeldingen laid the foundation for an accelerated utilization of Norwegian biomass resources that would reduce the CO_2 footprint of the metallurgical industry. The former document targets a 43% reduction of CO_2 by 2030 compared to 2005 levels. To enable this transformation, the whole biocarbon (BC) value chain for the metallurgical industry would need to be optimized to remove economic constraints, satisfy reductant quality demands, and develop predictable (amount, quality and price), long-term biomass resource demand.

Due to economic constraints, the BC reductants were imported from low-cost countries that use traditional, inefficient production technologies with undesirable environmental and climate impacts. BC utilization as a reductant in Norway was and still is more prevalent in Si and FeSi production. Quality constraints limit BC use in the Mn-alloy and Al production industries. Cost-efficient methods of producing and upgrading BC to match the quality demands of the different metallurgical processes would remove barriers to adoption and drive costs toward those of the fossil reductants.

This project responded to the national strategies and the goals of the metallurgical industry by analysing and optimizing the **BC value chain** to produce suitable and affordable reductants in a sustainable manner. Producing BC, a **renewable material** from **biomass resources**, would have a twofold effect: (1) reduce CO_2 emissions by substituting for fossil reductants and (2) increase forest resource utilisation by creating higher value material and/ or energy products. Due to the BC quality demanded by the metallurgical processes, **woody biomass, especially stem wood, was considered the most suitable candidate** for reductant feedstock.

Although BC has some desirable reductant properties, **substantial improvements would be needed in other properties to completely reproduce the characteristics of fossil reductants**. This especially relates to 1) **increased strength and density** and 2) **reduced reactivity** (for Mn-alloy and Al).

The BC reductant should not have significant negative influence on existing metallurgical processes, i.e. result in increased fixed carbon (fix-C) consumption, higher energy demand, or lower product quality. Hence, additional requirements for the BC include expectations for volatile matter and ash.

Maximising the BC yield and utilising by-products efficiently would ensure cost-effective and sustainable BC production. By optimizing carbonization, the fix-C yield can approach a theoretical yield defined by thermodynamic considerations. Fix-C is essential for the metallurgical industry as it is the key for the final removal of oxygen from the metal oxide ores, thereby producing pure metals or alloys.

In KPN BioCarb+, the predecessor to KPN BioCarbUp, the focus was partly on BC for energy production using forest residues as main biomass resource, and partly on BC production for metallurgical processes, using both forest residues and higher quality wood as resource. A main conclusion from BioCarb+ was that enabling the BC value chain for sustainable metallurgical industry in Norway would require the use of higher quality wood and that the BC quality and the overall BC value chain must be optimized. Figure 1 compares BioCarb+ with the proposed activities in BioCarbUp. BioCarbUp was to build on BioCarb+, advancing the knowledge further while focusing on BC for use in the metallurgical industry.

In BC production the by-products are normally burned for producing process heat and/or electricity, for primarily internal but also for external use. However, tar collection for further utilization and possible upgrading to higher value products or biofuels is an option. Another by-product in the BC value chain is charcoal fines, resulting from BC handling. This is a source for upgraded BC via compression or agglomeration, or can be used for energy production. In BioCarbUp we were to look at these options. The BC value chain for the metallurgical industry involves the resource side (forest operations), further handling, logistics and storage of the resource, BC production and by-products utilization or collection and upgrading, BC

BioCarb+ (2014-17)

- Energy end reductant focus
- Forest residues focus
- Broad BC production approach
- Simplified carbonisation reactor modelling
- No BC upgrading focus
- No biooil/tar upgrading focus
- General BC characterisation
- Value chain establishment

BioCarbUp (2019-22)

- Reductant focus, and by-products utilisation
- Stem wood focus
- Targeted BC production approach
- CFD carbonisation reactor modelling
- BC upgrading focus
- Biooil/tar upgrading focus
- BC characterisation at metallurgical conditions
- Value chain optimisation

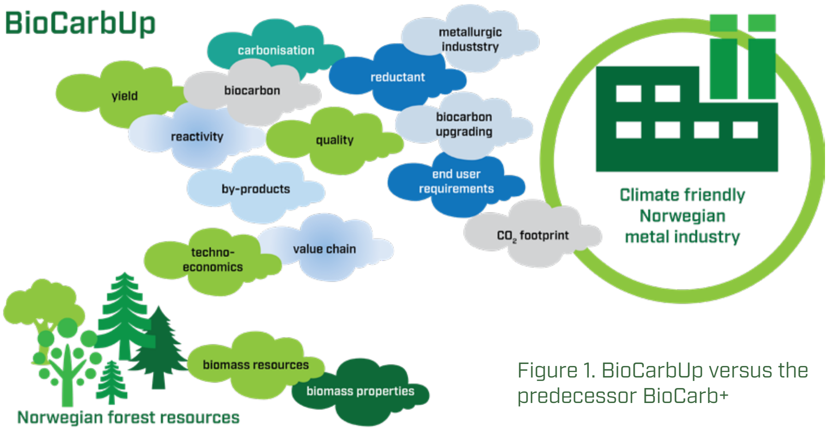


Figure 1. BioCarbUp versus the predecessor BioCarb+

upgrading, BC logistics, and the end-use as reductant. The whole BC value chain was included in BioCarbUp. The target was BC for sustainable metallurgical industry. Through sourcing of biomass resources to produce different BC qualities, several TWh/year increased biomass utilisation would be possible within a moderate timeframe. For this to happen, research was needed across the span of the BC value chain. **The BioCarbUp project consortium covered all the necessary aspects, from resources to end-use, and included large and central industrial players in the metallurgical and bioenergy areas in Norway**: Norsk Biobrensel, Elkem, Eyde Cluster, Eramet Norway, Alcoa Norway and Norsk Hydro.

Frontiers of knowledge and technology

The large volume flows in Nordic forestry were and still are directed to sawmills (high quality roundwood), pulp&paper (mid-quality roundwood) and energy production (low quality roundwood, logging residues). Limited demand of wood resources for pulp and bioenergy in Norway, reduced value of low quality roundwood; value of logging residues was, and still is, absent. Pulp quality roundwood was to a large extent exported to foreign industry, and the annual utilization of low grades was minimal compared to the potential usage. Norwegian forests might therefore be a suitable supplier of woody biomass for BC production, as medium grade roundwood was exported for moderate prices and low-grade wood resources were left in the forest. However, establishing a successful BC industry would depend on confirming supply and demand with respect to biomass assortment, biomass properties, delivery rates, and other parameters ensuring stable production and a manageable supply. The requirements and expectations of a BC plant would differ from those of existing wood industries of which the forest sector already is familiar.

One ambition of this project was to identify optimum forest resources for specific BC qualities and metallurgical processes, as well as to tailor the supply chain with respect to production costs, supply security, and feedstock quality. Existing knowledge of national wood resources, within biomass supplied for heat and power, and knowledge about wood properties of different species and tree components is highly relevant in tailoring biomass supply for BC production. Still, there existed knowledge gaps providing options for supply cost reduction, improving feedstock quality and broadening/narrowing the resource base for BC production. It was likely that the wood supply monitoring system at that time used by the Norwegian forest sector would not fully cover the requirements for BC supply. The resolution of lesser grade wood assortments was rather low (pulp quality, energy mix, and dry spruce), and the system was not developed for tracking storage conditions, or for predicting moisture content, fix-C content and chemical composition in the wood pile. It was therefore important to identify shortcomings in current wood flow monitoring systems and suggest improvements that would be relevant for BC production processes. It was also likely that certain mixes of species and wood assortments would be optimal for the BC production process and for specific metallurgical processes. New knowledge on this issue, together with existing knowledge on wood resources in different regions, would make it possible to identify geographical locations suitable for BC production.

Tree species differ both anatomically and in chemical composition providing a range of properties across different species. Properties also vary from one tree component (part) to another. Furthermore, trees are organic material which mean that they are susceptible to changes by biological and physical agents over time, for example dry matter content, fix-C, volatile matters and ash elements (e.g. K, Na, P, B, S). These changes may be advantageous or harmful to the feedstock properties. However, it was not well known how these properties will vary over time once the tree has been severed from the stump.

The chosen logistics will influence the quality of feedstock that eventually reaches the BC conversion site. The key elements here are time, i.e. how long it will take from stump to delivery, and environmental conditions. Both are of key importance and their influence on chemical and physical properties of the feedstock and the BC was to be considered in this project, keeping in mind the requirements set by the metallurgical industry.

Metallurgical processes require large amounts of carbonaceous materials of a certain and predictable quality. Mass yield and fix-C content of BC provided by conventional production processes are generally low, partly due to limited control of the carbonization process. This increases feedstock consumption and logistics and reduces the BC value chain profitability. Improvement of BC and fix-C yield can be realized by extending the residence time of pyrolysis vapours, using larger particle size, increasing carbonization pressure etc. This promotes secondary reactions that enhance tar cracking and recondensation of tarry vapours onto the solid, thereby increasing yields of BC and fix-C. In comparison to other process conditions, increasing pressure gives the most pronounced effect on BC and fix-C yield. In a constant volume reactor this can be achieved at modest pressure and temperature. Very little tar and a gas product composed of steam and CO_2 and a trace amount of CO are produced. This called for further detailed studies to investigate secondary char formation and the consequent increased BC and fix-C yield under combined effects from constant volume and pressure. The BC and fix-C yield can also, to some extent, be promoted by recycling pyrolysis volatiles and/or bio-oil that can undergo cracking and polymerization and then condense on the surface of wood undergoing pyrolysis, resulting in higher BC yields.

In metallurgical processes, BC quality is closely related to physical and chemical properties of BC, including volatile matter and fix-C content, concentration of unwanted inorganic elements (e.g. P, K, Na, B), reactivity, surface area and porosity, mechanical strength, bulk density, electrical resistivity etc. BC properties are influenced by type and characteristics of feedstock, production process conditions, post treatment etc. BC from woody biomass has low ash, high fix-C and low volatile matter contents when produced at sufficiently high temperature. However, quality and properties of woody BCs can be significantly different, when produced from different wood species and under different process conditions. Therefore, detailed analysis and assessment of BC properties are primary steps to ensure proper and efficient utilization of BC in a specific metallurgical process, and also needed for tuning and optimizing carbonization process parameters to produce BC with desired properties. At that time, analysis and characterization of BC normally focused on general properties (proximate and ultimate analysis), heating value and limited physical properties (surface area, porosity, strength). Systematic and quantitative studies on the amount of main chemical components and inorganic elements of BC produced from different raw feedstocks and under various conditions were seldom. Additionally, mostly the cold BC was characterized. As used in metal production processes, BC will be fed into high temperature conditions. Hence, establishment of reliable and efficient analysis methods and procedures to understand changes in BC properties and reactivity at these conditions was needed. Increased process integration and use of by-products are important to improve economics of BC production processes. Pyrolysis vapours could be used for heat and power production or as feedstock to produce valuable chemicals, other higher value products or be recirculated to increase the fix-C yield. Slow pyrolysis can produce pyrolysis oils with high selectivities of lignin-based mono- and oligophenolic compounds. This is achieved by making use of the higher temperature stability of phenols as compared to cellulose/hemicellulose based primary products. The properties of the liquid by-products can be characterized via advanced analysis methods including liquid state C13-NMR, GCxGC-FID/MS, ICP-MS-MS and FT-ICR-MS. Treatment of the pyrolysis vapours can maximise the phenolics selectivity by 1) deposition of highly reactive sugar-based humins on the catalyst surface, 2) mild cracking of oligomeric compounds into monomers and 3) adjusting condensation temperature and diffusion length.

BC can be upgraded via different methods to improve properties crucial for metallurgical processes, to increase volume and energy density as well as compressive strength of BC. Agglomerating composites of biocarbon (e.g. fines) and ores or, alternatively, depositing elemental carbon from e.g. cracking of biogenic derived methane onto the BC internal surfaces was another interesting option. Feedstock pretreatment such as sieving and washing, including acid washing, are also possible, but with a stem wood focus in this project, the latter was not in focus. Further work was needed focussing on optimizing parameters to compact BC produced at different conditions, assessing reactivity and identifying logistic solutions for the densified BC. Densification and agglomeration can also be efficient ways to use fines from BC handling, reducing both mass and fix-C losses.

Further research on biomass carbonization should aim for achievement of high energy efficiency and tailoring the conditions to produce the desired product types and properties in properly scaled BC production plants. Reactor and process modelling and simulation are valuable tools to achieve these goals. A cost-efficient thermally thick particle model properly considering secondary char formation and intra-interparticle mass transfer was wanted. Combining modelling and simulation provides a foundation for design of modern and efficient BC production processes capable of matching quantity and quality requests from the different metallurgical processes.

For production of Si and ferroalloys with today's technologies (no blast furnace/Fe focus in this project), solid carbon as fix-C is needed to remove oxygen and thereby convert the raw materials to alloy/metal/carbide. The fix-C, which could come from BC, is not used as an energy source. The carbon materials used in the metallurgical processes have large effects on the total cost, the energy consumption, the stability of the operation and the quality of the final product. Textbooks describing processes for Si/FeSi[1] and for Mn-alloy[2], written by researchers from SINTEF/NTNU are used by the industry globally. Flows of material and gases in the furnaces are affected by carbon properties including particle size distribution, strength and density. In Mn-alloy production, the process gas contains CO_2. If it reacts with carbon to form CO, both energy consumption and CO_2 emissions will increase. A carbon material with low CO_2 reactivity is thus preferred. For reduction to Mn-alloys, a high slag-reactivity is preferred, and to ensure an optimal energy distribution and high energy efficiency the carbon materials should have a high electrical conductivity. In Si-production, SiO-gas generated in the high temperature zone, reacts with carbon to SiC in the upper part of the furnace. A good SiO-reactivity of the carbon materials

[1] Schei A., Tuset J.K., Tveit H., (1998), Tapir Forlag, ISBN 82-519-1317-9, Norway.
[2] Olsen, S., Tangstad, M., Lindstad, T. (2007). Trondheim: Tapir Forlag, ISBN-978-82-519-2191-6.

is crucial for a high productivity of SiC in the high temperature zone and to ensure that all SiO-gas is captured and the energy consumption minimised. The SiO-reactivity varies with the carbon source. Use of composite agglomerates consisting of fines of raw materials that cannot be directly used, but which could be intimately mixed with BC materials, would give new opportunities, e.g. affecting reaction rates. This had not been studied for Mn-ores, but investigation of agglomerates of iron ore and BC seemed promising. The possibility to use biocarbon in Norwegian ferroalloy industry had been investigated earlier. This did not result in increased BC use due to several obstacles, both price and technical as low densities, dusting propensity and effects on furnace performance. These challenges were to be addressed in BioCarbUp.

The Al industry is a large consumer of petrol cokes and pitch to produce anodes for the electrolysis process (in Norway around 650000 ton/year carbon anodes). The carbon anodes are made by mixing petrol coke, coal tar pitch and recycled anode butts to a paste. The paste is formed to anodes and then calcined in a baking furnace at around 1250 °C. Norsk Hydro uses closed anode baking furnaces while Alcoa uses open. The consumption of packing coke is around 35 and 9 kg per ton anode for respectively closed and open furnaces, giving a total CO_2 emission of around 44500 ton/year in Norway. When anodes are baked in the furnaces, the packing coke (ordinary petrol coke) is used to prevent air-burn of the anodes during the baking cycle. Bio-coke: To replace the coke in the anode itself by bio-coke is a great challenge for many technical reasons. Therefore, the main aim for bio-coke in this project was to study the replacement of petrol cokes as packing cokes in anode baking furnaces with bio-cokes. Both the Mn-alloy and Al-industry require biocarbon with low reactivity, low content of alkalis and high strength. To deposit carbon from methane into the pores of biocarbon has been proposed as a method to obtain these properties. This was in BioCarbUp to be studied in a postdoc work, using apparatus developed in IPN SiNG. By using methane originating from biomass this will still be a non-fossil carbon source.

Bio-based binder: 12-15% of the anode paste is currently coal tar pitch. The main reason for using coal tar pitch is its high aromaticity, which gives a high coking value and good electrical conductivity in the baked anode. Changes in the steel industry is reducing the coal tar pitch availability. Coal tar pitch is carcinogenic and on the REACH list of substances of very high concern. Replacing the coal tar pitch with a bio-based pitch would therefore have a positive impact on HSE and CO_2 emissions. The main challenge of alternative binders was considered to be the low coking value which results in low density, high resistivity and high porosity of the anodes.

Metallurgical industry history and future in Norway

Metallurgical industry in Norway has long traditions, and the access to affordable renewable hydropower at strategically selected plant locations along the coast of Norway has contributed to put Norwegian metallurgical industries in the forefront with respect to their CO_2 footprint. However, still different fossil based reductants and materials are needed in the metallurgical processes, and e.g. the Si/FeSi, Mn-alloy and Al industries participating in the BioCarbUp project all have clear plans for reducing their fossil based consumption, where the substitution with biobased alternatives is a key effort. The **Norwegian process industries' roadmap** set clear reduction targets in 2016, including for a reduction of the in total 3.1 million tons of annual CO_2 emissions from today's use of fossil reductants and materials within 2050. Recently **Prosess21** was established to strengthen the coordination between the competence environments in and connected to the process industry and the public actors. Prosess21 shall give strategic advices and recommendations on how to minimize emissions from the process industry while achieving sustainable growth. The metallurgical industry is a very important part of the Norwegian process industry.

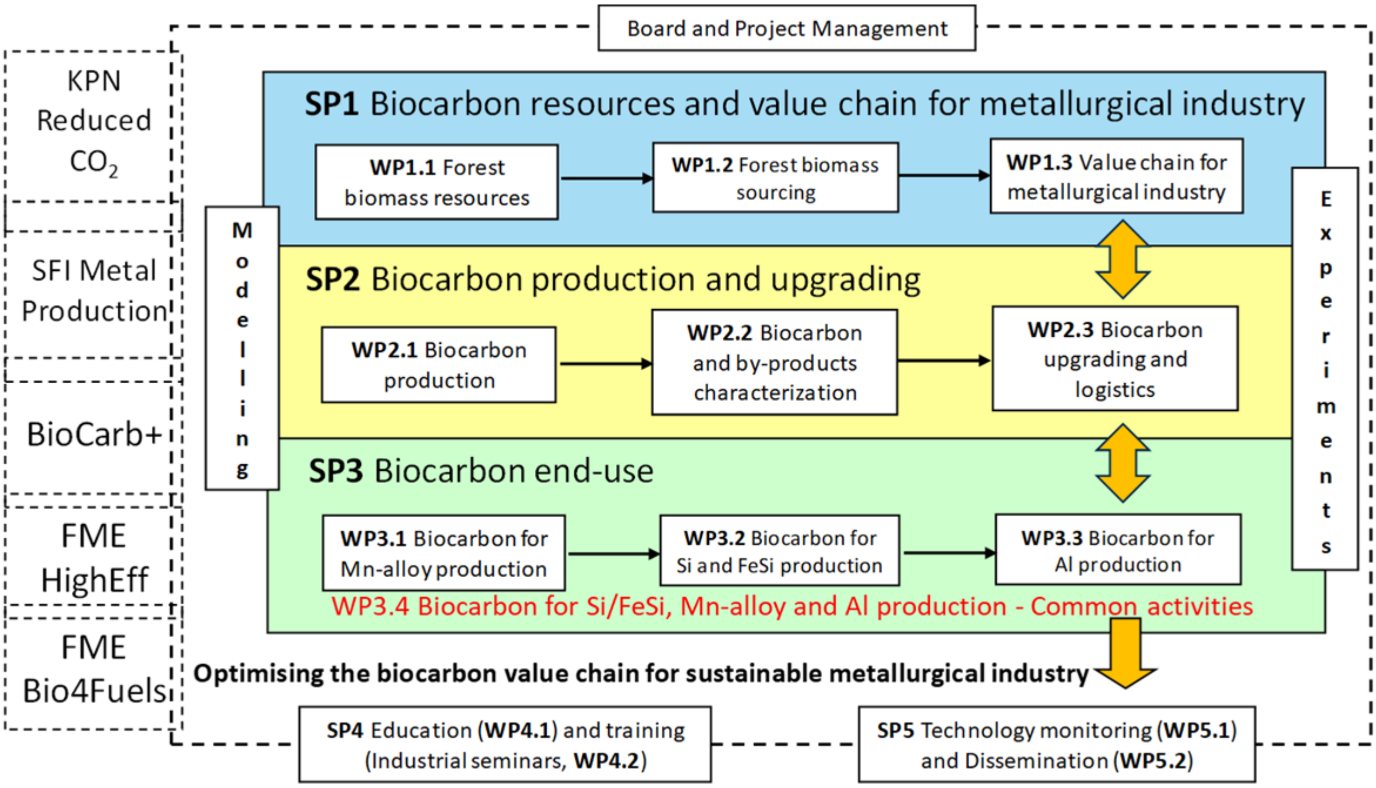
Biocarbon production history and future in Norway

Biocarbon (biochar, charcoal) production has a long history in Norway as in most of the rest of the world, for producing charcoal to be used for iron making. Still today remains of a large number of ancient charcoal production pits can be found around the country. However, it is first by the end of the 20th century that renewed activity towards establishing commercial biocarbon production took place, due to global warming awareness and the need for replacing fossil reductants and materials in metallurgical industries. At that time research efforts did not result in establishment of commercial biocarbon production in Norway, but in the last decade an accelerated effort has taken place, driven by the industry itself and with support from an increasing number of different kinds of research and innovation projects partly funded by the **Research Council of Norway** and more recently also **Enova** for market introduction. Different industrial actors are now involved in establishing biocarbon production, for multiple purposes. **Oplandske Bioenergi** was the first to establish a commercial biochar production plant in Norway, in 2021. Several other actors have invested in small-scale pyrolysis units, to produce biochar for soil amendment. However, for metallurgical industries, large volumes of biocarbon with specific qualities depending on the type of metallurgical process are needed. Elkem was the first from the metallurgical industries to **erect a biocarbon production plant** to provide biocarbon to their own process. This plant is erected next to their metallurgical plant in Chicoutimi, Quebec, Canada. Eramet Norway **recently got support** from Enova to establish production of biocarbon quality matching their requirements, and WAI Environmental Solutions together with other industrial partners have also received funding from Enova to erect a **biocarbon production plant** to provide biocarbon matching Si industry requirements. VOW is another company **receiving Enova funding** for establishing biocarbon production, and **they are collaborating** with Elkem. All in all, there has been an accelerating effort towards establishing commercial biocarbon production in Norway, with the metallurgical industry themselves driving much of this effort or in companionship with industrial companies wishing to produce biocarbon from different types of domestic biomass resources.

In parallel with the industrial and research efforts, networks have been established to assist in the development of industrial establishment and for information exchange. **Norsk Biokullnettverk** was established in 2018, and includes many industrial companies, including several from metallurgical industries, as well as others, e.g. research institutions. On the research side, the **Nordic Biochar Network** was established in 2019 as a research based arena covering biocarbon production for multiple purposes. On the European arena the **European Biochar Industry Consortium** (EBI) is supporting the development of biochar applications and is a network of many industrial actors connected to biochar production and utilisation. On the international arena the **International Biochar Initiative** (IBI) is a source of extensive information connected to the biochar field.

Project structure

BioCarbUp management and work break down structure and project links and information flow:



BioCarb+:
Enabling the biocarbon value chain for energy,
SFI Metal Production,
FME HighEFF:
Centre for an Energy Efficient and Competitive Industry for the Future,
KPN Reduced CO_2
emissions from metal production,
FME Bio4Fuels

BioCarbUp was to run for four years (2019-2022) and had a total cash budget of 25 million NOK, which was 80% financed by the **Research Council of Norway** through the **ENERGIX** program and 20% financed by the industrial partners.

The BioCarbUp consortium

The project consortium covered all the necessary aspects, and included large and central industrial players in the metallurgical and biomass utilization areas in Norway, complemented by recognized international research institutions.

SINTEF Energy Research led the project and focussed on biocarbon production and upgrading and the value chain for metallurgical industry. **NTNU** (Norwegian University of Science and Technology) supervised the PhD, PostDoc and Master candidates. **SINTEF Industry** focussed on biocarbon end-use and bio-based binder. **NIBIO** (Norwegian Institute of Bioeconomy Research) focussed on biocarbon resources and value chain for metallurgical industry. **University of Hawaii** focused on biocarbon production at pressurised conditions, while **Hungarian Academy of Sciences** focussed on biocarbon and by-products characterization.

The industrial partners contributed with finances as well as access to infrastructure and their extensive industrial knowledge generated through their commercial activities within the metallurgical areas: Elkem, Eramet Norway, Hydro Aluminium, Alcoa Norway, Eyde Cluster, and Norsk Biobrensel as a biomass supplier to metallurgical industry.

The constellation of project partners was very strong, bringing together leading research organisations within the field and major industrial players.

Project overview

The project was divided into 5 subprojects (SP), each subproject was itself divided into several work packages (WP).

- Biocarbon resources and value chain for metallurgical industry - SP1
- Biocarbon production and upgrading - SP2
- Biocarbon end-use - SP3
- Education and training - SP4
- Technology monitoring and dissemination - SP5

Biocarbon resources and value chain for metallurgical industry - SP1

The main objectives of SP1 were to identify optimum forest resources for the specific metallurgical processes, identify shortcomings in existing biomass quality monitoring systems, and increase the expertise throughout the biocarbon value chain for metallurgical industry.
SP1 leader: Senior Scientific Adviser **Simen Gjølsjø**, NIBIO

Biocarbon production and upgrading - SP2

The main objectives of SP2 were to develop novel (new) or improved solutions to produce and upgrade biocarbon dedicated for metallurgical processes with optimized logistics and maximize use of by-products.
SP2 leader: Research Scientist **Liang Wang**, SINTEF Energy Research

Biocarbon end-use - SP3

The main objective of SP3 was to identify biocarbon products that can be used in Mn, Si and Al industry to reduce fossil CO_2 emissions while having neutral or positive impacts on process performance and energy efficiency. SP3 was to develop fundamental competence about effect on specific metallurgical processes of changes in properties of carbon sources. Sources

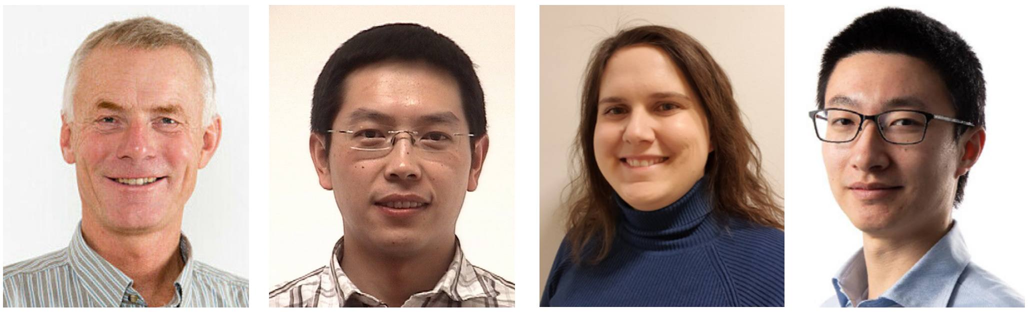
currently in use was to be compared with bio-based carbon sources.
SP3 leader: Research Scientist **Gøril Jahrsengene**, SINTEF Industry

Education and training - SP4

The major objective of SP4 was to strengthen the education within this field through MSc and PhD students, and a postdoc candidate. The objective was also to increase the competence level in the industry. The long-term goal was knowledge building and strengthening of the education within the biocarbon value chain for metallurgical industry.
SP4 leader: Associate Professor **Tian Li**, NTNU

Technology monitoring and dissemination - SP5

The major objectives of SP5 were to monitor the latest research and technological developments and to disseminate research results.
SP5 leader: Chief Scientist **Øyvind Skreiberg**, SINTEF Energy Research, who also was the BioCarbUp project leader



From left: Simen Gjølsjø, Liang Wang, Gøril Jahrsengene and Tian Li

Project achievements

The research activities in BioCarbUp have been centred around the three scientific sub-projects SP1, SP2 and SP3, where key findings are summarised in the following sections.

Biocarbon resources and value chain for metallurgical industry (SP1)

During the last couple of years, new plans for climate, renewable energy and the EU forest strategy for 2030 have been presented. The EU parliament will reduce the consumption of primary wood for energy purposes. This is expected to be implemented in the new Renewable Energy Directive. It is expected that this third version of the directive will be finalized in spring 2023 after negotiations between the EU-parliament, EU-council and EU-commission. Norway is normally following the EU-directives so this directive will have big impact on the harvesting level and on utilizing forest residues (grot).

However, the ambition in Norway is to increase the annual harvesting (Figure 2) to about 15 mill m^3. In Norway it is ongoing discussions regarding CO_2 emissions from soil after harvesting clear-cuts. However, two complementary meta-analyses from Canada show no effects of removing bole-only from clear cuts. In Norway studies are ongoing about C- emissions from harvesting. Today's production of bioenergy and bioenergy products in Norway is approximately 17 TWh, the majority is based on wood, corresponding to some 8-9 million m^3 solid wood. Firewood makes up 6 TWh, by-products used for heating/energy in the wood industry make up about 3.5 TWh and 7.5 TWh goes to district heating, production of biogas or liquid biofuel, and other purposes.

In January-February 2022, a market survey was conducted among suppliers and buyers of energy wood in Norway. 112 companies and other players in the forest-based energy market were sent the survey (attached) with 36 questions. About 50% of these submitted their answers.

The purpose of the market survey was to find out which expectations the market players had for the development in the energy market in terms of price and volume, five and ten years into the future.

The actors who took part in the survey were either energy suppliers, energy buyers, they could operate a combination of these, or

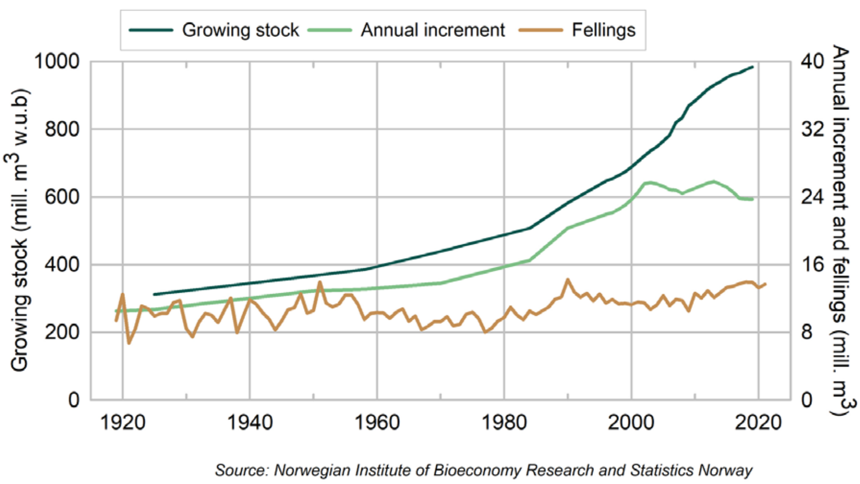


Figure 2. Annual fellings, growing stock and fellings (harvesting) in Norway

they could have other roles in the market. The energy suppliers who participated in the survey accounted for a turnover of approximately 170,000 tons of biomass, corresponding to 0.8 TWh, while those described as both suppliers and buyers had a turnover of 500,000 tons of biomass (2.5 TWh). The buyers of energy wood had a turnover of almost 400,000 tons (2 TWh).

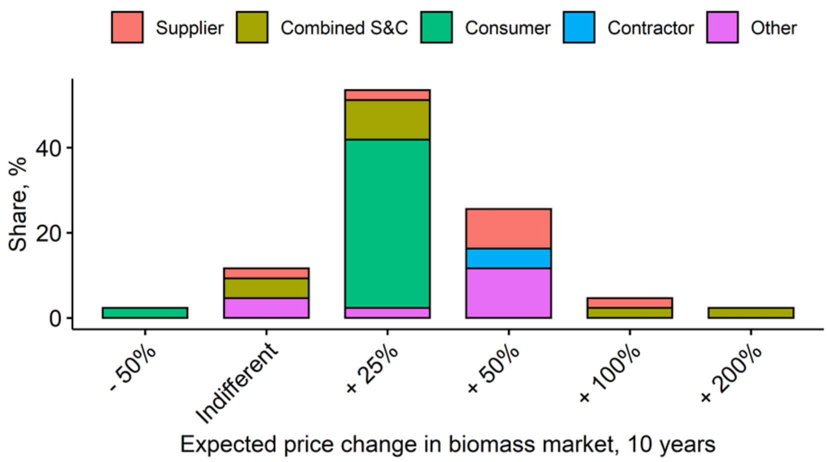


Figure 3. A majority expected growth of 25-50% in both volume and price over the next five years

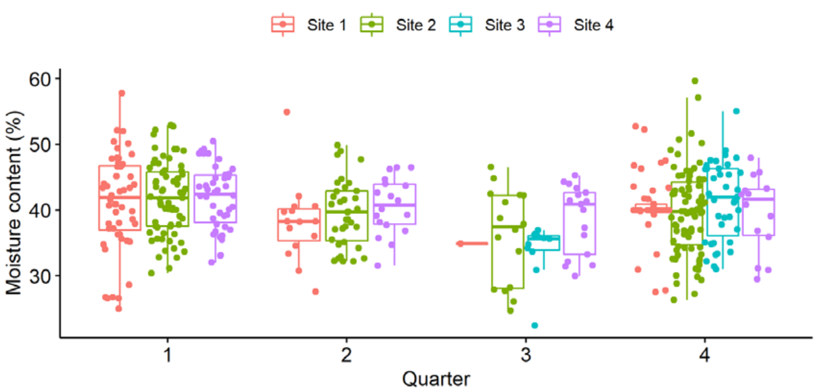


Figure 4. Variation of moisture content in biomass deliveries, grouped in four quarters of the year

A majority expected the biomass market to grow some 25-50% in both volume and price in general over the next 10 years (Figure 3). Regarding their own biomass turnover, the biomass buyers expected to grow 67% in average, while the wood suppliers was expecting an increased volume in the order of 50 - 100% of their current volume.

Most respondents highlighted the resource base of low-grade biomass as one of the more important barriers to a significant increase in the turnover of energy wood. There was nevertheless a contrast between biomass suppliers and buyers when it comes to the ranking of various barriers and bottlenecks for such an expansion of this market.
The end users are most concerned about resource access, while the suppliers are most concerned about the competitiveness of the end products. This may indicate that there is still plenty of wood available, if only the willingness to pay is high enough.

Controlling the moisture content (MC) is sometimes considered crucial in order to tailor the biomass deliveries for various purposes. Even though the MC is important for the efficiency of any conversion process, there is no single ideal MC as this depends on the downstream technology used in the conversion from wood to other products (like heat, power, biochar, cellulose, etc.). Data from biomass quality monitoring and valuing systems illustrates quite well how biomass quality may vary and may relate to environmental and seasonal parameters such as weather and climate, as shown for the MC in Figure 4.

The value chain perspective has been at the core of the BioCarbUp project, and as a part of that a value chain model has been built enabling analysing different value chains with respect to mass and energy balances and assessing their CO_2 footprint. Special focus was directed towards the biocarbon production and upgrading steps to be able to assess the influence of these on the value chain performance. A value chain illustration is included in the handbook cover.

Biocarbon production and upgrading (SP2)

In SP2, one key focus is tuning of traditional carbonization processes to increase the biocarbon (BC) and fixed carbon (fix-C) yields, and to some extent decrease the reactivity (CO_2) and increase the strength of the produced biocarbon. Norwegian spruce and birch wood were pyrolyzed in a laboratory scale reactor at SINTEF Energy Research under different conditions. The experimental results clearly show that both BC and fix-C yields were enhanced for the experiments conducted with reduced inert purge gas flow, constrained flow conditions by a lid covering on the sample bed and staged carbonization as well (Figure **5**(a)). These conditions promote secondary reactions that enhance cracking and recondensation of tarry vapours onto the solid, thereby increasing yields of BC and fix-C. Higher BC and fix-C yields were also obtained by using biomass wood pellets and steam exploded pellets, which have compact structure and much higher density

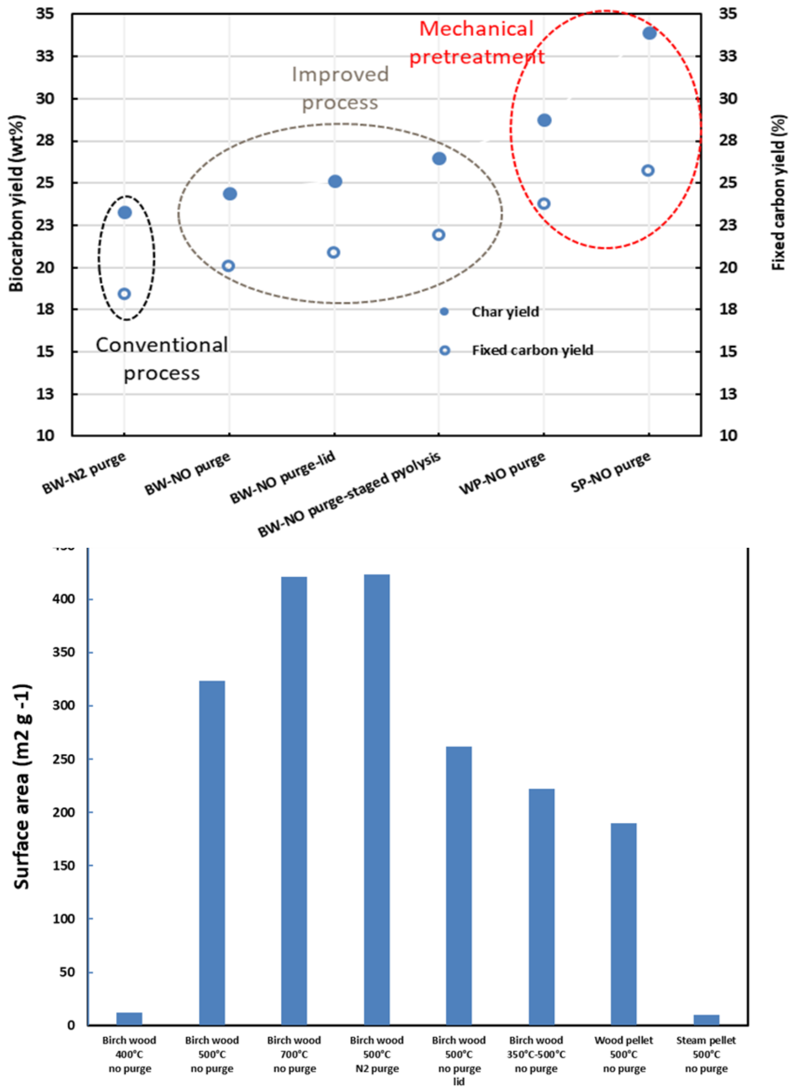


Figure 5. (a) Biocarbon and fix-C yields obtained from carbonization of biomass under different conditions, and (b) BET surface area of the produced biocarbon

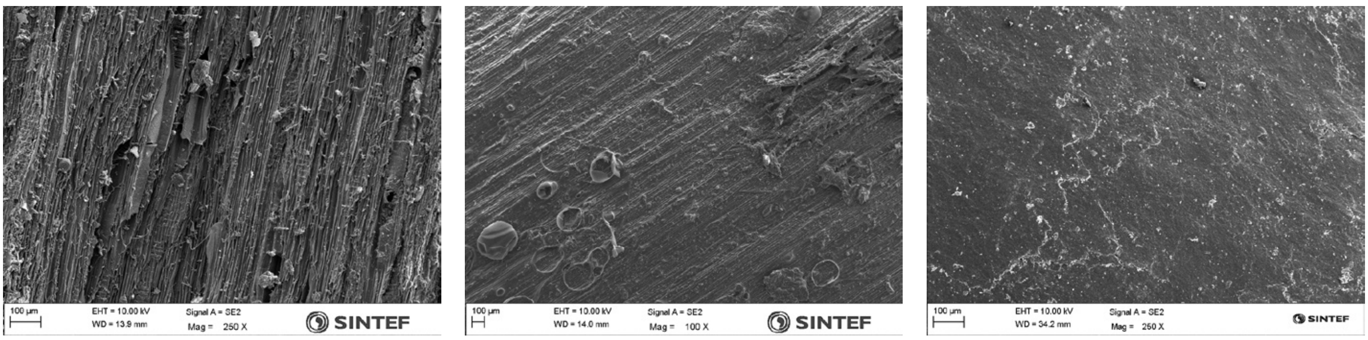


Figure 6. SEM analysis on surface morphology of (a) birch wood biocarbon produced at 500 °C with continuous purging of N_2 gas, (b) birch wood biocarbon produced without purging gas and with a lid covering on sample bed, and (c) biocarbon produced from steam exploded pellet at 500 °C without purging gas

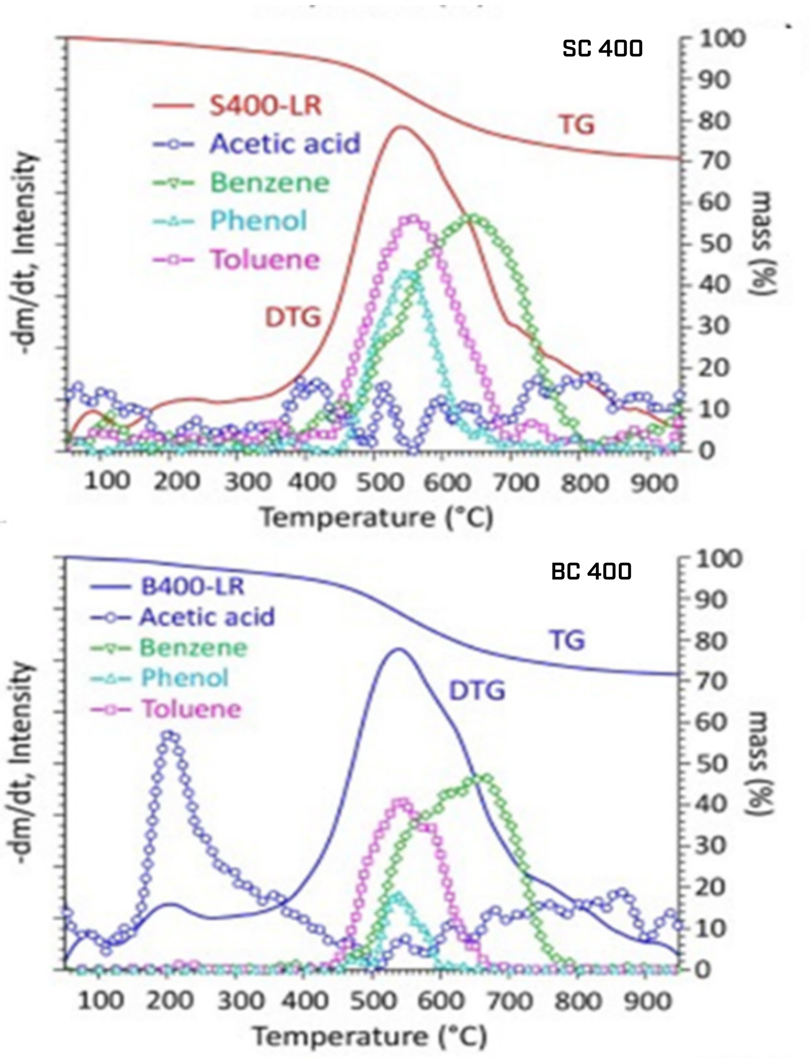


Figure 7. (a) weight loss behaviour and release of volatiles from the spruce (SC 400) and birch biocarbon (BC 400) produced at 400 °C, and (b) Py-GC-MS analysis on main volatile species released from birch biocarbon produced at 400, 500 and 700 °C

than wood chips. Further characterization showed that biocarbons produced under different conditions have considerably different physiochemical properties. Figure **5**(b) summarizes BET surface area of the biocarbons produced in SP2. The analysis results show a dramatic surface area increase for biocarbon produced from birch wood at the highest carbonisation temperature. SEM analysis on the surface morphology of the produced biocarbon agree well with BET analysis results. The birch wood biocarbon produced with continuous N_2 purging has porous structure with many openings and cracks (Figure **6**(a)). Whereas the birch wood biocarbon produced without N_2 purging has compact surface and closed structure (Figure **6**(b)). Figure **6**(c) shows that, in comparison to biocarbon produced from wood chips, the biocarbon produced from the steam exploded pellet has a dense structure and an intact and smooth surface with no openings can be observed.

As used for metallurgical production processes, the amount and type of volatile matter in the biocarbon are of importance. In the BioCarbUp project, the effects of feedstock and carbonization conditions on volatile matter (VM) content and the evolution profiles of volatiles from the biocarbons were characterized by thermogravimetry/mass spectrometry. The composition of volatiles was analysed in detail by pyrolysis–gas chromatography/ mass spectrometry. Figure **7**(a) shows that considerable amounts of acetic acid and aromatic compounds like benzene, toluene and phenol are released from the spruce and birch biocarbon produced at 400 °C. The intensities of the evolved aromatic compounds were higher from spruce biocarbon compared to birch biocarbon. Py-GC/MS analysis results (Figure **7**(b)) show that the major volatile degradation

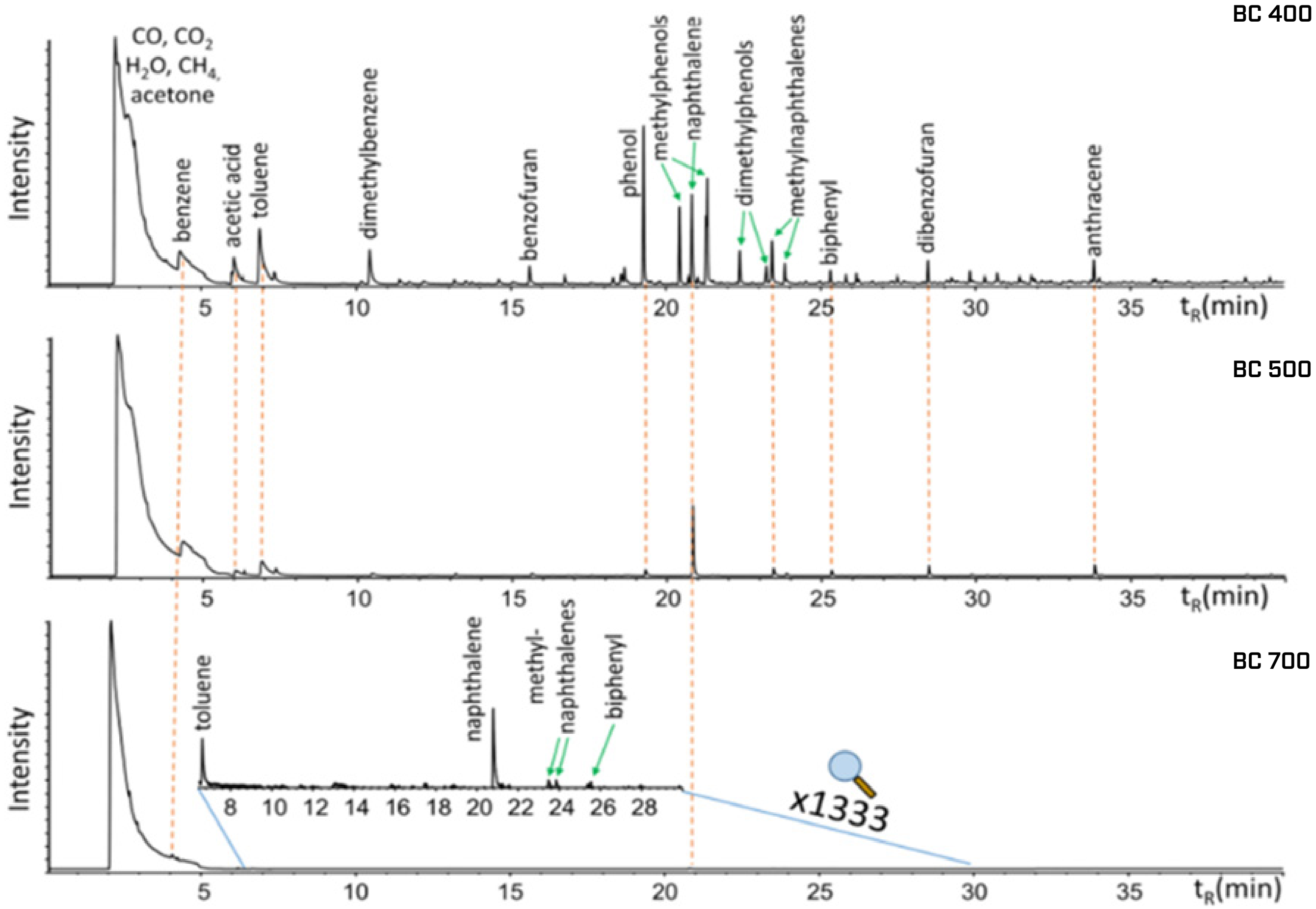


Figure 7. (b) Py-GC-MS analysis on main volatile species released from birch biocarbon produced at 400, 500 and 700 °C

products were carbon dioxide, carbon monoxide, water, methane, benzene, toluene, and naphthalene from each of the produced biocarbons. The relative amount of aromatic and polyaromatic pyrolysis products drastically decreased by increasing the carbonization temperature.

Reactivity is one of most important properties as biocarbon is used for metallurgical applications. In the BioCarbUp project, the reactivities of biocarbons produced under different conditions and from different feedstocks were measured and assessed by conducting macro-TGA experiments in an atmosphere of 50% CO and 50% CO_2 at 1100 °C. Figure **8**(a) shows that biocarbons produced under different conditions have different CO_2 gasification reactivities. The biocarbons produced from wood chips in an atmospheric fixed bed reactor have the highest reactivity. This biocarbon has a porous structure (Figure **8**(b)), especially compared to a carbonized steam exploded pellet (Figure **8**(c)). In addition, SEM-EDS analysis (Figure **9**(a) and (b)) revealed evident migration and transformation of catalytic inorganic elements (i.e., Ca and Mg), which accumulate and agglomerate on the surface of the biocarbon. All these favours the Boudouard reaction and consumption of fixed carbon, explaining the high gasification reactivity of the birch biocarbon (BW 500-P) produced at atmospheric conditions with a slow heating rate and purging of N_2 (Figure **9**(c)). On the contrary, the biocarbon produced from steam exploded pellet has a dense and compact structure, which also contains much less inorganic elements (Figure **9**(d)), and has the lowest gasification reactivity compared to the other studied biocarbons.

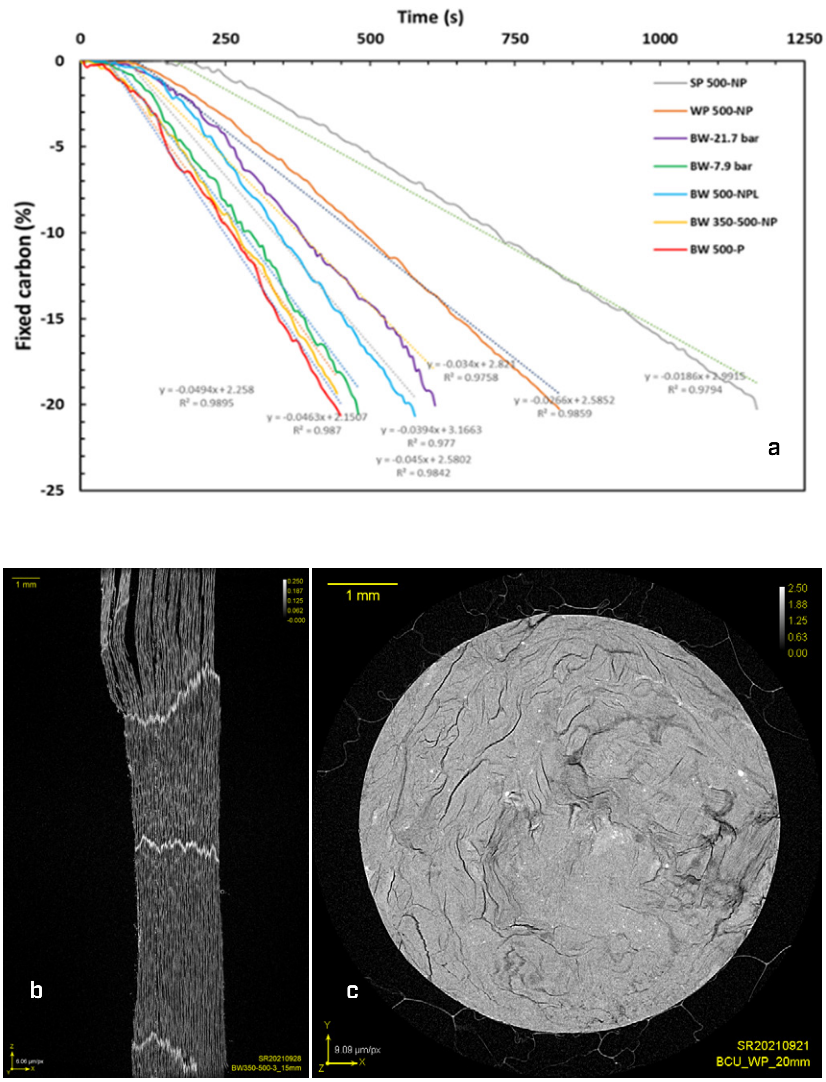
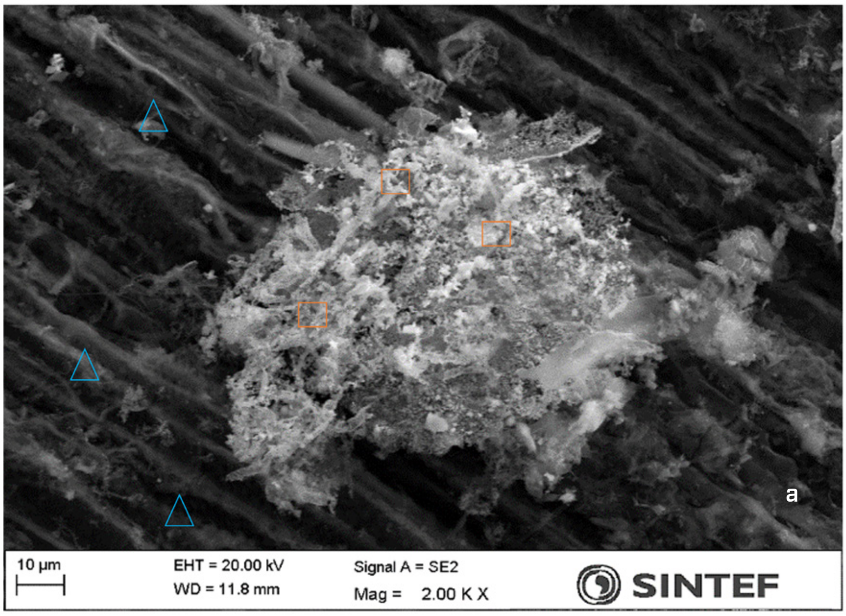


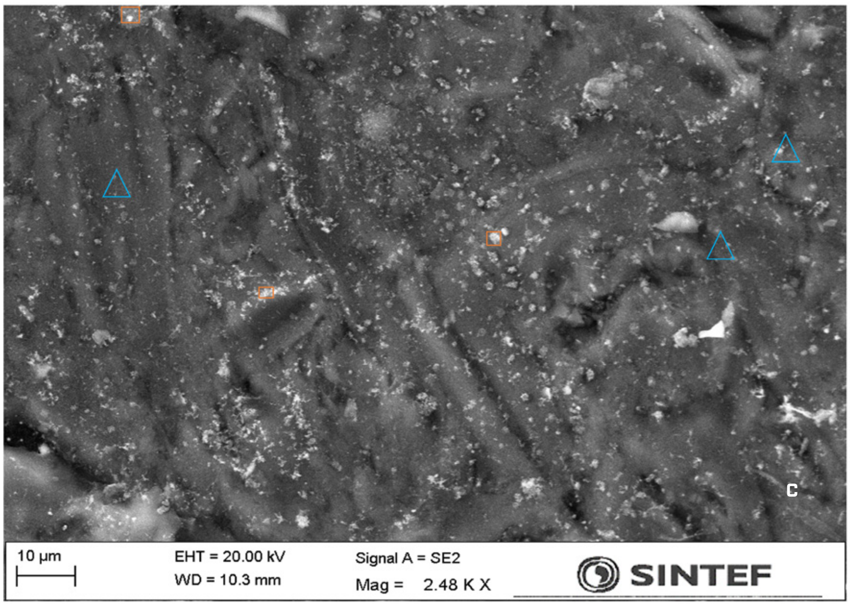
Figure 8. (a) Fix-C loss of biocarbons produced at different conditions and μCT analysis on biocarbon produced from wood chip (b) and steam exploded pellet (c)

Biomass pellets with high bulk and energy density are a promising carbon source for metallurgical production processes. Heat treatment can efficiently reduce the volatile matter content and enhance the carbon content of the pellets. However, mechanical properties of the biomass pellets can be reduced. It is mainly due to partial decomposition of compositions (i.e., lignin) upon heat treatment, resulting in decrease of binding forces between particles. It further limits large-scale utilization of the heat-treated pellets with considering the loss of mass and carbon due to fragmentation and formation of fines during logistics and conversion of them. Mechanical durability and compression strength of both raw and heat-treated pellets were systematically tested (Figure **10**). The biocarbons produced in the BioCarbUp project were also pelletized for improving mechanical strength. In addition, the mechanical properties of partially gasified carbonized pellets were tested. It was found that both the mechanical durability and compression strength of biomass pellets were reduced as they were heat treated. It indicates that the studied biomass pellets lose their capability to withstand cracking or breaking due to crushing force and have higher dusting potential upon heat treatment. Further reduction of mechanical strength of biomass pellets was observed after they underwent severe heat treatment (i.e., higher treatment temperature). The biocarbons produced in the BioCarbUp were pelletized using bio-oil as a binder. Although the biocarbon pellets have promising mechanical durability, they have much lower compressive strength and high potential to break into pieces under given forces. Following studies and tests are needed to identify efficient measures for further improving mechanical properties of the biocarbon pellets.



b

Element (norm.wt%)	Area 1	Area 2
C	11.9	84.4
O	27.6	15.2
Ca	49.7	2.0
Fe	0.8	n.d.
Mg	6.5	n.d.
P	0.6	n.d.
Si	0.3	n.d.
K	0.6	1.4
Mn	0.6	n.d.
Al	1.5	n.d.



d

Element (norm.wt%)	Area 1	Area 2
C	58.88	83.69
O	27.82	14.39
Ca	2.68	0.65
Fe	n.d.	n.d.
Mg	8.69	0.76
P	n.d.	n.d.
Si	n.d.	n.d.
K	0.85	0.51
Mn	1.08	n.d.
Al	n.d.	n.d.

Figure 9. SEM(a,c) and EDS (b,d) analysis of biocarbon produced from birch wood and steam exploded pellet after gasification reactions

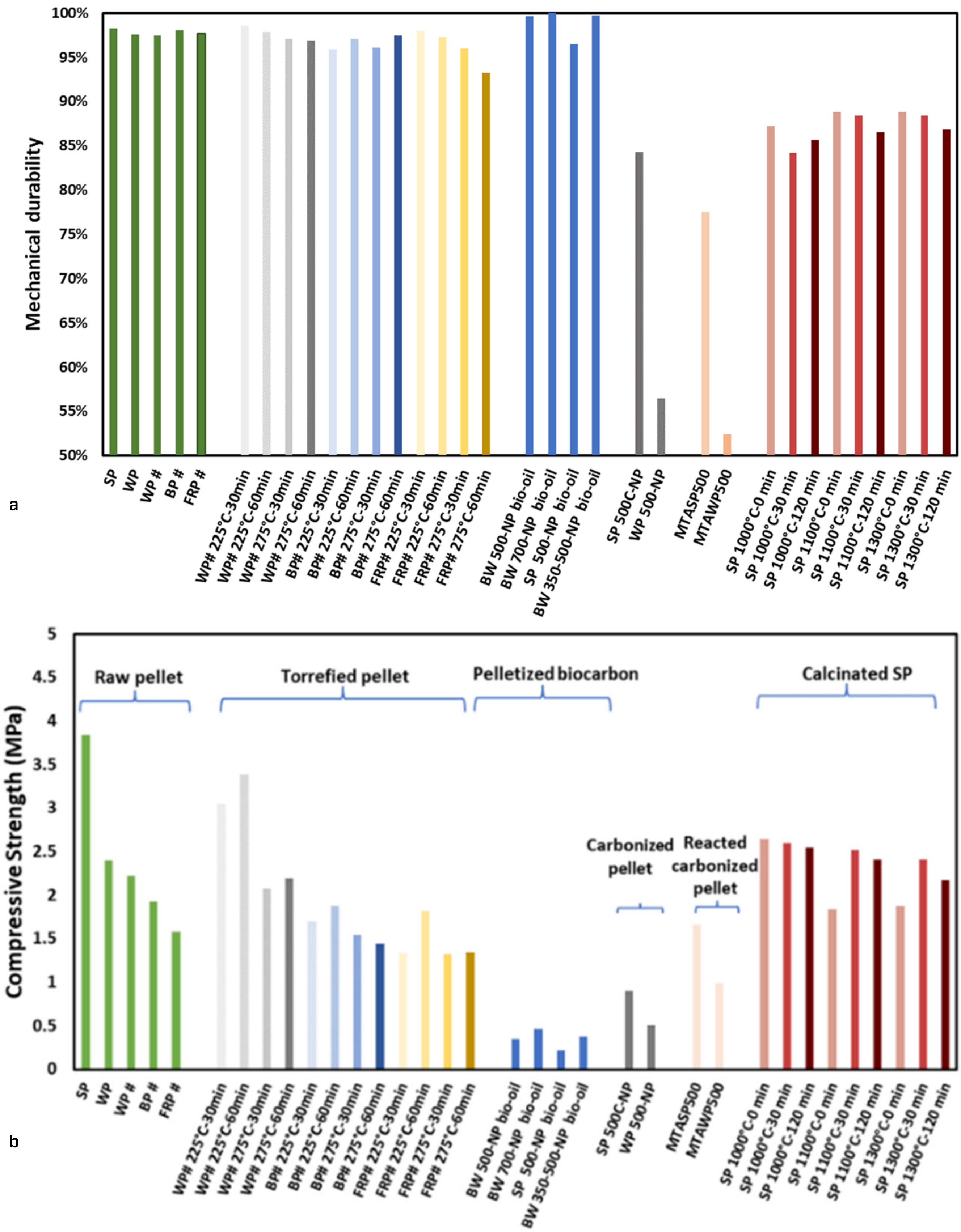


Figure 10. Mechanical durability (a) and compressive strength (b) of biomass pellets, pelletized biocarbon and biomass pellets with different heat treatment

Biocarbon end-use (SP3)

To identify biocarbon products that can be used in metallurgical industries, it has been important to develop **fundamental competence** about the effect on each of the specific metallurgical processes by c**hanging the properties of the carbon sources**. Bio-based carbon sources have been compared with sources currently in use, to best understand these effects, and methods of evaluation have been identified.

Silicon, ferroalloy and aluminium industries have traditionally relied on fossil-based carbon sources, and their processes are tailored to utilize carbon materials with these specific properties. With the introduction of biocarbon to the processes it is important to understand the properties and effects of the materials currently in use, methods to measure **critical parameters**, and evaluate if these needs to be changed when evaluating new materials.

In BioCarbUp, a good overview was given on the properties and measurement methods of critical parameters for all industries, with an in-depth evaluation on the different evaluation methods of CO_2 reactivity relevant for metallurgical industries. Furthermore, an evaluation was done on what effect changing these parameters, e.g., by introducing biocarbon, may have on the process. Finally, it is recognized that each process is so complex and different that it is not possible to have certain testing criteria to decide if a material is useful or not. However, a **strategy on testing** has been proposed in the form of a test matrix (Figure 11). The goal of the matrix is to evaluate the most important parameters first, so that in the case the new material does not meet the critical requirements, it is not investigated further. Strength and dusting have been identified together with the proximate analysis and ash composition to be the first parameters to evaluate. Biocarbons are known to have lower strength and higher dusting potential than traditional materials, which will affect both transport and handling of materials and furnace operation. Biocarbons produced in the project were shown to have similar or improved strength and dusting behaviour than commercial charcoals.

The understanding of the **effect of alkalis** is important in the **FeMn process**. Potassium and other alkalis are introduced to the furnace with the manganese ore, accumulating and circulating in the furnace, introducing negative effects on the smelting operation. Potassium is known to speed up the Boudouard reaction of different cokes, and biocarbons are also more reactive than traditional cokes.

In BioCarbUp, both metallurgical cokes and charcoals have been impregnated with potassium. Materials with different potassium content were investigated in a thermogravimetric apparatus (TGA) in a 50:50 $CO:CO_2$ gas atmosphere, similar to the one in the FeMn furnace. In non-isothermal experiments it was demonstrated that the onset of the reaction was higher for cokes than charcoals, and that potassium reduced the onset temperature for both materials with up to 100 °C. The reaction rate was affected by the potassium content and temperature. Isothermal experiments on charcoal revealed a linear increase in reaction rate with temperature, and increasing the potassium increased the effect of increasing the temperature below 1000 °C, and was higher for charcoals than cokes with similar potassium content. Densification of charcoal through methane deposition increased density and decreased porosity, decreasing the CO_2 reactivity compared to non-densified charcoal. At 1100 °C, the reactivity was found to be in the same area for charcoal, densified charcoal and metallurgical coke when impregnated with >3.5 % K, indicating that at the furnace temperature, independently of carbon material, effect of alkalis will be similar.

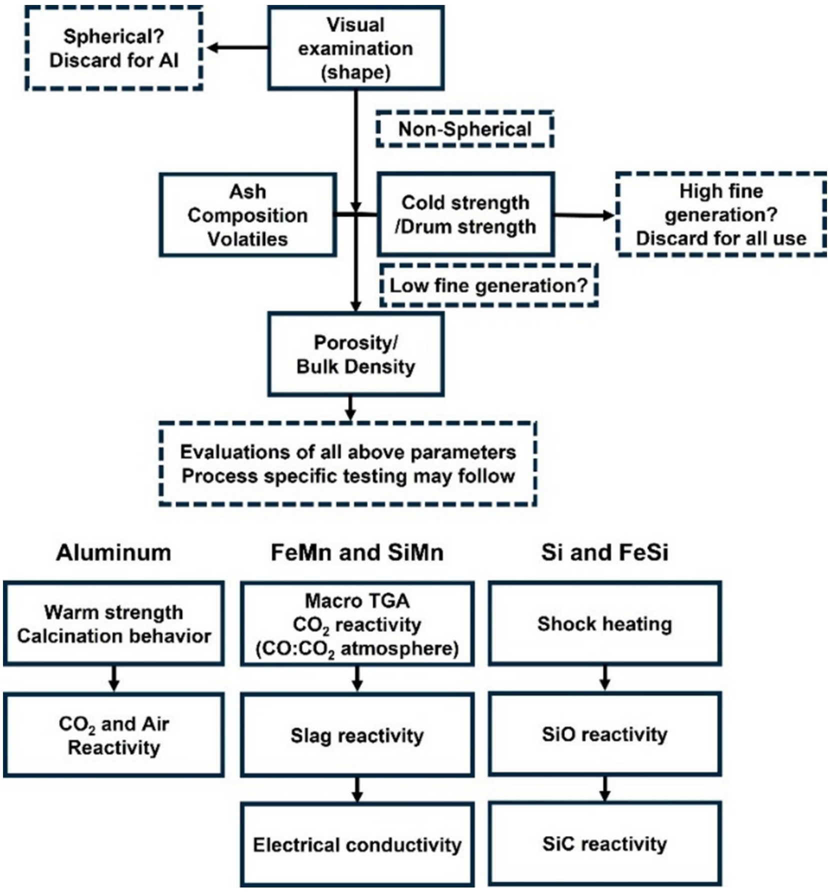


Figure 11. Test matrix to decide if a material is useful or not

During the primary **Si production**, favourable physical and chemical properties of carbon materials is very crucial for an effective transformation of C to SiC. Carbon materials such as charcoal, coal, char, coke, and woodchips are the primary reduction materials for Si production. The preeminent physical properties that requisite for the carbon reductants is higher porosity, higher surface area, thin cell wall thickness, particle size, and desirable bulk density.

In the BioCarbUp project, how these physical properties of different carbon reductants affect on **SiO-reactivity** was investigated. In addition, tried to establish the correlation between SiO - and CO_2 reactivity of the selected carbon sources. Overall smaller particle size will give a higher SiO reactivity and only measurements with same particle size can be compared. Investigated charcoals have higher SiO-reactivity, higher CO_2 reactivity, higher porosity, lower bulk density, and lower cell wall thickness than the investigated coal and char. It was not found any clear correlation between SiO-reactivity and any of the other parameters that can be used to predict SiO-reactivity for all carbon sources. All these properties affect SiO reactivity of the materials, but their interaction with the reactions that take place are too complex to give a clear correlation.

Replacing the coal tar pitch with a bio-based binder type has been identified as the best option in the pre-baked carbon anodes used for the **Al electrolysis process**. Understanding the **interaction between bio-binders and calcined petroleum coke** and what occurs during **baking** is an important aspect of introducing this type of biocarbon in the process.

In BioCarbUp, pyrolysis condensates have been upgraded to binders by heating with a slow heating rate and changing the maximum temperature and holding time at this temperature. By changing these parameters, the produced materials either had excellent interaction with coke by means of **wetting**, some interaction with the coke, or no interaction with the coke. The results were similar independently of the source tree materials and the pyrolysis conditions, and with the appropriate parameters the resulting binders had far better wetting behaviour than traditional materials. Furthermore, upon calcination no significant differences was observed between these and bio-binders produced from commercial biooil, as they all are observed to be amorphous. Anodes are traditionally baked at high temperatures partly to achieve a higher graphitization of the binder phase, making it anisotropic, however, the calcination temperature had little effect on these properties for the bio-binders. The results suggest that, by using bio-binders, energy savings can be introduced in the anode baking process by reducing the mixing and baking temperature.

In BioCarbUp, **micro computed tomography** (μCT) has also been applied to characterize carbons in laboratory experiments simulating the conditions in the respective metallurgical processes. μCT gives a 3D map of atomic densities. Since the method is non-destructive, the very same carbon grains have been investigated before and after the experiments, allowing a deeper understanding of how the carbon transforms in the reactive gas atmosphere. This has been done for all processes in the BioCarbUp project, and includes C-deposition via CH_4, high temperature treatment in argon, CO_2, SiO and K-impregnation.

Education and training (SP4)

Education and training are an important part of a knowledge building project, involving both knowledge transfer to the industry and education of Master students and PhD and PostDoc candidates. In BioCarbUp, the PhD candidate Boyao Wang and the PostDoc candidate Jingyuan Zhang, both from China, contributed to the work in sub-project 2, while the PostDoc candidate Hamideh Kaffash from Iran similarly contributed to sub-project 3. Boyao and Jingyuan were supervised by Professor **Terese Løvås**, and Associate Professor Tian Li who led SP4, and Hamideh by Professor **Merete Tangstad**. Boyao left his position to join the industry, but his work was continued by Jingyuan. Hamideh is now continuing her professional career in the industry. Several Master students have also been connected to BioCarbUp, contributing to different topics through a specialisation project or a Master thesis. In addition, a summer job student has been financed by BioCarbUp for two summers, through the annual SINTEF summer job project. The combined contribution from the students has been invaluable for the project, making it possible to achieve more within the given budget. Finally, annual workshops targeting the BioCarbUp industry partners were arranged, with the purpose of dissemination as well as discussions, benefitting all parties in the project.

Hamideh Kaffash focused her research on biomass densification at the Department of Materials Science and Engineering (MSE), NTNU. Densification of various types of charcoal has been achieved using carbon from methane. The densified charcoals were characterised and analysed systematically. Multiple parameters of charcoals, such as density, porosity, carbon content, and CO_2 reactivity, were investigated. It was found that it is feasible to densify biocarbon and achieve better physical properties using carbon from methane. The densified charcoal also behaves more similarly to metallurgical coke than untreated charcoal in terms of CO_2 reactivity. Through the gaseous impregnation of K_2CO_3, the effect of potassium content on the CO_2 reactivity of densified charcoal and metallurgical coke was further studied. The postdoc worked closely with other researchers and industry partners in the project and provided inputs mainly to SP3.

The main task of Boyao Wang and Jingyuan Zhang at the Department of Energy and Process Engineering (EPT), NTNU, was to develop mathematic models to optimise the production of charcoal with a focus on char yield prediction, and close collaboration between SP4 and SP2 was achieved through this work. The model considers the mass transfer inside the micro-pores of the biomass particle as well as the void between the particles and how it affects the final char yield. A novel coupling method for unresolved CFD-DEM (Computational Fluid Dynamics - Discrete Element Method) modelling has been proposed. Jingyuan will finalise his work in 2023, and several scientific publications on model development have been planned.

Finally, BioCarbUp collaborated with two PhD students, also resulting in several joint publications:

Lorenzo Riva, a PhD student at University of Agder in Norway, who defended his PhD thesis with the title "**Production and application of sustainable metallurgical biochar pellets**" in 2020.

Aekjuthon Phounglamcheik, a PhD student at Luleå University in Sweden, who defended his PhD thesis with the title "**Bio-coal for the Sustainable Industry**" in 2021.

Technology monitoring and dissemination (SP5)

Technology monitoring and dissemination are default activities in a knowledge building project, and in addition to the default state-of-the-art scientific monitoring within the core areas of the project, also more general monitoring in a broader area is carried out, and is also disseminated where appropriate. Dissemination to the general public has been carried out through the BioCarbUp website and through two newsletters per year, as well as through popular science publications. Dissemination to the scientific community has been carried out through scientific presentations at workshops, seminars and conferences, as well as publications in conference proceedings and in international scientific journals. The BioCarbUp industry partners have continuously through the project period been kept informed about project progress and achievements. All in all, extensive dissemination of project results has been carried out, in line with the expectations from the Research Council of Norway for a knowledge building project.

Collaboration with other projects

During the four years of the BioCarbUp project, several parallel projects have been running on connected topics, with direct mutual beneficial collaboration or only information exchange. **KPN Reduced CO_2** led by SINTEF Industry has been the direct collaborating project in BioCarbUp and has contributed significantly to the BioCarbUp output, and several of its industrial partners also participated in BioCarbUp. It enabled maximising outputs and being efficient.

Internationalisation

BioCarbUp has been an international project, having two international research partners and as well both an international PhD candidate and 2 international PostDoc candidates. Extensive dissemination of project results internationally has been carried out, as well as dissemination of international activities to the project partners.

All in all, the combined research and development efforts on the optimisation of the biocarbon value chain for metallurgical industry ensures a strengthening of competence and research capacity, benefitting the metallurgical industry and connected industries throughout the value chains while ensuring a continuous focus on sustainability.

Recommendations

The BioCarbUp project has contributed with knowledge building on a broad range of topics connected to the biocarbon value chain for metallurgical industries. The focus has indeed been on value chains, including from the resource side (the forest, with focus on stem wood) to the end-user side (a metallurgical plant).

On the resource side, to cover all the needs of the metallurgical industry, as well considering future resource limitations due to increasing demands of biomass resources to substitute fossil resources in a wide range of areas, expansion of the resource base is recommended. Such an expansion, to also include lower quality biomass resources, will broaden the biomass resource base, but will also put higher demands on the biocarbon production process, and also on biocarbon upgrading. To abate this, also pretreatment of the biomass could be beneficial, e.g. removal of challenging ash elements.

Biocarbon production has been a central topic in BioCarbUp, especially the possibility to increase the fix-C yield by process control. The key to an increased fix-C yield is restricted carbonisation conditions prolonging the residence time in the pyrolysis process, allowing for increased contact between tarry vapours and the char matrix, leading to secondary char formation on the primary char surface. This can be achieved internally, or by external recirculation of tarry vapours. If carrying out the biocarbon production in a pressurised vessel, the theoretical fix-C yield can be approached, since both residence time and gas concentrations scale linearly with the pressure increase, i.e. a tenfold increase in pressure gives 100 times longer residence time for reactions to occur. If applying a constant volume process, then all tarry vapours can find the time to crack and form secondary char, achieving the theoretical fix-C yield.

At high enough pressure together with given other operating conditions, a molten biocarbon appearance can be achieved, which has proven very beneficial for achieving high strength materials by subsequent compression, and thereby biocarbon qualities closer to the requirements of some metallurgical processes can be reached. Still, scaling up such a pressurised carbonisation process remains to be done.

The tarry vapours can also be condensed and hence provide tars/biooil that can be upgraded to a binder that can replace coal tar pitch (CTP) when baking anodes for use in the Al production process. In BioCarbUp biooil from atmospheric slow pyrolysis was thermally upgraded to produce bio-binder that showed good wetting properties, i.e. good ability to bind coke grains together in the anode baking process. As the composition of the bio-binder is different from CTP, the ability to form fix-C is also different, and in practise lower. Hence, further work is needed to characterise different physicochemical properties of anodes made with biobased binder, assess effects of the use of bio-binder on the anode baking process itself, as well as to optimise the separation and the upgrading of the biooil.

Compaction of biocarbon has been carried out through several approaches in BioCarbUp, showing that the properties of the compacted biocarbon achieves quality enhancements in the direction of satisfying quality requirements. One special and promising way of compaction is the cracking of methane on the surface of the biocarbon, producing a more dense and less reactive biocarbon, with hydrogen as by-product.

By the end of the BioCarbUp project the following general remarks can be provided regarding needs for further work:

1) broadening of the biomass resource base for the specific metallurgical processes, including biomass pretreatment,
2) identifying enhanced biocarbon production processes and scale-up requirements of these to produce optimum yields and qualities,
3) developing methods for upgrading biocarbon and biooil to increase their suitability for the specific metallurgical processes,
4) sustainability assessment of value chain performance of existing and improved metallurgical processes and connected systems for different metallurgical industries in Norway,
5) assessment of the future role of woody biomass for reductants and materials in the Norwegian metallurgical industry within the context of progress towards the UN SDGs,
6) and further increasing expertise throughout the biocarbon value chains for the metallurgical industries

The Research Council of Norway has granted funding for a new knowledge building project on biocarbon for the metallurgical industries, that aims at exactly this.

The industry partners

Norsk Biobrensel

Norsk Biobrensel is a supplier of solid biofuel based on raw material from Norway. The company was founded in 2002 and are today one of the largest bioenergy companies in Norway. The main products are briquettes, animal bedding and wood chips. Key customers for Norsk Biobrensel are large energy companies such as Statkraft, Dong Ørsted and Agder Energi. Sustainability is very important for Norsk Biobrensel and hold, as the only company in Norway (2017), a SBP certificate.

Norsk Biobrensel has since 2004 been a supplier of wood chips to silicon producers in Norway, mainly Elkem. Norsk Biobrensel aim to be a supplier of biocarbon/charcoal in the future based on Norwegian forest resources. In this aspect it was important to take part in BioCarb+ to hence increase the competence and knowhow in this area. In this aspect BioCarb+ has been a success. Norsk Biobrensel is still, together with other companies, aiming for biocarbon production in Norway. Feel free to contact us at www.norbio.no

Elkem

Elkem ASA is one of the world's leading companies for environment-friendly production of silicon-based materials. It consists of three business areas: Silicon Products, Silicones and Carbon Solutions, and has about 6800 employees (2021). The company is a fully integrated producer with operations throughout the silicon value chain from quartz, silicon and downstream silicone specialties, as well as specialty alloys for the foundry industry, carbon products and microsilica. Headquarter is in Oslo, Norway.

Elkem is at the forefront when it comes to understanding the complexities of the silicon alloy process. Elkem's research contributes to safer and more material and energy efficient production. Elkem is committed to ambitious climate targets and continuous improvements, reducing the emission to net zero by 2050. The company endorses the intention of the Paris agreement of limiting the global warming to well below 2 degrees with the target for 2031, with 2020 as a basis:

- Reduce the absolute CO_2 emissions in scope 1 (direct) and scope 2 (indirect) with 28%
- Reduce the product carbon footprint by 39%

Elkem's direct and indirect emission (scope 1 and 2) today amount to 3.3 mt of fossil CO_2 equivalents, which will be reduced by 28% to 2.4 mt by 2031. The majority of Elkem's direct emissions come from its silicon smelters in Europe, mainly in Norway and Iceland. The most important mitigation on medium term is to replace fossil coal with biocarbon produced from sustainable biomass. To tailor make a biocarbon suitable for silicon alloy production Elkem is running systematic research programs. This work has resulted in the building of a pilot plant for biocarbon development and demonstration. Elkem is also involved in several other activities related to R&D on biocarbon, in Norway and other countries around the world. This includes work to develop competitive and sustainable sources of biocarbon as well as longer-term R&D projects.

Eyde Cluster

The Eyde Cluster is the Norwegian Centre of Expertise (NCE) for Sustainable Process Industry, working for the transition towards a sustainable future. The 82 members range from multinational companies delivering high quality materials to a global marked, to regional suppliers, research organizations and education institutes

The Eyde Cluster joined the BioCarbUp project to ensure increased focus on the need for transfer from fossil to renewable carbon sources for the process industry. Transfer to bio-based raw materials is a key factor for the transfer to the low emission society. Contributing to increased knowledge in this field is therefore crucial.

Many of the Eyde Cluster members today depend on fossil sources as raw material or reduction agent. By businesses cooperating in this field we can gain more knowledge in a resource efficient way.

The Eyde Cluster's role is to facilitate knowledge sharing and best practise between companies in this field.

Eramet Norway

Eramet Group, with its more than 13 000 employees on five continents, is the result of the gradual alignment of mining, metallurgy and industrial expertise. More than 140 years of investment, transformation and innovation make Eramet what it is today: a key mining and metallurgy player that is fully committed to an effective and sustainable industry.
The Group is currently accelerating its repositioning as a pure player in mining and metals with a two-folded strategy:

- Grow in metals supporting global economic development: manganese ore & alloys, nickel, and mineral sands
- Develop critical metals and activities for energy transition: lithium, nickel/cobalt salts and battery recycling

Eramet Norway, with its three smelters in Porsgrunn, Sauda and Kvinesdal and an R&D group in Porsgrunn, play a major role in the Group's manganese alloys activities, which also consists of the smelters in Marietta (USA), Dunkerque (France), and Moanda (Gabon). The company is a world-leading producer of refined manganese alloys for the global steel industry and currently has around 550 employees. The vast majority off the world's manganese is used in the production of carbon steel in the form of alloys, thus being an essential material in the green shift. Manganese makes steel stronger, more elastic and wear-resistant. It is widely used in the construction and automotive sectors.

Eramet Norway is today one of the world's most climate and environmentally friendly producers of manganese alloys due to several years of systematic knowledge building,

targeted investments and continuous development of the organisation. This work continues, and the company's roadmap for climate and environment includes ambitious goals and ongoing development projects related to biocarbon, carbon capture, energy efficiency and circular economy.

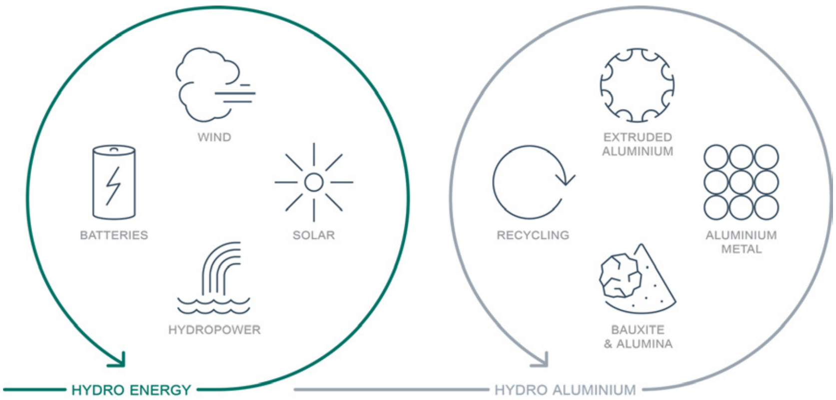
Hydro Aluminium

Hydro is a leading industrial company that builds businesses and partnerships for a more sustainable future. We develop industries that matter to people and society. Since 1905, Hydro has turned natural resources into valuable products for people and businesses, creating a safe and secure workplace for our 31, 000 employees in more than 140 locations and 40 countries. Today, we own and operate various businesses and have investments with a base in sustainable industries. Hydro is through its businesses present in a broad range of market segments for aluminium, energy, metal recycling, renewables and batteries, offering a unique wealth of knowledge and competence.

Hydro is committed to leading the way towards a more sustainable future, creating more viable societies by developing natural resources into products and solutions in innovative and efficient ways. An important part of this work is the potential use of biochar and bio-oil in anode production. The anodes are consumed in the electrolytic cells that produce aluminum and biochar and bio-oil thus will support the goal of becoming carbon neutral by 2050.

Alcoa Norway

Alcoa Norway ANS is a general partnership owned by Alcoa Corporation (**Alcoa-Home**) a company that operates all parts of the aluminum value chain from mining to foundry products. Alcoa Norway ANS operates 2 smelters, Lista and Mosjøen, which together produce about 300,000 yearly MT of primary aluminum. Both plants have integrated foundries that produce high-alloyed special products for the European market. Around 350,000 yMT finished goods are delivered to the European automotive-, building- and packaging- industry. We are Europe's largest producer of can-ends with about 40% market share. The plant in Mosjøen also produces anodes for sister plant Alcoa Fjardaal in Iceland and exports 200,000 yMT of carbon anodes. Alcoa Norway handles a total of 350,000 yMT of coke and pitch products. Our participation in BioCarbUp has thus taught us about the possibilities of replacing parts of this consumption with Biocarbon in a sustainable way. Although Alcoa's main strategy for carbon neutrality is ELYSIS (**ELYSIS | A new era for the aluminium industry**), biocarbon could be part of the transition phase towards 2050, where the ELYSIS™ technology will be carrying the Aluminum production of Alcoa Corp. (**Alcoa - Strategic Long-Term Goals**)



The research partners

SINTEF

SINTEF is one of Europe's largest independent research organisations. Every year we carry out several thousand projects for customers large and small. For more than 70 years, SINTEF has developed solutions and innovation for society and customers all over the world. This is how we have become a world-leading research institute. We deliver innovation by developing knowledge and technologies that are brought into practical use. SINTEF is a broad, multidisciplinary research organisation with international top-level expertise in the fields of technology, the natural sciences, medicine and the social sciences. We conduct contract R&D as a partner for the private and public sectors, and we are one of the largest contract research institutions in Europe. Our vision is Technology for a better society.

NTNU

NTNU is a university with an international focus, with headquarters in Trondheim and campuses in Ålesund and Gjøvik. NTNU has a main profile in science and technology, a variety of programmes of professional study, and great academic breadth that also includes the humanities, social sciences, economics, medicine, health sciences, educational science, architecture, entrepreneurship, art disciplines and artistic activities.

NIBIO

Norwegian Institute of Bioeconomy Research (NIBIO) is subject to the Ministry of Agriculture and Food as an administrative agency with special authorization and its own supervisory board.
The goal of the Institute is to contribute to food security, sustainable resource management, innovation and value creation through research and knowledge production within food, forestry and other biobased industries. NIBIO delivers research, managerial support and knowledge for use in national preparedness, as well as for businesses and the society at large. Approximately 700 employees are present in all parts of the country. The main office is located at Ås in Akershus, just outside Oslo. Forest research in Norway has a long history of providing research data, giving a unique opportunity to answer several central questions regarding the green shift. The Division of Forest and Forest Resources covers most of Norway's land area, and optimal usage of the areas and production potential is crucial when it comes to providing materials, nature value and social benefits which can contribute to new, green value creation in Norway.

Hungarian Academy of Sciences

The Research Centre for Natural Sciences (TTK), the Centre of Excellence of the Hungarian Academy of Sciences carries out multidisciplinary research in the fields of materials- and environmental chemistry, enzymology, organic chemistry, cognitive neuroscience and psychology. The mission of the Institute of Materials and Environmental Chemistry of TTK is to explore new functional and structural materials and related chemical technologies for sustainable environment and sustainable health. Our activities cover the explanation and reduction of environmental impact of human activity and the transformation of renewable energy sources. The Renewable Energy Research Group aims to promote the uptake of renewable energy sources through effective science. Research is conducted in order to understand the fundamental principles governing the conversion of renewable energy in thermal, photo- and electrochemical reactions. During decades of research activity the thermal properties and pyrolysis processes of biomass, synthetic polymers and plastics have been studied in details in our laboratory. Our research activities focus mainly on the thermal and thermocatalytic decomposition of macromolecules, and on the reactions taking place during pretreatment processes.

University of Hawaii

The Hawai'i Natural Energy Institute (HNEI), a research unit of the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawai'i at Mānoa (UHM), conducts research of state and national importance to develop, test, and evaluate novel renewable energy technologies. The Institute leverages its in-house work with public-private partnerships to demonstrate real-world operations and enable integration of emerging technologies into the energy mix. Founded in 1974, HNEI was established in statute in 2007 to address critical State energy needs. Biomass based renewable energy systems have been a core focus of HNEI since its inception.

The Research Council of Norway

The Research Council works to promote renewal and innovation in the public sector, competitiveness and growth in Norwegian trade and industry, through a variety of research funding instruments.

Publications

Scientific papers

Biocarbon Materials in Metallurgical Processes – Investigation of Critical Properties.
Nicholas Smith-Hanssen, Gøril Jahrsengene, Eli Ringdalen. Accepted for publication in proceedings of TMS 2023, 19-23 March, San Diego, USA.

Characterizing Bio-Carbon for Metallurgical Processes Using Micro X-Ray Computed Tomography With High Temperature Experiments.
Stein Rørvik, Nicholas Smith-Hanssen, Sethulakshmy Jayakumari, Liang Wang. Accepted for publication in proceedings of TMS 2023, 19-23 March, San Diego, USA.

Characterization of Liquid Products from Slow Pyrolysis of Woody Biomass.
Liang Wang, Zsuzsanna Czégény, Roman Tschentscher, Øyvind Skreiberg (2022). Chemical Engineering Transactions 96:247-252.

Characterizing Pilot Anodes made with CTP and Bio-Pitch using μCT.
Stein Rørvik, Gøril Jahrsengene, Asem Hussein, Houshang Alamdari (2022). The International Committee for Study of Bauxite, Alumina & Aluminium Conference Proceedings 2022, Volume 51, pp. 955-966.

Investigation of the properties and reactivity of biocarbons at high temperature in mixture of CO/CO_2.
Liang Wang, Øyvind Skreiberg, Nicholas Smith-Hanssen, Sethulakshmy Jayakumari, Gøril Jahrsengene, Stein Rørvik, Scott Turn (2022). Chemical Engineering Transactions 92:697-702.

Effect of calcination temperature and time on properties of steam exploded pellets.
Liang Wang, Lukas Baldauf, Øyvind Skreiberg, Gøril Jahrsengene, Stein Rørvik (2022). Chemical Engineering Transactions 92:355-360.

Effect of varying SiO contents on Si and FeSi production.
Sethulakshmy Jayakumari, Eli Ringdalen (2022). Proceedings of Silicon for the chemical and solar industry XVI, 14-16 June 2022, Trondheim, Norway.

CO_2 Gasification of Densified Biomass: The Influence of K on Reaction Rate.
Hamideh Kaffash, Merete Tangstad (2022). The Journal of The Minerals, Metals & Materials Society.

Bio-Binders and its Carbonization and Interaction with Petroleum Coke during Baking.
Gøril Jahrsengene, Stein Rørvik, Anne Støre, Liang Wang, Øyvind Skreiberg (2022). Light Metals 2022: Electrode Technology for Aluminum Production, pp. 883-889.

A critical review on production, modification and utilization of biochar.
Yanqi Xie, Hailong Li, Lena Johansson Westholm, Lara Carvalho, Liang Wang, Eva Thorin, Zhixin Yu, Xinhai Yu, Øyvind Skreiberg (2022). Journal of Analytical and Applied Pyrolysis 161, 105405.

CO_2 gasification reactivity of char from high-ash biomass.
Aekjuthon Phounglamcheik, Ricardo Vila, Norbert Kienzl, Liang Wang, Ali Hedayati, Markus Broström, Kerstin Ramser, Klas Engvall, Øyvind Skreiberg, Ryan Robinson, Kentaro Umeki (2021). ACS Omega 6, 49, 34115-34128.

Production of Bio-binders from Pyrolysis Condensates and its Interaction with Calcined Petroleum Coke.
Gøril Jahrsengene, Stein Rørvik, Anne Støre, Liang Wang, Øyvind Skreiberg (2021). The International Committee for Study of Bauxite, Alumina & Aluminium Conference Proceedings 2021, Volume 50, pp. 515-524.

Empirical Kinetic Models for the CO_2 Gasification of Biomass Chars. Part 1. Gasification of Wood Chars and Forest Residue Chars.
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2021). ACS Omega 6, 27552–27560.

The effect of densification on compressive strength of charcoal.
Hamideh Kaffash, Merete Tangstad (2021). Proceedings of Infacon XVI: International Ferro-Alloys Congress, 27-29 September, Trondheim, Norway.

Effect of slow pyrolysis conditions on biocarbon yield and properties: Characterization of the volatiles.
Bence Babinszki, Zoltán Sebestyén, Emma Jakab, Luca Kőhalmi, Janos Bozi, Gábor Várhegyi, Liang Wang, Øyvind Skreiberg, Zsuzsanna Czégény (2021). Bioresource Technology 338, 125567.

Densification of Biocarbon and Its Effect on CO_2 Reactivity.
Hamideh Kaffash, Gerrit Ralf Surup, Merete Tangstad (2021). Processes 9, 193.

Considerations on factors affecting biocarbon densification behavior based on a multiparameter model.
Lorenzo Riva, Liang Wang, Giulia Ravenni, Pietro Bartocci, Therese Videm Buø, Øyvind Skreiberg, Francesco Fantozzi, Henrik Kofoed Nielsen (2021). Energy 221, 119893.

Empirical Kinetic Models for the Combustion of Charcoals and Biomasses in the Kinetic Regime.
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2020). Energy & Fuels 34(12):16302-16309.

Effect of Torrefaction on Properties of Pellets Produced from Woody Biomass.
Liang Wang, Lorenzo Riva, Øyvind Skreiberg, Roger Khalil, Pietro Bartocci, Qing Yang, Haiping Yang, Xuebin Wang, Dengyu Chen, Magnus Rudolfsson, Henrik Kofoed Nielsen (2020). Energy & Fuels 34(12):15343-15354.

How to produce green coke?
Pietro Bartocci, Lorenzo Riva, Henrik Kofoed Nielsen, Qing Yang, Haiping Yang, Øyvind Skreiberg, Liang Wang, Giulio Sorbini, Eid Gul, Marco Barbanera, Francesco Fantozzi (2020). Proceedings of 2020 MIT A+B Applied Energy Symposium - e-conference, 13-14 August.

Effects of Pyrolysis Conditions and Feedstocks on the Properties and Gasification Reactivity of Charcoal from Woodchips.
Aekjuthon Phounglamcheik, Liang Wang, Henrik Romar, Norbert Kienzl, Markus Broström, Kerstin Ramser, Øyvind Skreiberg, Kentaro Umeki (2020). Energy & Fuels 34(7):8353-8365.

Charcoal and use of Green Binder for use in Carbon Anodes in the Aluminium Industry.
Camilla Sommerseth, Ove Darell, Bjarte Øye, Anne Støre, Stein Rørvik (2020). Light Metals 2020, The Minerals, Metals & Materials Series, pp. 1338-1347.

Non-isothermal kinetics: Best fitting empirical models instead of model-free methods.
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2019). https://doi.org/10.1007/s10973-019-09162-z.

Analysis of optimal temperature, pressure and binder quantity for the production of biocarbon pellet to be used as a substitute for coke.
Lorenzo Riva, Henrik Kofoed Nielsen, Øyvind Skreiberg, Liang Wang, Pietro Bartocci, Marco Barbanera, Gianni Bidini, Francesco Fantozzi (2019). Applied Energy 256, 113933.

Conference presentations

Pyrolyse for optimal produksjon av biokull og energiutnyttelse.
Øyvind Skreiberg (2022). Bioenergidagene 2022, 21-22 november, Gardermoen.

Investigation of the properties and reactivity of biocarbons at high temperature in a mixture of CO/CO_2.
Liang Wang, Øyvind Skreiberg, Nicholas Smith-Hanssen, Sethulakshmy Jayakumari, Gøril Jahrsengene, Stein Rørvik, Scott Turn (2022). The 28th International Conference on Impact of Fuel Quality on Power Production and the Environment, 19-23 September 2022, Åre, Sweden.

Characterization of biocarbon produced from woody biomass for metallurgical applications.
Liang Wang, Øyvind Skreiberg, Zsuzsanna Czégény, Kentaro Umeki, Stein Rørvik (2022). The 28th International Conference on Impact of Fuel Quality on Power Production and the Environment, 19-23 September 2022, Åre, Sweden.

Investigation of the properties and reactivity of biocarbons at high temperature in mixture of CO/CO_2.
Liang Wang, Øyvind Skreiberg, Nicholas Smith-Hanssen, Sethulakshmy Jayakumari, Gøril Jahrsengene, Stein Rørvik, Scott Turn (2022). IConBM2022, 5-8 June, Naples, Italy.

Effect of calcination temperature and time on properties of steam exploded pellets.
Liang Wang, Lukas Baldauf, Øyvind Skreiberg, Gøril Jahrsengene, Stein Rørvik (2022). IConBM2022, 5-8 June, Naples, Italy.

Investigation of the properties and reactivity of biocarbon at high temperature in mixture of CO/CO_2.
Liang Wang, Øyvind Skreiberg, Nicholas Smith-Hanssen, Stein Rørvik, Sethulakshmy Jayakumari, Gøril Jahrsengene, Yang Zhang, Aekjuthon Phounglamcheik, Kentaro Umeki, Scott Turn (2022). Pyro 2022, 15-20 May, Ghent, Belgium.

A comparative study on the effect of slow pyrolysis temperature on softwood and hardwood pyrolysis products yields and biochar properties.
Liang Wang, Karl Oskar Pires Bjørgen, Maria N.P. Olsen, Zsuzsanna Czégény, Øyvind Skreiberg, Morten Grønli (2022). Pyro 2022, 15-20 May, Ghent, Belgium.

Bio-Binders and its Carbonization and Interaction with Petroleum Coke during Baking.
Gøril Jahrsengene, Stein Rørvik, Anne Støre, Liang Wang, Øyvind Skreiberg (2022). TMS 2022 Annual Meeting & Exhibition, 27 February - 3 March 2022, Anaheim, California, USA.

Constant volume carbonization of biomass: results from an experimental investigation.
Robert Johnson, Christian Castillo, Kyle Castillo, Scott Turn, Liang Wang, Øyvind Skreiberg (2021). The International Chemical Congress of Pacific Basin Societies 2021 (Pacifichem), 16-21 December 2021, online.

The effect of densification on charcoal properties.
Hamideh Kaffash, Merete Tangstad (2021). The effect of densification on charcoal properties. The First Symposium on Carbon Ultimate Utilization Technologies for the Global Environment (CUUTE-1), 14-17 December 2021, Nara, Japan & online.

Study on Densification of Biocarbon for Metal Production Application.
Liang Wang, Lorenzo Riva, Øyvind Skreiberg, Zsuzsanna Czégény, Pietro Bartocci, Henrik Kofoed Nielsen (2021). International Conference on Applied Energy 2021, 29 Nov - 5 Dec, online.

Effect of carbonization conditions on the yield and properties of biocarbon and bio-oil products.
Zsuzsanna Czégény, Bence Babinszki, Zoltán Sebestyén, Emma Jakab, Luca Kőhalmi, Janos Bozi, Liang Wang, Øyvind Skreiberg (2021). International Symposium on Feedstock Recycling of Polymeric Materials (e-ISFR), 29-30 November 2021, online.

Biokarbon verdikjeden for metallurgisk industri.
Øyvind Skreiberg (2021). Bioenergidagene, 22-23 november 2021, Gardermoen.

Production and Characterization of Biochar from Woody Biomass under Different Pyrolysis Conditions.
Liang Wang, Øyvind Skreiberg, Zsuzsanna Czégény, Maria N.P. Olsen, Karl Oskar Pires Bjørgen (2021). 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), 10-15 October 2021, Dubrovnik, Croatia.

Study on Densification of Biocarbon for Metal Production Application.
Liang Wang, Lorenzo Riva, Pietro Bartocci, Zsuzsanna Czégény, Øyvind Skreiberg, Henrik Kofoed Nielsen (2021). 16th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), 10-15 October 2021, Dubrovnik, Croatia.

Effect of pyrolysis conditions and feedstocks on char gasification reactivity.
Aekjuthon Phounglamcheik, Ricardo Vila, Liang Wang, Norbert Kienzl, Markus Broström, Kerstin Ramser, Øyvind Skreiberg, Kentaro Umeki (2021). 7th International Symposium on Gasification and its Applications, 27-30 September 2021, online.

Production and Characterization of Biochar from Woody Biomass under Different Pyrolysis Conditions.
Liang Wang, Øyvind Skreiberg, Zsuzsanna Czégény, Maria N.P. Olsen, Karl Oskar Pires Bjørgen (2021). EUBCE 2021, 26-29 April, online.

Characterization of Liquid By-products from Slow Pyrolysis of Woody Biomass.
Liang Wang, Øyvind Skreiberg, Zsuzsanna Czégény, Roman Tschentscher, Maria N.P. Olsen, Karl Oskar Pires Bjørgen (2021). EUBCE 2021, 26-29 April, online.

Tu[r]ning the pyrolysis process in the direction of satisfying quality demands of metallurgical industries.
Øyvind Skreiberg, Liang Wang, Zsuzsanna Czégény, Scott Turn (2021). ePyro2021, 12-13 April, online.

CFD-DEM modelling of biomass pyrolysis using multi-component kinetics mechanism.
Boyao Wang, Tian Li, Terese Løvås, Liang Wang, Øyvind Skreiberg (2021). ePyro2021, 12-13 April, online.

Effect of slow pyrolysis conditions on biocarbon yield and properties: Characterisation of the volatiles.
Zoltán Sebestyén, Bence Babinszki, Janos Bozi, Emma Jakab, Luca Kőhalmi, Liang Wang, Øyvind Skreiberg, Zsuzsanna Czégény (2021). International Conference on Biotechnology for Sustainable Agriculture, Environment and Health, 4-8 April 2021, Jaipur, Rajasthan, India.

CFD-DEM modeling of biomass pyrolysis in a fixed bed reactor.
Boyao Wang, Jingyuan Zhang, Terese Løvås, Tian Li (2021). 38th International Symposium on Combustion, 24-29 January 2021, Adelaide, Australia.

Biokarbon verdikjeden for metallurgisk industri – Forskningsnytt og -behov.
Øyvind Skreiberg (2021). Norsk Biokullnettverk Fagseminar om biokarbon i Norsk prosessindustri, 21 januar 2021, Arendal.

Densification and CO_2 reactivity of charcoal.
Hamideh Kaffash, Merete Tangstad (2020). Nasjonal konferanse for materialteknologi, 2-3 December 2020, Trondheim, Norway.

Effect of Pyrolysis Conditions and Use of Condensates as Binder on Densification of Biocarbon.
Liang Wang, Lorenzo Riva, Øyvind Skreiberg, Pietro Bartocci, Henrik Kofoed Nielsen, Francesco Fantozzi (2020). 28th European Biomass Conference & Exhibition - e-conference, 6-9 July.

Ulike pyrolyseteknologier og teknikker.
Øyvind Skreiberg (2020). Norsk Biokullnettverk Fagseminar Metallindustri, 17 januar 2020, Trondheim.

Oppsummering og oversikt over relevant forskning i Norge og Norden.
Øyvind Skreiberg (2020). Norsk Biokullnettverk Fagseminar Metallindustri, 17 januar 2020, Trondheim.

Charcoal and use of Green Binder for use in Carbon Anodes in the Aluminium Industry.
Gøril Jahrsengene, Camilla Sommerseth, Ove Darell, Bjarte Øye, Anne Støre, Stein Rørvik (2020). TMS 2020 Annual Meeting & Exhibition, 23-27 February 2020, San Diego, California, USA.

Non-isothermal kinetics: best fitting empirical models instead of model-free methods.
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2019). 2nd Journal of Thermal Analysis and Calorimetry Conference (JTACC), 18-21 June 2019, Budapest, Hungary.

Karbonisering - av hva, og hvordan?
Øyvind Skreiberg (2019). Norsk Biokullnettverk seminar, 17 juni 2019, Oslo.

Comparative study of torrefaction oils of rape straw and black locust waste.
Bence Babinszki, Viktor Terjék, Luca Kőhalmi, Eszter Barta-Rajnai, Zoltán Sebestyén, Zoltán May, Emma Jakab, Zsuzsanna Czégény (2019). 10th International Symposium on Feedstock Recycling of Polymeric Materials (ISFR), 26-29 May 2019, Budapest, Hungary.

Student reports

Biokarbon for metallurgisk industri - utvikling av biobaserte dekkmaterialer for anodebakeovner.
Lukas Baldauf (2021). SINTEF Summer Job Project report. Main supervisor: Liang Wang, Co-supervisor: Øyvind Skreiberg.

Biocarbon for metallurgical industry.
Lukas Baldauf (2020). Biocarbon for metallurgical industry. SINTEF Summer Job Project report. Main supervisor: Liang Wang, Co-supervisor: Øyvind Skreiberg

BioCarbUp in the media

Is it enough wood resources?
Simen Gjølsjø (2022). KPN Reduced CO2 & KPN BioCarbUp webinar, 15 November 2022.

Production of biocarbons - methods, and their relevance for metallurgical industries.
Øyvind Skreiberg (2022). KPN Reduced CO2 & KPN BioCarbUp webinar, 15 November 2022.

BioCarbUp – Optimalisering av biokarbon verdikjeden for en bærekraftig metallurgisk industri.
Øyvind Skreiberg (2019). SINTEF blogg 12 august 2019.

Optimising the biocarbon value chain for a sustainable metallurgical industry.
Øyvind Skreiberg (2019). EERA Bioenergy News 11, June 2019, pp. 7-8.

Publications in progress

Several publications in progress will be listed on the publication page of the BioCarbUp website.

BioCarbUp

Industry partners:

Elkem AS - Department Elkem Technology, Eramet Norway AS, Hydro Aluminium AS, Alcoa Norway ANS, Norsk Biobrensel AS, Eyde Cluster

Research partners:

SINTEF Energy Research, Norwegian University of Science and Technology, SINTEF Industry, Norwegian Institute of Bioeconomy Research, Hawaii Natural Energy Institute at University of Hawaii at Manoa, Hungarian Academy of Sciences

Contact:

Øyvind Skreiberg • Oyvind.Skreiberg@sintef.no
SINTEF Energi AS (SINTEF Energy Research) Trondheim, Norway • www.sintef.no/energy

https://www.sintef.no/projectweb/BioCarbUp