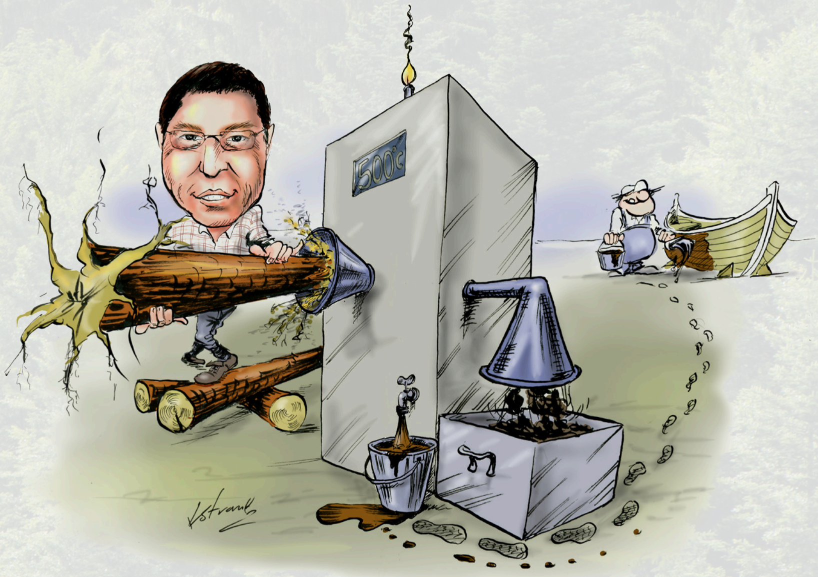
SINTEF

BioCarb+

Enabling the biocarbon value chain for energy



BioCarb+
Enabling the biocarbon value chain for energy

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Background

This handbook is prepared by SINTEF Energy Research with the purpose to provide both partners in the BioCarb+ project, relevant research projects and centres, policy makers and others with a simple and easy to read guide on use of biomass resources for biocarbon production and conversion for industrial applications (reduction agent / metallurgical coke) and conversion for energy purposes.

The information in this handbook is based on studies performed throughout a 4 year period in the competence building project entitled “BioCarb+ – Enabling the biocarbon value chain for energy”.

BioCarb+ is a spin-off project of the CenBio (Bioenergy Innovation Centre) FME (Centres for Environment-friendly Energy Research). It has run for four years (2014-2017) with a total budget of 20 million NOK, whereof 80% financed by the Research Council of Norway through the ENERGIX program and 20% financed by the industrial partners.

The **overall objective** of BioCarb+ has been development of new strategies for use of low-grade biomass, pulpwood and energy wood resources for biocarbon (**BC**) production for raw material for industrial applications (reduction agent / metallurgical coke) and conversion for energy purposes.

The **sub-objectives** were:

- New or improved **biomass harvesting and logistics solutions**, with special attention to forest residues, but also pulpwood and energy wood (including hardwood), and their properties
- New or improved **biocarbon production solutions** through development or improvement of biomass pretreatment methods, biocarbon production processes and applications and biocarbon logistics solutions
- New or improved **biocarbon conversion solutions** through development or improvement of biocarbon conversion applications with focus on high energy efficiency and low emissions, and biocarbon properties for industrial applications
- Efficient **utilisation of by-products from the biocarbon production** process to improve overall economy and improve sustainability (CO_2-footprint) of biocarbon production and utilisation
- **Education** of highly skilled candidates within this area and training of industry partners
- Monitoring of activities and state-of-the-art within this area and **dissemination** of knowledge to the industry partners, and other interested parties where applicable

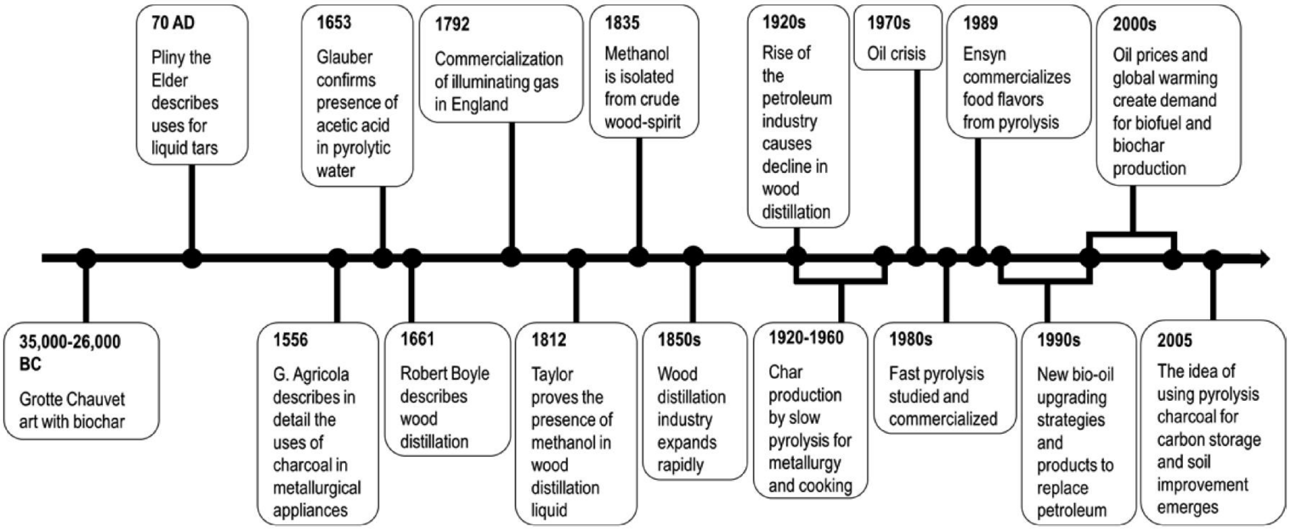
The anticipated results of the project were reduced harvesting and logistics costs for low-grade biomass resources, maximised BC yield and quality in the BC production process and maximised energy efficiency and minimised emissions in the BC end use applications.

BioCarb+ Enabling the biocarbon value chain for energy

Introduction

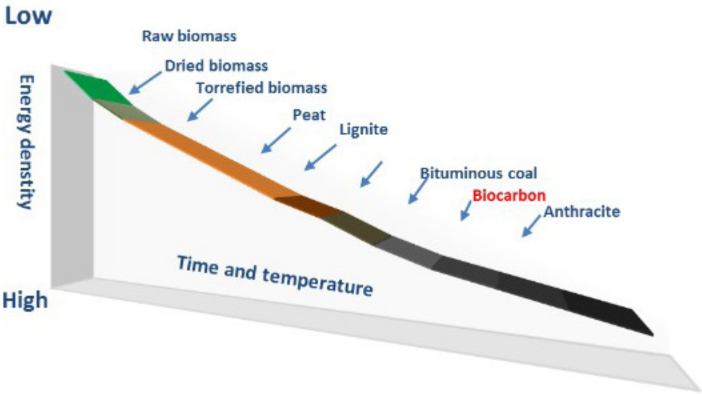
Since the discovery of fire, charcoal (also termed biocarbon) has been used by humans as a multipurpose material, starting as a drawing tool in Grotte Chauvet in year 35 000 – 26 000 BC. Charcoal is in fact the first synthetic material to ever be produced by humans. It is also the only material that was intended to be produced ever since the invention of wood pyrolysis. Charcoal has many advantages over raw wood, an important one is the higher heating value and the associated advantages in combustion properties that it gains relative to its original raw form. For instance, the typical wood fire temperature is below 850 °C while that for charcoal can be as high as 2700 °C. This important property was the reason for the use of charcoal in metallurgical processes for the melting of ores for copper production in the bronze age, in 3000 B.C. Charcoal was also the designated source for energy (cooking and heating) in China’s Tang dynasty in 700 A.D. As the technology was further developed, new by-products such as tars, acetic acid and methanol were finding their useful use as well. The ancient Egyptians, for instance, used liquids from the thermal treatment of wood (tars and other pyroligneous acids) in the embalmment of their dead. The technology for recovering liquids from wood pyrolysis became well developed by the end of the 18th century. This process was further developed in the 19th century by the rise of the ”wood distillation industry” which had the purpose of producing useful by-products in addition to charcoal. This industry, in particular, gained the acknowledgement of being the precursor to the petrochemical industry. However, since the industrial revolution, the use of the cheaper fossil alternatives has caused a decline in the charcoal usage and in technology development. The oil crisis in the 1970s has however forced a revival of interest in the charcoal and by-products development as such products made sure of sustaining a security of energy supply in industrial countries. Also in Europe during World War II, a renewed interest in charcoal made sure that vehicles at that time, still kept moving despite dramatic shortages in gasoline supply. This was possible through the design of engines that operated on wood gas, a mixture of carbon monoxide and hydrogen that was generated through the gasification of charcoal. Throughout history, charcoal have been used for different purposes as briefly mentioned above. A timeline figure showing milestones in the development of the pyrolysis technology is depicted below.

As so many years have been invested in developing the technology for charcoal making, one would think that production has been perfected with no room for further improvements. And yet we have a long term competence building project that still captures the interest of different industry clusters in Norway today. What is it then that still makes charcoal production a challenge today? One reason for this is the heterogeneous properties of biomass that makes producing charcoal with specific properties a challenge. Another reason is the requirements of large chunks of charcoal that makes handling and automation a challenge as well. There are also many parameters



Milestones in the development and use of pyrolysis, J. A. Garcia-Nunez et al., Energy & Fuels, 2017 during the thermal conversion that will have a substantial influence on the end-product properties and by that adding another layer of complexity to producing the ”perfect” charcoal. Also, charcoal today is being used in wide spectre of products requiring different properties depending on the end user. These property variations span across the entire scale of possible variations in the reactivity, porosity, density, strength and many others. So, what is the ”perfect” charcoal? As beauty is in the eye of the beholder, similarly, the perfect charcoal will depend on the eye that is looking at it. Despite all the challenges, charcoal is being widely used in our modern society. The food and agriculture Organisation of the United Nations has estimated that 2.4 billion people are using charcoal as domestic fuel in developing countries. According to the same source, more than 52 million tons of charcoal have been produced globally in 2015. This means that around 260 million tons of wood are being processed yearly for charcoal production, emitting around 1 – 2.4 gigatons of CO_2 equivalent in greenhouse gases in the production and use of charcoal. Producing charcoal in a sustainable manner has therefore a substantial potential for reducing greenhouse gas emissions, which is, currently, the main motivation for using charcoal in our modern society. This leaves a hope that BioCarb+ together with follow-up projects will give a meaningful contribution in exploring the charcoal potential in Norway.

Biocarbon is a product that is made by heating biomass in the absence of oxygen or in lean oxygen to a temperature above 300 °C with a residence time from minutes to days. Owing to release of hydrogen and oxygen in the dehydration and decarboxylation reactions during the production process, the carbon content of the solid biocarbon can be very high (above 90 wt% on an ash-free basis), with only a small content of oxygen and hydrogen. For this reason, regarding elemental composition and chemical bonds and their relative quantity, the chemical structure of the biocarbon more closely resembles high quality coal than products from biomass treated by other thermochemical treatment processes, including torrefaction. It makes biocarbon more attractive for use as an alternative to coal for energy production and also contribute to greenhouse gas emission mitigation. Biocarbon production is a highly promising way for sustainable energy generation and displacing fossil fuel use while combating global climate change at the same time.



Optimisation of the biocarbon value chain is required, i.e. improve harvesting and logistics of biomass resources, develop biocarbon production processes to enhance energy efficiency and biocarbon yield and quality, and convert the biocarbon efficiently for maximising energy yields and minimising emissions.

Charcoal/biocarbon

> The rationale behind BioCarb+ has been that biomass is the carbon source of the future, and an important energy source, and a renewable and climate friendly resource. At the same time the Norwegian biomass potential is far from exhausted, in fact it increases. Biocarbon has many uses and many positive properties, and carbonization is in principle a biomass upgrading method.

Forest resources for biocarbon production

Norway has large forest resources which are far from utilised to its full potential. The annual growth in the forest, of stem wood only, is about 25 million solid m^3. The annual utilisation is only about 10 million solid m^3. Of this the major part is going to the pulp and paper and the sawmill industry. In addition there is a large amount of forest residues that could be harvested, e.g. tops and branches. A shrinking pulp and paper industry in Norway has not led to a decreased forest harvest, but to more wood being exported. If a market for Norwegian biocarbon for e.g. the metallurgical industry could be established, and with a willingness to pay more for the wood than the competitors, then the current export would reduce and more of the annual growth could be harvested.

The forest resources in Norway consist mainly of Norway spruce (45.2 %), pine (29.5 %) and birch (16.0 %) and other hardwoods (9.3 %). The geographical distribution is not even, and the different tree species have different physical and chemical properties, e.g. density and chemical composition. Also the different parts of the trees (stem, bark, top, branches, needles, stump) have different physical and chemical properties. These properties, e.g. the amount of hemicellulose, cellulose and lignin, influence the amount and properties of the biocarbon produced, and this is one aspect to consider when sourcing different tree species for different end uses.

Of the elements in the trees, the amount of carbon and the fraction of this that can form fixed carbon (the carbon left after the volatiles are released), the amount of minor elements that can form emissions (N, S, Cl) and the amount and composition of the ash are important. During biocarbon production, the ash elements will either create emissions (aerosols, fly ash) or stay in the solid product, biocarbon. Depending on e.g. the type of metallurgical industry, there will be quality restrictions with respect to the amount of ash in the biocarbon and its composition.

Key aspects in BioCarb+ on the resource side have been

- Fuel properties influencing biocarbon production and use (for energy and metallurgical purposes)
- Identification, quantification and cost-efficiency aspects of biomass resources in Norway of relevance for biocarbon purposes
- Harvesting and logistics solutions for biomass for biocarbon production

The Norwegian Institute of Bioeconomy Research (NIBIO) has led the work connected to the resource side, and has identified the biomass resources for biocarbon in Norway, while SINTEF Energy Research has studied the influence of fuel properties downstream in the value chain. To assess improvement potentials and connected costs, NIBIO has further carried out analysis and modelling, e.g. connected to harvesting and logistics, showing that **there is significant improvement potential that will contribute to increased efficiency and reduced costs**, which will contribute to optimising the biocarbon value chain.

The key open publications connected to the resource side in BioCarb+ deals with 1) predicting delay factors when chipping wood at forest roadside landings and 2) optimum harvesting and logistics solutions for GROT, stumps, energy wood and pulpwood.

Biocarbon production and upgrading

Biocarbon production started millenniums ago. A vast amount of technologies exist, batch or continuous operated. Some are Stone Age technologies, and their use has serious health and environmental effects. Others are more advanced, but still rather far from optimum. Biocarbon is usually the only product, by-products are then in the best case burned for heat production, in the second best case flared off, or in the worst case just (partly) emitted. The fixed carbon yield (mass of fixed carbon vs mass of dry ash free biomass) is rather low compared to what's theoretically achievable. To become economical attractive and at the same time sustainable, a carbonization technology for production of biocarbon from domestic forest resources and for domestic use in an industrialised country will need to perform beyond what's available today. Integration of the carbonization process with industrial processes can be beneficial.

The biocarbon quality depends on its intended end use, while the **biocarbon yield** depends on a number of feedstock properties and carbonization process parameters, and is not a measure of quality. For use in metallurgical processes, the fixed carbon content (% fixed carbon in the dry biocarbon) is essential, but depending on the metallurgical process, a number of other biocarbon properties are important, even crucial. From an economical point of view the fixed carbon yield should be essential, while **fixed carbon content** is not a measure of carbonization process performance. Approaching the theoretical **fixed carbon yield** (which can be established through an equilibrium calculation) is wanted, i.e. maximising it by optimising the carbonization process parameters and feedstock properties. Carbonization of biomass has a very long history, as do carbonization research, so why have we not come further?

Influencing process parameters are temperature, residence time, inert gas flow rate or amount, heating rate, pressure and the carbonization reactor type/configuration. Influencing feedstock parameters are moisture content, physical properties, e.g. particle size, chemical properties, e.g. lignin content, elemental composition, especially carbon, ash amount and composition, e.g. catalytic elements.

In BioCarb+, after carrying out a state-of-the-art survey of atmospheric and pressurised biocarbon production processes, work has mainly been carried out connected to bench-scale and carbonization reactor experiments.

The properties of the produced biocarbon are also important, including chemical composition, proximate composition, ultimate composition, particle size, particle surface area, particle strength, combustion reactivity, gasification reactivity, reduction agent qualities, transport/handling qualities, moisture uptake, grindability, pelletability/briquetteability and fines generation propensity.

The ultimate goal is the right biomass resource to produce biocarbon with acceptable end use properties, in a sustainable manner.

A large number of carbonization experiments in various analysers and reactors have been carried out in BioCarb+, at SINTEF Energy Research and at Hawaii Natural Energy Institute (HNEI). This includes thermogravimetric analyser (TGA): atmospheric and pressurised (High Pressure-TGA), pressurised flash carbonization reactor (HNEI): lab-scale and demonstration size and constant volume reactor (HNEI). The conditions tested includes temperature, pressure, residence time / inert gas flow rate or amount, heating rate, free or restricted volatiles flow and using different types of biomass.

The biocarbon has been analysed with respect to yield and fixed carbon content, properties, reactivity, conversion stability, emissions and efficiency. E.g. pressurised conditions enhance the fixed carbon yield.

Modelling has also been carried out on thermochemical degradation, combustion reactivity and gasification reactivity. The BioCarb+ PhD candidate, Kathrin Weber, focused her study towards pyrolysis modelling.

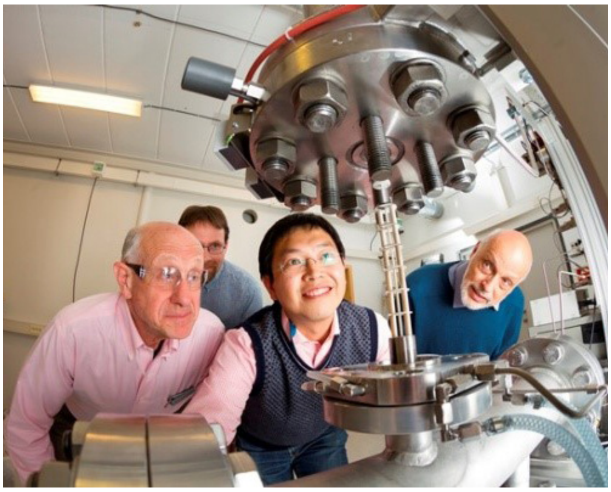
The main message from these works is that the biocarbon yield and quality can be heavily influenced by the choice of carbonization process conditions. Process parameters, e.g. pressure, that enhance the contact time between tarry vapours and the char matrix are key to achieve increased fixed carbon yields and to influence the biocarbon properties.

For some end uses, especially concerning the metallurgical industries, the produced biocarbon will anyway not meet the quality required. In such cases further upgrading of the biocarbon is possible through different processes. The point then is to satisfy minimum quality criteria. This can e.g. involve further heat treatment (calcination) to remove remaining volatiles. As biocarbon can easily be crushed to small particles, biocarbon can also be compressed to pellets and briquettes, using binder or mixing with e.g. sawdust. This enables biocarbon qualities of higher density and potentially strength, and substantially reduced reactivity, e.g. beneficial for Mn production.

Biocarbon has many qualities and areas of use, as a fuel or for other purposes. Biocarbon is in principle the optimum solid biomass fuel. It

- gives the most stable combustion conditions with the least emission variations and can easily and energy efficiently be crushed to small and close to spherical particles
- gives the highest heating value
- gives the highest energy density (mass, and volume when compressed) and bulk density (when compressed)
- gives the highest fixed carbon content
- has a high reactivity
- takes up very little water
- do not degrade bacteriologically during storage
- gives reduced logistics costs when compressed (transport and storage)
- gives reduced bioenergy plant investment needs

Compared to fossil coal biocarbon has lower N, S and metal, e.g. Hg, contents, lower ash content, and last but not least, it is renewables based.



An international team in front of the HP-TGA. From the left: Michael J. Antal, Jr. from Hawaii, assistant BioCarb+ project leader Liang Wang from China and SINTEF and Gabor Varhegyi from Hungary. BioCarb+ project leader Øyvind Skreiberg from Norway and SINTEF in the background.
Photo: Thor Nielsen

Biocarbon conversion and utilisation

The biocarbon can be used as e.g. peak load fuel in existing bioenergy plants, as a substitute fuel for oil boilers, as quality fuel for high efficiency and low emission small-scale heating appliances, and in general for abating operational problems in bioenergy plants. From its properties, biocarbon ranks on top of the solid biomass fuel quality ladder.

Solid biomass fuel quality ladder

1. Carbonized (slow to moderate heating rate pyrolysis)
2. Torrefied (slow and mild pyrolysis)
3. Mechanically upgraded (e.g. pellets, briquettes, powder)
4. Untreated (e.g. dry wood chips, wood logs)
5. Low quality biomass (e.g. wet wood chips, GROT, straw)
6. Waste (e.g. MSW)

In the metallurgical industry biocarbon is a preferred reductant from a properties point of view in the production of e.g. silicon (Si), FeSi, and silicon carbide (SiC), and would also be for manganese (Mn), as SiMn and FeMn, and aluminium (Al), if satisfying certain quality criteria. E.g. Si is used in the solar cell industry for production of solar cell panels. For solar cells one unit biomass energy in, gives around one thousand units of electricity out during the lifetime of a solar cell. This is indirect bioelectricity.

Finally, biocarbon can be used for different other purposes, e.g. as active carbon for cleaning/purification purposes or as soil productivity enhancer.

For all uses of biocarbon there will be optimum biocarbon production conditions that produce the best or the preferred biocarbon quality for the specific use. This optimum can also depend on the properties of the virgin biomass.

The focus in BioCarb+ connected to biocarbon conversion and utilisation has been on biocarbon logistics options, biocarbon products optimisation for secure and cost-efficient logistics, biocarbon conversion applications (for energy and metallurgical purposes), biocarbon combustion and biocarbon gasification (incl. reactivity in metallurgical processes). Energy efficiency, cost-efficiency and environmental aspects of biocarbon conversion applications are key issues, also coupled to the biocarbon value chain.

Regarding biocarbon as a fuel, specific works in BioCarb+ have investigated:

- the combustion kinetics of biocarbon, using very small biocarbon particles in a TGA
- the use of different charcoals in a wood stove
- the use of combined biocarbon and sawdust pellets in a boiler (collaboration with the University of Perugia in Italy)
- techno-economics connected to the biocarbon as fuel value chain

The following conclusions can be drawn from these works:

- Reactivity is no challenge during combustion
- Impurities and minor elements causing emissions can be a challenge, depending on the feedstock properties
- Larger scale combustion as powder is no challenge
- Smaller scale conversion applications are more sensitive to fuel quality variations

GROT is the Norwegian acronym for branches and treetops

- Smaller scale combustion as powder, charcoal, briquettes and pellets demands optimised combustion technologies. CO emissions may be a challenge. Catalytic converters can take care of the CO
- Gasification of charcoal for energy purposes is an option, but maybe the other way around is more interesting, i.e. combustion of biocarbon residues from gasification plants

Regarding biocarbon as a reductant, specific works in BioCarb+ have investigated:

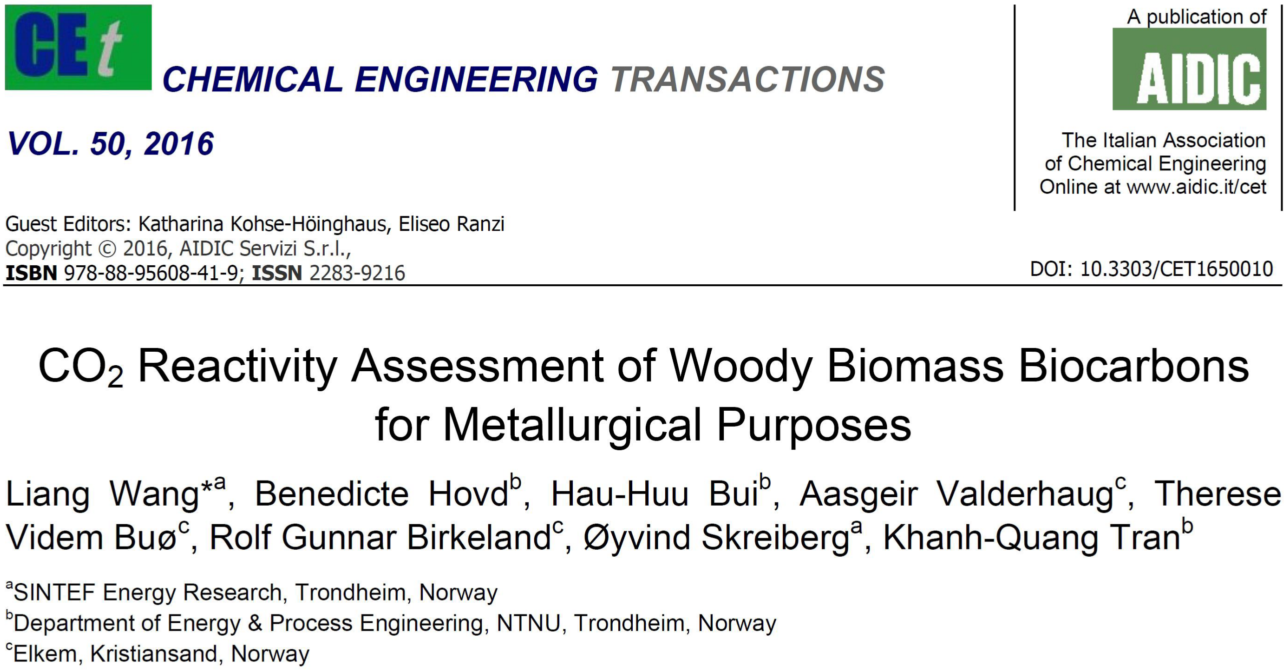
- the CO_2 reactivity of biocarbon produced from various feedstocks and under various carbonization process conditions
- the CO_2 reactivity of upgraded biocarbon
- techno-economics connected to the biocarbon as a reductant value chain

The CO_2 reactivity of biocarbons has been chosen as the main parameter for characterisation of the biocarbon with respect to its end use suitability, even though several other parameters also are important. In BioCarb+ the CO_2 reactivity has been investigated using TGA and a special reactivity test setup in the Elkem Carbon laboratory in Kristiansand. Two SINTEF summer job candidates have carried out the experiments in the Elkem Carbon laboratory, and the first one out, Benedicte Hovd, is now even a PhD candidate on the subject.

The following conclusions can be drawn from these works:

- The feedstock and its properties influence the reactivity, also the presence of catalytic ash elements
- The carbonization process parameters influence the reactivity, e.g. temperature, pressure, heating rate and residence time
- The reactivity can be influenced and reduced by selecting combinations of feedstock properties and carbonization process parameters
- Upgraded biocarbon through compression significantly reduce the reactivity, in addition to help satisfy other quality criteria

To arrive at more specific conclusions regarding the biocarbon qualities suitable for the different metallurgical processes there is a need for testing also in environments more closely resembling the actual metallurgical processes. This can be done in special small-scale furnaces.



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CO_2 Reactivity Assessment of Woody Biomass Biocarbons for Metallurgical Purposes

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A joint publication between research partners, students and the industry partner Elkem

The biocarbon value chain

Biocarbon has many uses and benefits, as fuel, reductant or for other purposes. A main driver for the increased focus on biocarbon today is that it is renewables based and ultimately CO_2 neutral.

The metallurgical industry in Norway is today mainly based on fossil reductants, close to 1 Mton of mainly coal and coke annually, resulting in large (about 3 Mton/year) CO_2 emissions from this industry. About 0.03 Mton of charcoal is used in Si production annually, however, this charcoal is not domestically produced. Hence, the replacement of the fossil reductants with biocarbon would give a large contribution to reducing Norway's CO_2 emissions.

Biocarbon as a fuel also has potential to reduce CO_2 emissions, due to its favourable combustion properties, enabling easier controllable and more stable combustion conditions. This then enable reduced emissions of indirect greenhouse gas forcers and achieving higher efficiencies, i.e. improved fuel utilisation and reduced emissions of climate forcers, including CO_2. A result of the improved fuel quality is the possibility to reduce the complexity of the combustion applications, which has the potential to contribute to reduced plant investments and also reduced upstream emissions of climate forcers.

A biocarbon value chain analysis can become very complex, as there are so many influencing factors and variables involved. The term sustainability, which today becomes increasingly important, covers both environmental, economic and social aspects. In BioCarb+, focus has been on energetic/environmental and economic aspects. Techno-economic analysis has been carried out for biocarbon both as a fuel and as a reductant. In addition simplified value chain analysis has been carried out to assess the sensitivity of the overall performance of the value chain with respect to key parameters of the elements in the value chain.

Obviously, cost-efficiency is key for a commercially based implementation of the different biocarbon value chains. To achieve the necessary cost-efficiency, efforts must be made throughout the value chains to enable biocarbon as an overall sustainable solution. This means a focus on improvements with respect to efficiencies, emissions and costs throughout the value chains.

In BioCarb+ focus has been on the
- forest resource side to improve the efficiency and costs of harvesting and logistics
- possibilities for enhancing the carbonization process, to achieve higher biocarbon and fixed carbon yields and proper utilisation of the by-products tar and gas
- biocarbon logistics and possibilities for reducing loss of biocarbon, e.g. as fines
- biocarbon as a fuel to improve the operation and performance of combustion plants
- biocarbon as a reductant, satisfying the quality demands of the different metallurgical industries, to be used as efficiently as possible in the metallurgical processes

Below examples of biocarbon value chains are shown, showing the energy distribution through the value chain up to final end use for a poor value chain (typically with low yield biocarbon as the only product) and for improved value chains (good: high yield biocarbon and fixed carbon, by-products utilisation, and reduced external energy supply, carbonization plant heat losses and fines generation/losses). With a proper incorporation of economics, value chain analysis becomes a tool to identify where the main bottlenecks are, and the effects of resolving these bottlenecks.

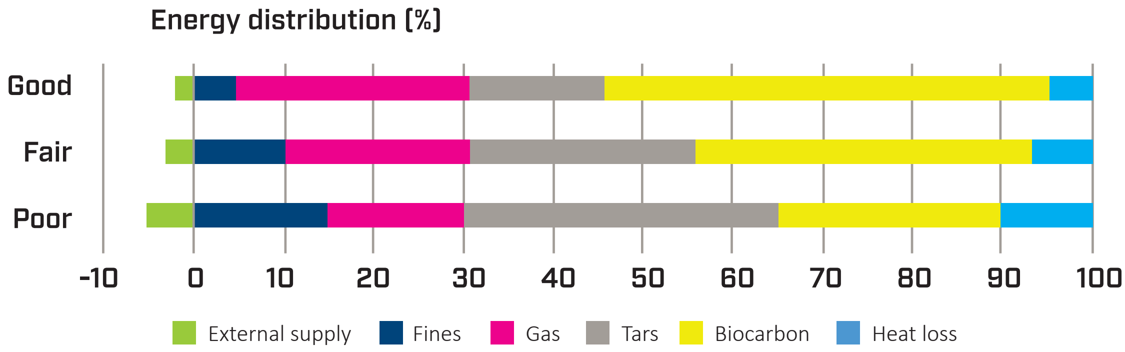

Illustration of different carbonization process and value chain energy performance up to final end use for same feedstock and carbonization temperature. Feedstock drying and carbonization process heat demand to be covered by combustion of by-product(s), to the extent needed.

Recommendations for a successful implementation

Assessing the sustainability of the biocarbon value chain for energy purposes and as a reductant in metallurgical processes and providing recommendations based on this is a huge task. The work carried out in BioCarb+ has made it possible to reflect on this, but not to give final answers. In principle we are talking about three main value chains: 1) Forest biomass to energy, 2) Forest biomass to metallurgical industry without biocarbon upgrading and 3) Forest biomass to metallurgical industry with biocarbon upgrading. Within these there will in principle be numerous variants possible.

For all the elements in the value chain, from the resource side to the end use, choices need to be made, e.g. regarding the biomass resource to use, the harvesting of it, the further handling of it (e.g. chipping at roadside or not), its transport (e.g. for how far), pre-drying to some degree or not, the choice of carbonization process localisation and possible integration, the choice of carbonization process and process conditions (to reach e.g. specific yields and composition of biocarbon, tar and gas), the maximum utilisation of the by-products (tar, gas), the handling and transport of the biocarbon (e.g. minimising fines generation), the potential need for upgrading the biocarbon to meet specific quality criteria and finally the end use of the biocarbon (as efficiently as possible). In all of these stages there are a number of variables to consider, and where the choice influences the downstream elements in the value chain.

On the previous page, simplified value chain examples were shown, with respect to the energy distribution and indirectly efficiency through the value chain. This can be expanded further to look at direct CO_2 emissions, and even further by including other climate forcers. Then economics could be included. In a Norwegian context the latter becomes especially important, as e.g. the labour cost is high. Biocarbon has been produced for millenniums. From a Norwegian perspective, it then becomes crucial to lift the value chain to a new level that can enable sustainable biocarbon production in Norway, based on Norwegian forest resources, and for end uses in Norway.

Regarding recommendations, **the most important recommendation is simply to start with the end user if this already exists and has certain quality criteria.** Then you know what's expected from the carbonization process and which type of biomass that is best suited,

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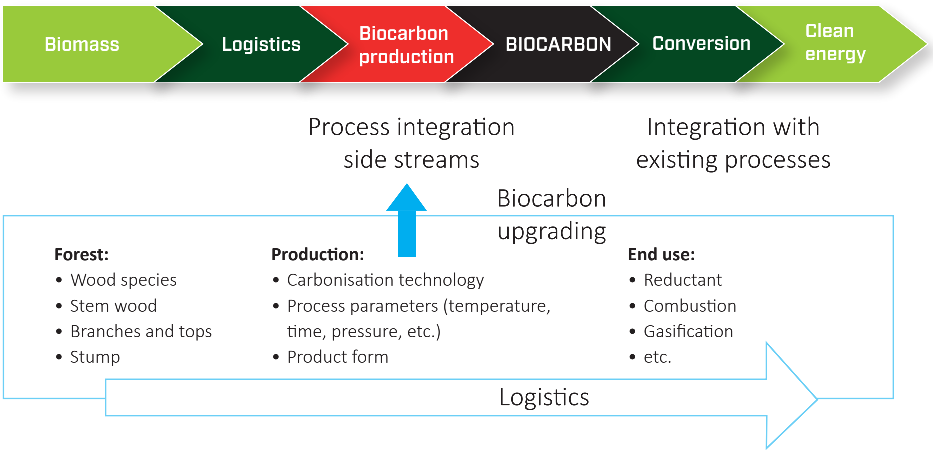


and if there anyway is a need for upgrading of the biocarbon. After that value chain optimisation is key, and this is a considerable but very important task.

For any value chain it becomes crucial in the end to optimise it based on a set of unique parameters for that specific value chain. The Norwegian process industry, which includes the metallurgical industry, has the ambitious goal of growth while becoming CO_2 neutral by 2050. Then the optimisation of the biocarbon value chain for the metallurgical industry, building on the extensive and broad work carried out in BioCarb+, in a follow-up project is recommended.

Partner description - 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**

Partner description - AT Skog

AT Skog is owned by nearly all the family forest owners in Agder and Telemark. The forest owners realised 100 years ago that they would be stronger together. By offering the timber from single entities through a joint enterprise, the forest owners could negotiate better terms. AT Skog has a genuine feel for the forest, the region and the people. The name says it, we are here for the forest owners- and we will continue to be! AT Skog is committed to its forest owners, which is shown through our actions. AT Skog participates in the whole value chain, from seed to industry. This engagement can be seen through our local presence, innovation, development and our traditions in a long term perspective through environmentally friendly and sustainable forestry.

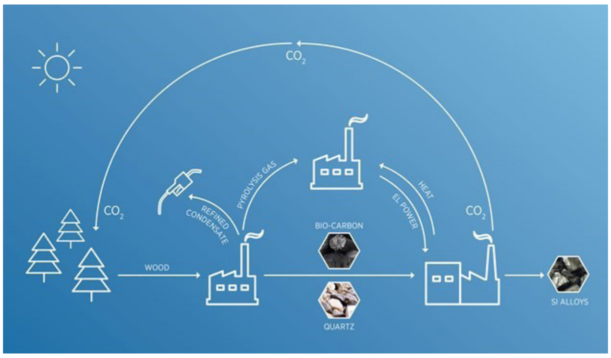
Partner description - Elkem

Elkem is one of the world's leading providers of silicon-related advanced materials. 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. Headquartered in Norway, Elkem has a strong global footprint, with approximately 3800 employees, 24 production plants, two research centres and sales offices in over 50 countries. Elkem is owned by China National Bluestar.

By replacing fossil coal with biocarbon as chemical reduction agents in our production process, Elkem will take a significant step towards our goal of cutting 40 per cent of our CO_2 emissions by 2030 and, ultimately, towards our long-term goal: carbon neutral production of silicon and ferrosilicon.

By replacing fossil coal with charcoal produced from sustainable biomass, the production processes could become carbon neutral. Studies have shown that charcoal (and woodchips) can perform even better in the chemical reaction than fossil coal and at the same time reduce our carbon footprint.

In 2015, Elkem initiated a research programme called Carbon Neutral Metal Production (CNMP). The concept of CNMP was to produce charcoal in the same production facility as ferrosilicon or silicon production, connecting this to an energy recovery unit to produce electricity from the excess heat. In an optimal situation



with 100% biocarbon use and optimal energy recovery, such a plant would become both CO_2 and energy neutral, delivering enough electricity to run the electric arc furnaces. The concept would thus integrate the forest industry with metal production, producing new, circular value chains. The initial R&D project of the CNMP programme was funded by the Research Council of Norway and concluded that with existing furnace technology, we can reduce energy consumption by over 50 per cent with considerable reduction of fossil CO_2 emissions. In 2017, Elkem successfully received funds from by the Norwegian Research Council for initiating a new biocarbon related research project: Pyrolysis of wood optimised for production of energy and tailor-made biochar for silicon production (PyrOpt). PyrOpt is looking into pyrolysis of wood optimised for production of energy and tailor-made biochar for silicon production. The project is a collaboration with SINTEF Energy Research and RISE PFI. This project looks at resource-effective production of high quality charcoal. Elkem's long-term goal is that charcoal will replace fossil coal in the production of speciality silicon as well as standard silicon and ferrosilicon production.

Partner description - Eyde Cluster

The Eyde Cluster consists of 15 large process industry companies and 30 competence suppliers. The goal of the cluster is to strengthen the competitiveness of the companies within the limits of the Paris agreement by focussing on resource efficiency and development of sustainable solutions on the basis of circular economy. The Eyde cluster shall maintain the innovation culture in the companies to ensure the Norwegian process industry maintains its leading position based on the goals set by the "Process Industry Roadmap – increased growth with zero emissions in 2050". By cooperating on innovation, co-development of human resources and development of new business concepts the Eyde cluster will contribute to increased competitiveness for businesses in the low emission society, strengthen the value chains and contribute to developing world class technology.

The Eyde-cluster joined the BioCarb+ 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 crucial 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.

BioCarb+ and other projects with focus on bio-based materials is headed by Eyde innovation Centre (EIC), an umbrella which acts as the research and project hub of the cluster. Projects range from regional exchange of "best practice" to international research projects. Projects are initiated in industrial focus groups that are made up of company members according to topics of relevance. These projects are then developed further via the Eyde Innovation Centre in cooperation with complementary external research and innovation partners. The Eyde Innovation Centre, through its members, manages extensive research and innovation structures such as piloting centre ranging from lab to industrial scale. This has led to one of Norway's two first Catapult centres, named FutureMat Catapult for Future Materials. The accumulated knowhow in this field provides the platform for the efficient development of new material solutions in the cluster.

A work session in the Eyde Cluster offices

Partner description - Eramet Norway

Eramet Norway is one of the world's most efficient manufacturers of manganese alloys, whether that efficiency is measured in costs per produced tonne or in terms of climate and the environment. Eramet Norway is a part of the French mining and metallurgy group, ERAMET. ERAMET is a world leader in alloying metals, particularly manganese and nickel, and in high-quality metallurgy. Eramet Norway is part of the ERAMET manganese business with processing plants at Sauda, Kvinesdal and Porsgrunn, and an R&D group in Trondheim.

ERAMET is the world's second largest producer of manganese ore and manganese alloys and the world's leading producer of refined manganese alloys. The company concentrates its business around mining and metallurgical industry and is a large international player within the three business areas manganese, nickel and special steels. Eramet Norway realised early on that environmentally sustainable onshore industry is the way of the future for Norway. Since ERAMET acquired the processing plants in Norway in 1999 (Porsgrunn and Sauda) and 2008 (Kvinesdal), about half a billion Norwegian kroner has been spent on developing and adopting green technology. Today, Eramet Norway can proudly boast that we operate the world's cleanest manganese alloy production facilities.

Around 90% of world manganese is used for the production of carbon steel in the form of alloys. Manganese makes steel harder, more elastic and more wear-resistant. It is widely used in the construction and automotive sectors. The chemical industry, that account for approximately 10% of the manganese, utilises the metal for applications such as in batteries, fertiliser and paint pigments. The ERAMET group employs about 13 000 people in 19 different countries, of which around 500 are employed at Eramet Norway.

Partner description - Saint Gobain Ceramic Materials

SAINT-GOBAIN

Saint-Gobain is clearly established as the worldwide leader in the business of silicon carbide (SiC) grains and powders. At the heart of industry, we pride ourselves in serving many customers, leaders in their own segment, across the world, through long-term, trust-based relationships. Our industrial expertise relies on a century-old tradition inherited from the entities such as Norton, Carborundum, Casil, and Mountain Abrasives. In recent years, we have streamlined and improved our processes to better serve our customers in applications such as metallurgy, refractories, and abrasives. Moreover, we have successfully launched new products for emerging applications in the field of electronics, passive armor, and energy-efficient or emissions-control technologies. Our customers typically value our support over time through the experience our committed professionals strive to offer- Reliability of Supply, Consistency of Quality, Innovation in conjunction with our customers (Co-Development), Respect of Confidentiality for each customer, Local presence combined with global excellence standards.

Saint-Gobain Ceramic Materials AS, located in Lillesand and Eydehavn produce approximately 20 000 tons of silicon carbide (SiC) each year and supply our customers with approximately 200 different material qualities. Our main silicon carbide R&D effort takes place in Lillesand where we also have the capability to produce tail-or-made SiC material based on specific customer needs – including small scale test batches for various new applications.

Partner description - Alcoa Norway

ALCOA

Since the dawn of the aluminium industry, the name Alcoa has been synonymous with operational excellence and leadership in the production of Bauxite, Alumina and Aluminium products. We invented the aluminium industry in 1888 and we continue to innovate with new technologies and processes- World's largest bauxite mining portfolio, An attractive global alumina refining system, Optimised aluminium smelting network, Innovative cast products network, Flexible energy portfolio, Maximising synergies between can sheet and other Alcoa markets.

In today's aluminium market, where lean operation is critical, our comprehensive portfolio of assets and our operating experience make Alcoa uniquely built to lead. We are known worldwide as a values-based company that holds to the highest standards of excellence–operational, environmental, and ethical—as essential for our business. We never stop looking for ways to be more productive, efficient, innovative and sustainable in order to deliver the best products and outcomes to our customers and shareholders.

Alcoa was established in Norway in 1962 through a cooperation with Elkem. Together they operated two plants, in Lista and Mosjøen. Today these plants are 100% owned by Alcoa. Through modern casting technology and pure electrolysis metal, Alcoa is supplying Europe with quality aluminium products.

Publications

Journal publications

Properties of biochar.
Kathrin Weber, Peter Quicker. Accepted for publication in Fuel.

CO_2 Gasification of Chars Prepared by Fast and Slow Pyrolysis from Wood and Forest Residue. A Kinetic Study.
Liang Wang, Tian Li, Gabor Varhegyi, Øyvind Skreiberg, Terese Løvås. Accepted for publication in Energy & Fuels.

Carbonization of biomass in constant-volume reactors.
Maider Legarra, Trevor Morgan, Scott Turn, Liang Wang, Øyvind Skreiberg, Michael Jerry Antal, Jr. Accepted for publication in Energy & Fuels.

Towards a meaningful non-isothermal kinetics for biomass materials and other complex organic samples.
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg. Accepted for publication in Journal of Thermal Analysis and Calorimetry.

Techno-economics of biocarbon production processes under Norwegian conditions.
Maciej Olszewski, Rajesh S. Kempegowda, Øyvind Skreiberg, Liang Wang, Terese Løvås. Accepted for publication in Energy & Fuels.

Performance evaluation of a modern wood stove using charcoal.
Alexis Sevault, Roger Khalil, Bjørn Christian Enger, Øyvind Skreiberg, Franziska Goile, Liang Wang, Morten Seljeskog, Rajesh Kempegowda. Accepted for publication in Energy Procedia.

Study of CO_2 gasification reactivity of biocarbon produced at different conditions.
Liang Wang, Przmeysław Maziarka, Øyvind Skreiberg, Terese Løvås, Mariusz Wądrzyk, Alexis Sevault. Accepted for publication in Energy Procedia.

Effect of carbonization conditions on CO_2 gasification reactivity of biocarbon.
Liang Wang, Nicolai Alsaker, Øyvind Skreiberg, Benedicte Hovd. Accepted for publication in Energy Procedia.

Effect of torrefaction on physiochemical characteristics and grindability of stem wood, stump and bark.
L. Wang, E. Barta-Rajnai, Ø. Skreiberg, R. Khalil, Z. Czégény, E. Jakab, Zs. Barta, M. Grønli. Accepted for publication in Applied Energy (Co-publication with GAFT).

Comparative study on the thermal behavior of untreated and various torrefied bark, stem wood, and stump of Norway spruce.
E. Barta-Rajnai, L. Wang, Z. Sebestyén, Z. Barta, R. Khalil, Ø. Skreiberg, M. Grønli, E. Jakab, Z. Czégény (2017). Applied Energy 204: 1043-1054. (Co-publication with GAFT).

Thermal Decomposition Kinetics of Wood and Bark and their Torrefied Products.
Eszter Barta-Rajnai, Gábor Várhegyi, Liang Wang, Øyvind Skreiberg, Morten Grønli, Zsuzsanna Czégény (2017). Energy & Fuels 31(4):4024-4034. (Co-publication with GAFT).

Stochastic reactor modeling of biomass pyrolysis and gasification.
K. Weber, T. Li, T. Løvås, C. Perlman, L. Seidel, F. Mauss (2017). Journal of Analytical and Applied Pyrolysis 124:592-601.

Experimental Study on Charcoal Production from Woody Biomass.
Liang Wang, Øyvind Skreiberg, Sam Van Wesenbeeck, Morten Grønli, Michael Jerry Antal, Jr. (2016). Energy & Fuels 30(10):7994-8008.

A kinetic study on simultaneously boosting the mass and fixed-carbon yield of charcoal production via atmospheric carbonization.
Maria Zabalo Alonso, Khanh-Quang Tran, Liang Wang, Øyvind Skreiberg (2017). Energy Procedia 120:333-340.

Techno-economic assessment of integrated hydrochar and high-grade activated carbon production for electricity generation and storage.
Rajesh S. Kempegowda, Khanh-Quang Tran, Øyvind Skreiberg (2017). Energy Procedia 120:341-348.

Biomass Charcoal Properties Changes during Storage.
L. Wang, E. Barta-Rajnai, K. Hu, C. Higashi, Ø. Skreiberg, M. Grønli, Z. Czégény, E. Jakab, V. Myrvågnes, G. Várhegyi, M. J. Antal, Jr. (2017). Energy Procedia 105:830-835.

Biocarbonization process for high quality energy carriers: Techno-economics
Rajesh S. Kempegowda, Øyvind Skreiberg, Khanh-Quang Tran (2017). Energy Procedia 105:628-635.

Techno-economic assessment of thermal co-pretreatment and co-digestion of food wastes and sewage sludge for heat, power and biochar production.
Rajesh S. Kempegowda, Øyvind Skreiberg, Khanh-Quang Tran, P.V. P. Selvam (2017). Energy Procedia 105:1737-1742.

Simultaneously boosting the mass and fixed-carbon yields of charcoal from forest residue via atmospheric carbonization.
Khanh-Quang Tran, Maria Zabalo Alonso, Liang Wang, Øyvind Skreiberg (2017). Energy Procedia 105:787-792.

CO_2 Gasification of Charcoals in the Context of Metallurgical Application.
Hau-Huu Bui, Liang Wang, Khanh-Quang Tran, Øyvind Skreiberg, Apanee Luengnaruemitchai (2017). Energy Procedia 105:316-321.

Comprehensive compositional study of torrefied wood and herbaceous materials by chemical analysis and thermoanalytical methods.
Eszter Barta-Rajnai, Emma Jakab, Zoltán Sebestyén, Zoltán May, Zsolt Barta, Liang Wang, Øyvind Skreiberg, Morten Grønli, János Bozi, Zsuzsanna Czégény (2016). Energy & Fuels 30(10):8019-8030.

CO_2 gasification of charcoals produced at various pressures.
Hau-Huu Bui, Liang Wang, Khanh-Quang Tran, Øyvind Skreiberg (2016). Fuel Processing Technology 152:207-214.

Charcoal 'mines' in the Norwegian woods.
Sam Van Wesenbeeck, Liang Wang, Frederik Ronsse, Wolter Prins, Øyvind Skreiberg, Michael J. Antal, Jr. (2016). Energy & Fuels 30(10):7959-7970.

CO_2 reactivity assessment of woody biomass biocarbons for metallurgical purposes.
Liang Wang, Benedicte Hovd, Hau-Huu Bui, Aasgeir Valderhaug, Therese, Videm Buø, Rolf Gunnar Birkeland, Øyvind Skreiberg, Khanh-Quang Tran (2016). Chemical Engineering Transactions 50:55-60.

Value chain analysis of biocarbon utilisation in residential pellet stoves.
Rajesh S. Kempegowda, Zsolt Barta, Øyvind Skreiberg, Liang Wang (2016). Chemical Engineering Transactions 50:7-12.

Isothermal and non-isothermal kinetic study on CO_2 gasification of torrefied forest residues.
Khanh-Quang Tran, Hau-Huu Bui, Apanee Luengnaruemitchai, Liang Wang, Øyvind Skreiberg (2016). Biomass and Bioenergy 91:175-185.

Combustion Characteristics of Biomass Charcoal Produced at Different Carbonization Conditions: A Kinetic Study.
Liang Wang, Gábor Várhegyi, Øyvind Skreiberg, Tian Li, Morten Grønli, Michael J. Antal, Jr. (2016). Energy & Fuels 30(4):3186-3197.

Biomass pyrolysis in sealed vessels. Fixed-carbon yields from Avicel cellulose that realize the theoretical "limit"!.
Sam Van Wesenbeeck, Charissa Higashi, Maider Legarra, Liang Wang, Michael Jerry Antal, Jr. (2016). Energy & Fuels 30(1):480-491.

Conference publications

Technical and economical feasibility of combusting biocarbon in small scale pellet boilers.
P. Bartocci, R. S. Kempegowda, F. Liberti, G. Bidini, Ø. Skreiberg, F. Fantozzi (2017). Proceedings of 25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden, pp. 1128-1134.

Hydrochar slurry fuels and high-grade activated carbon for electricity production and storage - Conceptual process design and analysis.
Khanh-Quang Tran, Terese Løvås, Øyvind Skreiberg, Rajesh S. Kempegowda (2016). 2016 IEEE International Conference on Sustainable Energy Technologies (ICSET) Proceedings, pp. 251-255.

Energy efficiency, environmental aspects and cost-efficiency of small-scale biocarbon conversion applications – value chain analysis
Rajesh S. Kempegowda, Zsolt Barta, Øyvind Skreiberg, Liang Wang (2016). Proceedings of 24th European Biomass Conference and Exhibition, 6-9 June 2016, Amsterdam, The Netherlands, pp. 717-721.

CO_2 Gasification of Norwegian Charcoals Prepared at Different Pressures.
Hau-Huu Bui, Liang Wang, Khanh-Quang Tran, Øyvind Skreiberg, Apanee Luengnaruemitchai (2016). Proceedings of The Petroleum and Petrochemical College International Symposium, Chulalongkorn University, 24 May 2016, Bangkok, Thailand, pp. 49-55.

Combustion Characteristics of Biomass Charcoal Produced at Different Carbonization Conditions.
Liang Wang, Gábor Várhegyi, Øyvind Skreiberg, Morten G. Grønli, Michael J. Antal, Jr. (2015). Proceedings of 23rd European Biomass Conference and Exhibition, 1-4 June 2015, Vienna, Austria, pp. 1196-1199.

Charcoal Production from Forest Residues.
Liang Wang, Charissa Higashi, Øyvind Skreiberg, Morten G. Grønli, Michael J. Antal, Jr. (2015). Proceedings of 23rd European Biomass Conference and Exhibition, 1-4 June 2015, Vienna, Austria, pp. 1184-1187.

Effect of Storage Time and Conditions on Biomass Charcoal Properties.
Liang Wang, Kathryn Hu, Charissa Higashi, Øyvind Skreiberg, Viktor Myrvågnes, Morten G. Grønli, Michael J. Antal, Jr., Gábor Várhegyi (2015). Proceedings of 23rd European Biomass Conference and Exhibition, 1-4 June 2015, Vienna, Austria, pp. 1180-1183.

Presentations

BioCarb+ and biocarbon research at SINTEF Energy Research and NTNU.
Øyvind Skreiberg (2017). BioCarb+ open workshop, 9 November 2017, Trondheim, Norway.

The BioCarb+ project.
Øyvind Skreiberg (2017). SFI Metal Production Autumn Meeting, 7-8 November 2017, Trondheim, Norway.

Biocarbon research needs, for the metallurgical industry.
Øyvind Skreiberg (2017). SFI Metal Production Autumn Meeting, 7-8 November 2017, Trondheim, Norway.

Biocarbon production and utilization.
Liang Wang, Øyvind Skreiberg, Morten Grønli (2017). SFI Metal Production Autumn Meeting, 7-8 November 2017, Trondheim, Norway.

Biocarbon properties and how to influence them.
Liang Wang, Øyvind Skreiberg (2017). SFI Metal Production Autumn Meeting, 7-8 November 2017, Trondheim, Norway.

Pressurized Biocarbon Production: Constant-Volume Carbonization of Biomass.
Maider Legarra Arizaleta, Trevor Morgan, Scott Turn, Michael J. Antal, Jr., Øyvind Skreiberg, Liang Wang, Morten Grønli (2017). SFI Metal Production Autumn Meeting, 7-8 November 2017, Trondheim, Norway.

Biokarbon.
Øyvind Skreiberg (2017). SINTEF Energy Research leader group meeting, 6 November 2017, Trondheim, Norway.

The pressure influence on biocarbon yield and quality.
Øyvind Skreiberg, Liang Wang, Morten Grønli (2017).25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden.

A Layered Particle Approach to Model the Conversion of Thermally Thick Particles.
K. Weber, T. Li, T. Løvås, C. Perlman, F. Mauss (2017). 25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden.

Constant Volume Pyrolysis of Biomass for the Production of Char with High Fixed-Carbon Content.
M. Legarra Arizaleta, S. Van Wesenbeeck, S. Turn, T. Morgan, M. Antal, Jr., Ø. Skreiberg, L. Wang, M. Grønli (2017). 25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden.

Gasification behaviours of different biomass charcoals under CO_2 atmosphere.
Liang Wang, Nicolai Alsaker, Øyvind Skreiberg, Therese Videm Buø, Rolf Gunnar Birkeland, Aasgeir Valderhaug, Benedicte Hovd (2017). 25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden.

CO_2 gasification reactivity of biocarbon produced at different conditions.
Liang Wang, Przmeysław Maziarka, Øyvind Skreiberg, Terese Løvås, Mariusz Wądrzyk (2017). 25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden.

Performance evaluation of a modern wood stove when using charcoal.
Alexis Sevault, Roger Khalil, Bjørn Christian Enger, Øyvind Skreiberg, Franziska Goile, Liang Wang, Morten Seljeskog, Rajesh Kempegowda (2017). 25th European Biomass Conference & Exhibition, 12-15 June 2017, Stockholm, Sweden.

Towards a Meaningful Non-isothermal Kinetics for Biomass Materials and Other Complex Organic Samples.
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2017). 1st Journal of Thermal Analysis and Calorimetry Conference, 6-9 June 2017, Budapest, Hungary.

Thermoanalytical characterisation of torrefied stem wood, stump and bark of Norway spruce.
Eszter Barta-Rajnai, Liang Wang, Zoltán Sebestyén, Zsolt Barta, Roger Khalil, Øyvind Skreiberg, Morten Grønli, Emma Jakab, Zsuzsanna Czégény (2017). 1st Journal of Thermal Analysis and Calorimetry Conference, 6-9 June 2017, Budapest, Hungary.

Biocarbon production and utilization.
Liang Wang, Øyvind Skreiberg, Morten Grønli (2017). 2nd International Bioenergy (Shanghai) Conference and Exhibition, 19-21 April 2017, Shanghai, China.

The manufacturing of charcoal in sealed vessels.
Maider Legarra Arizaleta, Scott Turn, Trevor Morgan (2017). 253rd American Chemical Society National Meeting & Exposition - Advanced Materials, Technologies, Systems & Processes, 2-6 April 2017, San Francisco, USA.

Biomass upgrading for improved combustion processes.
Øyvind Skreiberg (2017). CenBio Final Conference, 13-14 March, Ås, Norway.

Bio-carbonization process integration for high quality energy carriers: charcoal, biomethane, biocrude, and biofertilizer.
Rajesh S. Kempegowda, Øyvind Skreiberg, Khanh-Quang Tran, Pagandai V. Pannir Selvam (2016). 24th European Biomass Conference and Exhibition, 6-9 June 2016, Amsterdam, The Netherlands.

Carbon Yield Predictions in Biochar Based on Stochastic Reactor Modelling.
Kathrin Weber, Tian Li, Terese Løvås (2016). 24th European Biomass Conference and Exhibition, 6-9 June 2016, Amsterdam, The Netherlands.

Reactivity assessment of biocarbons for metallurgical purposes.
Liang Wang, Hau-Huu Bui, Benedicte Hovd, Aasgeir Valderhaug, Therese Videm Buø, Rolf Gunnar Birkeland, Øyvind Skreiberg, Khanh-Quang Tran (2016). 24th European Biomass Conference and Exhibition, 6-9 June 2016, Amsterdam, The Netherlands.

Towards the maximum theoretical yields of charcoal from biomass pyrolysis.
Morten Grønli, Liang Wang, Øyvind Skreiberg (2016). Pyro 2016 (21st International Symposium on Analytical and Applied Pyrolysis), 9-12 May 2016, Nancy, France.

Stochastic reactor modelling for biomass pyrolysis.
Kathrin Weber, Tian Li, Terese Løvås, Lars Seidel, Cathleen Perlman, Fabian Mauss (2016). Pyro 2016 (21st International Symposium on Analytical and Applied Pyrolysis), 9-12 May 2016, Nancy, France.

BioCarb+ Verdikjeden for biokarbon: Fra biomasse til energi.
Øyvind Skreiberg (2015). Bioenergidagene 2015, 18-19 November 2015, Gardermoen, Norway.

Modelling of wood devolatilization using a stochastic reactor approach.
Kathrin Weber, Tian Li, Cathleen Perlman, Lars Seidel, Fabian Mauss, Terese Løvås (2015). Nordic Flame days 2015, 6 October 2015, Copenhagen, Denmark.

BioCarb+.
Øyvind Skreiberg (2015). Presented in the session «Grensesprengende forskning» at Energiforskningskonferansen, 21 May 2015, Oslo, Norway.

Thermogravimetric studies of charcoal formation from cellulose under different pyrolysis conditions.
Liang Wang, Øyvind Skreiberg, Morten G. Grønli, Michael J. Antal, Jr. (2014). AIChE Annual Meeting in Atlanta, GA, 16 - 21 November, 2014.

Book

Biokohle - Herstellung, Eigenchaften und Verwendung von Biomassekarbonisaten.
Peter Quicker, Kathrin Weber (2017). Springer Vieweg. ISBN 978-3-658-03688-1.

Student reports

CO_2 gasification reactivity of densified biocarbon.
Fredrik Buvarp (2017). SINTEF Summer Job Project report. Supervisors: Liang Wang, Øyvind Skreiberg.

Kinetic modelling of biomass pyrolysis.
David Lüdecke (2016). RWTH Aachen University Master thesis. Main supervisors: Peter Quicker, Terese Løvås, Co-supervisor: Kathrin Weber.

Reactivity of biochar with CO_2 using thermogravimetric analysis.
Przemysław Maziarka (2016). AGH University of Science and Technology Master thesis. Main supervisors: Mariusz Wądrzyk, Terese Løvås, Co-supervisors: Liang Wang, Øyvind Skreiberg.

The techno-economics of biocarbon production processes.
Maciej Pawel Olszewski (2016). AGH University of Science and Technology Master thesis. Main supervisors: Karol Sztekler, Terese Løvås, Co-supervisors: Rajesh S. Kempegowda, Øyvind Skreiberg.

Biocarbon for use in metallurgic industry.
Nicolai E. Alsaker (2016). SINTEF Summer Job Project report. Supervisors: Liang Wang, Øyvind Skreiberg.

A thermogravimetric and kinetic study on devolatilization of woody biomass.
Maria Zabalo Alonso (2016). NTNU Master thesis. Main supervisor: Khanh-Quang Tran, Co-supervisors: Liang Wang, Øyvind Skreiberg.

A study on the theory, generation, and retention of charcoal quality by thermochemical equilibrium calculations, efficient microcrystalline celulose carbonization, thermogravimetry, and psychrometric experiments.
Charissa Rachelle Mika Higashi (2016). University of Hawaii Master thesis. Supervisor: Michael J. Antal, Jr.

CO_2 gasification of charcoals produced from Norwegian stem wood and forest residues.
Hau-Huu Bui (2016). Chulalongkorn University Master Thesis. Main supervisor: Apanee Luengnaruemitchai, Co-supervisors: Khanh-Quang Tran, Liang Wang, Øyvind Skreiberg.

Use of charcoal as reductant in metallurgical industry.
Maria Zabalo Alonso (2015). NTNU Project thesis. Main supervisor: Khanh-Quang Tran, Co-supervisors: Liang Wang, Øyvind Skreiberg.

Charcoal in a nutshell: Biocarbon production from cellulose, Norwegian wood, Macademia nutshells and sewage sludge.
Sam Van Wesenbeeck (2015). University of Hawaii Master thesis. Supervisor: Michael J. Antal, Jr.

Biocarbon for energy - Biocarbon CO_2 reactivity.
Benedicte Hovd (2015). SINTEF Summer Job Project report. Supervisors: Liang Wang, Øyvind Skreiberg.

Prozesse und Anlagen zur Herstellung von Biomassekarbonisaten.
Sophie Kloepfer (2015). RWTH Aachen University Bachelor thesis. Main supervisor: Peter Quicker, Co-supervisor: Kathrin Weber.

BioCarb+ in the media

Enabling the biocarbon value chain for energy.
Øyvind Skreiberg. Accepted for publication in EERA Bioenergy Newsletter 8, December 2017.

Håper på en fortsettelse av BioCarb+.
Lars Petter Maltby, Øyvind Skreiberg (2017). Eyde Cluster.

Biocarbon in Small Scale Pellet Boilers, Technological and Economic Feasibility.
BEsustainable (2017).

Lopwood and brushwood make high-grade charcoal.
Lars Martin Hjorthol, Øyvind Skreiberg (2014). Gemini.

Kvist og kvas blir edelt kull.
Lars Martin Hjorthol, Øyvind Skreiberg (2014). Gemini. Reproduced on forskning.no, Aftenposten nett and Adresseavisen nett.

Publications in progress

A study on densification and CO_2 gasification of biocarbon.
Abstract accepted for presentation at IConBM 2018, 17-20 June, Bologna, Italy.
Liang Wang, Fredrik Buvarp, Øyvind Skreiberg, Pietro Bartocci.

Impact of storage time and conditions on properties and reactivity of biocarbon.
Abstract accepted for presentation at IConBM 2018
Liang Wang, Fredrik Buvarp, Øyvind Skreiberg, Roger Khalil.

Carbonization pressure influence on biocarbon yield and quality.
Abstract accepted for presentation at IConBM 2018
Øyvind Skreiberg, Liang Wang, Quang-Vu Bach, Morten Grønli.

Biocarbon pellet production: Optimization of pelletizing process.
Abstract accepted for presentation at IConBM 2018
P. Bartocci, M. Barbanera, F. Liberti, G. Bidini, Ø. Skreiberg, L. Wang, F. Fantozzi.

Enabling the biocarbon value chains for energy and metallurgical industries.
Accepted for presentation at EUBCE 2018, 14-17 May, Copenhagen, Denmark.
Øyvind Skreiberg, Liang Wang, Roger Khalil, Simen Gjølsjø, Scott Turn.

Characterization of biocarbon produced under different carbonization conditions.
Accepted for presentation at EUBCE 2018
Liang Wang, Øyvind Skreiberg, Sam Van Wesenbeeck, Maider Legarra, Morten Grønli, Michael Jerry Antal, Jr.

Constant-Volume Carbonization of Biomass.
Accepted for presentation at EUBCE 2018
Maider Legarra Arizaleta, Trevor Morgan, Scott Turn, Øyvind Skreiberg, Liang Wang, Morten Grønli.

Predicting Delay Factors when Chipping Wood at Forest Roadside Landings.
Submitted to International Journal of Forest Engineering
Helmer Belbo, Henriette Vivestad.

Optimum harvesting and logistics solutions for GROT, stumps, energy wood and pulpwood.
To be submitted to an international journal
Helmer Belbo et al.

CO_2 Gasification kinetics of Biomass Chars Derived from Flash Pyrolysis of Birch Bark and Forest Residue.
Abstract accepted for presentation at 2nd International Workshop on Oxy-Fuel Combustion, 14-15 February 2018, Bochum, Germany.
Kathrin Weber, Liang Wang, Sebastian Heuer, Viktor Scherer, Tian Li, Gabor Varhegyi, Øyvind Skreiberg, Morten Grønli, Terese Løvås.

A novel approach for the estimation of the char yield and its application for pyrolysis of birch residues.
To be submitted to Fuel
Kathrin Weber, Sebastian Heuer, Peter Quicker, Tian Li, Terese Løvås, Viktor Scherer.

Production and Properties of Biochar.
PhD thesis. To be submitted to the Norwegian University of Science and Technology
Kathrin Weber.

Constant-Volume Carbonization of Biomass.
Abstract accepted for presentation at 255th ACS National Meeting, 18-22 March 2018, New Orleans, USA.
Maider Legarra Arizaleta, Trevor J Morgan, Scott Q Turn, Michael J Antal, Jr., Øyvind Skreiberg, Liang Wang, Morten Grønli.

Comparative review of carbonization methods for biomass and coal.
To be submitted to Renewable and Sustainable Energy Reviews
Maider Legarra, Trevor Morgan, Scott Turn, Liang Wang, Øyvind Skreiberg, Morten Grønli, and Michael Jerry Antal, Jr.

The Manufacturing of Charcoal in Sealed Vessels.
PhD thesis. To be submitted to the University of Hawaii at Manoa
Maider Legarra Arizaleta.

Pyrolysis of torrefied stem wood, stump and bark of Norway spruce.
To be submitted to Journal of Analytical and Applied Pyrolysis
E. Barta-Rajnai, E. Jakab, Z. Sebestyén, B. Babinszki, L. Wang, Ø. Skreiberg, M. Grønli, Z. Czégény.

"Torrefaction of lignocellulosic biomass".
PhD thesis. To be submitted to the Budapest University of Technology and Economics; George A. Olah Doctoral School of Chemistry and Chemical Technology
Eszter Barta-Rajnai.

Pre-BioCarb+ publications in CenBio

Is elevated pressure required to achieve a high fixed-carbon yield of charcoal from biomass? Part 2: The importance of particle size.
Liang Wang, Øyvind Skreiberg, Morten G. Grønli, Gregory Patrick Specht, Michael J. Antal, Jr. (2013). Energy & Fuels 27(4):2146-2156.

The smart biofuels of the future.
Øyvind Skreiberg, Morten G. Grønli, Michael J. Antal, Jr. (2013). Biofuels 4(2):159-161.

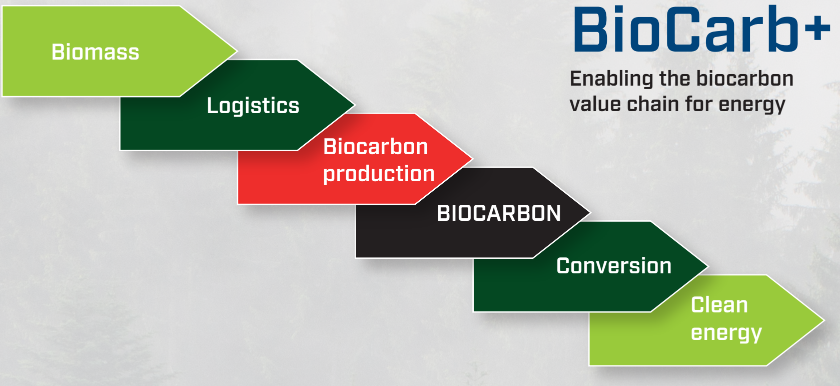
Is Elevated Pressure Required to Achieve a High Fixed-Carbon Yield of Charcoal from Biomass?
Michael J. Antal, Jr., Liang Wang, Øyvind Skreiberg, Morten G. Grønli (2013). International Symposium held at Osaka University, Japan at the 18th March 2013.

Attainment of High Fixed-Carbon Yields from Biomass.
Liang Wang, Øyvind Skreiberg, Morten G. Grønli and Michael J. Antal, Jr. (2013). 2nd Nordic Biochar Seminar in Helsinki, Finland, 14-15 February 2013.

Is Elevated Pressure Required to Achieve a High Fixed-Carbon Yield of Charcoal From Biomass?
Liang Wang, Øyvind Skreiberg, Morten G. Grønli, Michael J. Antal, Jr. (2012). AIChE Annual Meeting in Pittsburgh, PA, 28 October - 2 November, 2012.

Fundamentals of biocarbon production and utilization.
Michael J. Antal, Jr., Liang Wang, Øyvind Skreiberg, Morten G. Grønli (2012). CenBio days 2012, 18-19 January, Ås, Norway.

Is elevated pressure required to achieve a high fixed-carbon yield of charcoal from biomass? Part 1: Round-robin results for three different corncob materials.
Liang Wang, Marta Trninic, Øyvind Skreiberg, Morten G. Grønli, Roland Considine, Michael J. Antal, Jr. (2011). Energy & Fuels 25(7):3251-3265.



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Research partners:
SINTEF Energy Research, Norwegian Institute of Bioeconomy Research, Norwegian University of Science and Technology, Hawaii Natural Energy Institute at University of Hawaii at Manoa

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