BioCarbUp – Optimising the biocarbon value chain for a sustainable metallurgical industry

Newsletter 2-2021

Progress in 2021

In 2021 the focus on studies connected to the resource base in Norway for biocarbon production continues, carbonization experiments have continued in different experimental setups and increasing efforts are directed towards characterization and upgrading of the biocarbons and by-products. The characterization includes physio-chemical and mechanical properties and biocarbon CO_2 reactivity testing, and a summer job student has been working at SINTEF Energy Research connected to these topics and kinetics. Characterization methods and critical biocarbon characteristics with respect to the specific biocarbon end-uses have been evaluated and there has been a focus on how to improve biocarbon characteristics by tuning biocarbon production processes and by biocarbon upgrading. The latter is also investigated by the BioCarbUp postdoc candidate, who has shown that biocarbon can effectively be upgraded by deposition of carbon from methane on the surfaces of the porous biocarbon. She has now finished her study. In addition the utilization of the bio-oil from biocarbon production as binder in anode baking has been in focus. The BioCarbUp PhD student continues the work focusing on modelling related to the biocarbon production process. In general, the scientific activities are progressing rather well considering that the Covid-19 situation has inflicted on the progress of experimental activities.

BioCarbUp workshop and steering committee meeting by web

The fourth BioCarbUp workshop and steering committee meeting was arranged 13-14 October 2021 online. Results and progress were presented, and the program included ample time for discussions with the industry partners regarding the progress of the different project activities and the plans for 2022.

PostDoc work

The BioCarbUp PostDoc candidate working within composite agglomerates with biocarbon has finished her study. The PostDoc candidate, Hamideh Kaffash from Iran, has carried out her work at Department of Materials Science and Engineering, NTNU, with Professor Merete Tangstad as her supervisor.
Different types of industrial charcoals have been densified using C from CH_4. Properties of the charcoals before and after densification by C deposition were investigated. The C deposition resulted in significantly increased density and compressive strength, and reduced porosity and CO_2 reactivity. These are promising results, making charcoal more suitable for use in some metallurgical industries.
In addition to the publication Densification of Biocarbon and Its Effect on CO_2 Reactivity, a further work entitled The effect of densification on compressive strength of charcoal has been presented at Infacon XVI: International Ferro-Alloys Congress, with a paper published in proceedings.
Charcoals have also been impregnated with K to see how the CO_2 reactivity changes and it was found that with increasing K content in the charcoal of up to 2%, the CO_2 reactivity increased slightly, by a factor of 2, while we know from other works that for coke it increased by a factor of 10. A manuscript entitled "CO_2 gasification of densified biomass: The influence of K on reaction rate" has now been submitted to an international journal.
Also, densification experiments with a very different charcoal (compared to the 3 types of charcoal earlier tested) from South Africa were carried out to see if one could get the same good results, in terms of CO_2 reactivity and compressive strength.
Two summer master students who the PostDoc candidate co-supervised together with Merete Tangstad worked on densification of biocarbon and its characterization. This was a joint undertaking with the KPN Reduced CO_2 project.
A final conference presentation by the PostDoc candidate entitled "The effect of densification on charcoal properties" was given at The First Symposium on Carbon Ultimate Utilization Technologies for the Global Environment (CUUTE-1), in December.

- a Knowledge-building Project for Industry (KPN) co-funded by the Research Council of Norway through the ENERGIX-programme.
Contact: oyvind.skreiberg@sintef.no

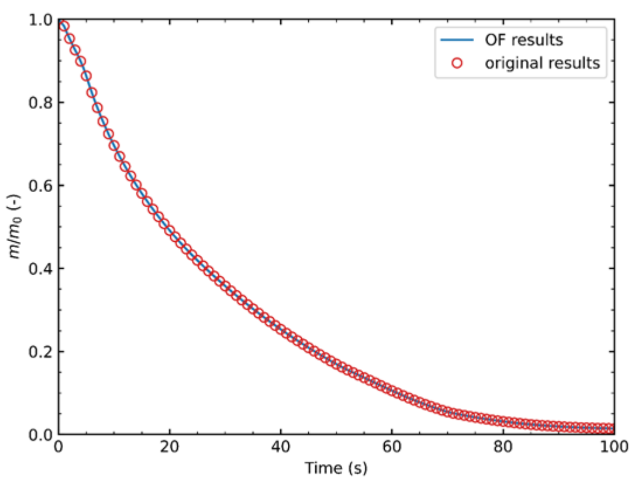
SINTEF

PhD work

The BioCarbUp PhD study within Modelling and CFD simulation of pyrolysis reactors is ongoing. The candidate, Boyao Wang from China, is employed at Department of Energy and Process Engineering, NTNU, with Professor Terese Løvås as supervisor and Adjunct Associate Professor Tian Li as co-supervisor. The candidate focusses on numerical modelling and simulation for efficient biocarbon production.

Boyao joined the ePYRO 2021 conference and presented the work of the PhD project. Different pyrolysis kinetic schemes have been compared and it was found that most of the kinetic schemes do not consider the secondary charring process. However, the secondary charring has noticeable effects on the char yield. Therefore, the investigation of the secondary charring processes will be in focus in the further work.

Now a mesh-based particle code has been successfully implemented in the OpenFOAM solver by Boyao. The mesh-based particle model will be beneficial for calculating thermally thick particles and can yield a better prediction of the biochar formation. The figure below shows a verification of the code in terms of mass loss during pyrolysis of a thermally thick wood particle. The simulated wood particle has a diameter of 20 mm, and the pyrolysis temperature is 1098 K.



Mass loss of a wood particle calculated by the original code (circle) and the newly developed OpenFoam solver (line)

SP1 (Biocarbon resources and value chain for metallurgical industry) work

Suggestions for more restrictions on harvesting methods and level in Norway and EU

During the last couple of years, new plans for climate, renewable energy and forest strategies have been presented. The new EU Forest Strategy is anchored in the European Green Deal and in the Biodiversity Strategy, and it must be seen in connection with the new climate regulations in the EU.

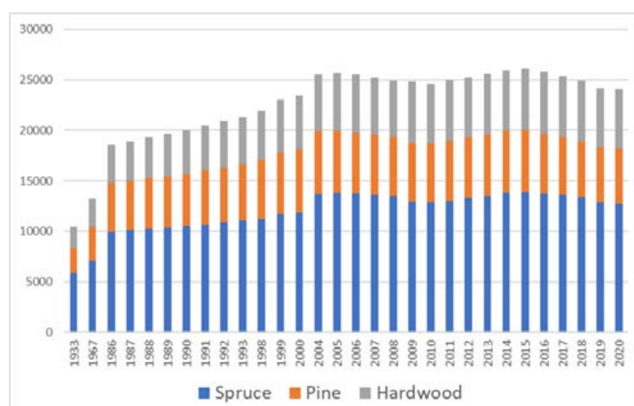
EU does not have a common forest policy. The New EU Forest Strategy for 2030 challenges this division of common forest policy to some extent, and it is emphasized that some policy areas related to forests are common competencies. The strategy also shows that forests are relevant in many political areas. The strategy assumes that the forest and the forest sector play a crucial role in Europe's transition to a modern, climate-neutral, resource-efficient and competitive economy.

No regulations have been proposed to prohibit clear-cutting in the forest strategy. It is said that some forms of operation, such as clear-cutting, should be "used with caution", and only in cases where it is necessary. This also applies to the harvesting of grot (branches and tops).

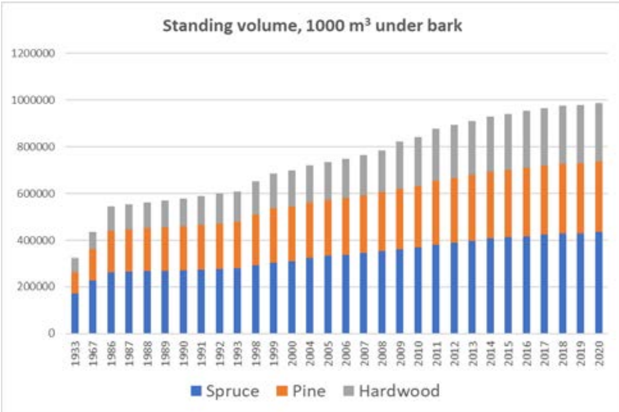
The new EU Forest Strategy will support the forest's socio-economic function for living rural areas and promote forest-based bioeconomy within a sustainable framework.

The new EU Forest Strategy will preserve, restore and strengthen the forest's contribution to combating climate change, reversing the loss of biological diversity and ensuring robust and multifunctional ecosystems in forests. Emphasis is placed on sustainable operation, and forms of operation that ensure biological diversity.

In Norway it is ongoing discussions in the media and between researchers regarding CO_2 emissions from soil after harvesting clear-cuts. However, the ambition in Norway is to increase the harvesting to about 15 mill m^3. In addition, there is a potential to harvest grot.



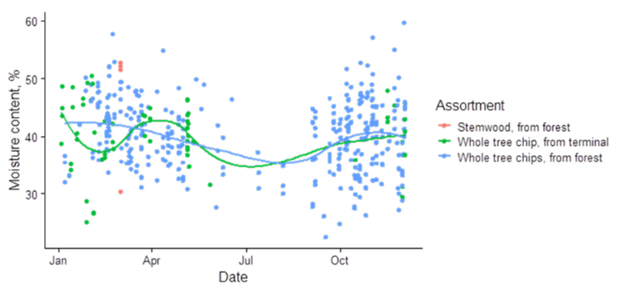
Annual growth in Norway under bark (1000 m^3 under bark)



Standing volume (1000 m^3 under bark)

Moisture content in woodchip deliveries

We have monitoring data from 2021 for biomass deliveries to several heating plants in south-eastern parts of Norway. Moisture content is important for storability and furnace performance, and to our knowledge moisture content also need to be reduced prior to biocarbon production. What we see from the delivery data is a huge variation in moisture content, especially in winter, early spring, and fall. The largest part of the deliveries is whole tree chips from forest, which indicates whole tree wood chips which is chipped at roadside of the forest road and delivered directly to end customer. The whole tree chips from terminal assortment are rather similar, but this assortment has been delivered via a terminal. Often this assortment will be a mixture of various origins and will therefore have more even moisture content. Stemwood from forest is also chipped at forest roadside.



Moisture content (% wet basis) records from biomass deliveries at some heating plants in south-eastern Norway during 2021

SP2 (Biocarbon production and upgrading) work

Study on densification of biocarbon for metal production application

Biocarbon is a promising alternative to fossil reductants for contributing to decarbonization of metallurgical industry. In comparison to conventional reductants (i.e., petroleum coke and coal), biocarbon has low bulk and energy density, poor mechanical strength and high reactivity. Densification is an efficient way to upgrade biocarbon and improve its undesirable properties. In this study, woody biocarbon was densified into pellets using condensates produced from a laboratory scale fixed bed reactor and an industrial scale continuous counter flow reactor. The biocarbon densification process, basic fuel properties and mechanical strength of the biocarbon pellets were studied. Effects of type and pre-treatment of binder on properties of the biocarbon pellets were evaluated. The results showed that both densification behaviour and pellet quality are different for biocarbon produced under different conditions and from different feedstocks. As indicated through the compression strength shown in Figure 1, the mechanical properties of pellets produced using biocarbon produced at high carbonization temperature (i.e., 700 °C) are evidently better than those produced by using biocarbon produced at lower carbonization temperatures. The condensate from an industrial scale biocarbon production process showed best performance as binder for producing pellets with compact and dense structure. On the contrary, the condensates from a laboratory scale reactor had rather poor capacity to bind biocarbon particles to make high strength pellets. The capacities of the condensates as binder are partially related to the content of water and chemical fractions of the studied condensates. The condensate initially collected from the biocarbon production experiment had a water content of 45.8 wt%. After heat treatment at a temperature of 160 °C for 60 minutes, the water content of the condensate reduced to 26.5 wt%. During the heat treatment process, distillation of water and release of light hydrocarbons might happen. It results in a residue with higher concentration of heavy molecular organic compounds, which gives better capacity to bind biocarbon particles together. Figure 2 shows representative SEM images of the morphology and microstructure of the pellets studied in this work. Compared to the others, the biocarbon pellet produced from birch wood carbonized at 700°C (Figure 2(a)) has more compact and dense structure. More cracks and openings can be observed from the biocarbon pellet produced from 500°C spruce wood biocarbon (Figure 2(c)). Observation of these cracks indicates more possible breakage and fragmentation of the 500°C spruce wood. The results of the present work indicate that densification of biocarbon is a promising measure to upgrade biocarbon properties for further logistics and final utilization as reductant and contribute to decarbonization of metallurgical industries.

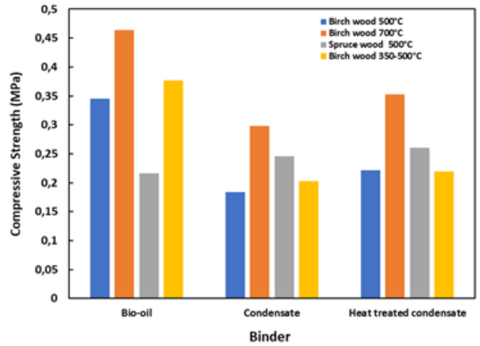


Figure 1. Compressive strength of biocarbon pellets using different binders

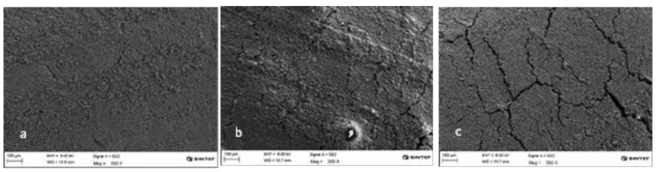


Figure 2. SEM image of biocarbon pellet produced from (a) Birch wood carbonized at 700°C, (b) Birch wood carbonized at 500°C and (c) spruce wood carbonized at 500°C, with using condensate as binder

Summer student project work on effect of calcination on properties of steam exploded pellets

A summer student, Lukas Baldauf, financed by BioCarbUp within the SINTEF summer job program worked from June to August with fruitful results. The primary objective of the work was to study the effect of calcination on properties of steam exploded pellets, through using a combination of different testing facilities (i.e., calcination furnace, tumbler and hardness tester) in the SINTEF Energy Research lab in Trondheim. The biocarbon or calcinated biomass materials are potential candidates to replace fossil-based packing coke for baking carbon anodes that are used for aluminium production. In this work, pellets produced from steam exploded stem wood were studied as a potential covering material for carbon anode production. The steam exploded pellets were calcinated at temperatures relevant to the industrial anode baking process (i.e., 1000, 1100 and 1300 °C) with different residence times (i.e., 0, 30 and 120 min). The critical properties of the raw and calcinated steam exploded pellets as covering material were characterized and assessed, including weight loss, volatile matter content, ash content and mechanical durability and strength. Additionally, the microstructure and ash chemistry of the pellets calcinated at different conditions were investigated by using a scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). Results showed that both volatile matter content and mechanical durability of the steam exploded pellets decrease upon increase of calcination temperature and residence time (Figure 3). SEM analysis revealed that untreated pellets have dense and compact structure with rather smooth and intact surface (Figure 4-a). Calcination caused formation of cracks and openings on the surface of the treated pellets, partially explaining the decrease of mechanical strength of the pellets (Figure 4-b). In addition, visible migration and agglomeration of ash on calcinated pellets surfaces was observed. With increasing calcination severity, inorganic elements sinter and form a compact layer with Ca as main element (Figure 4-c).

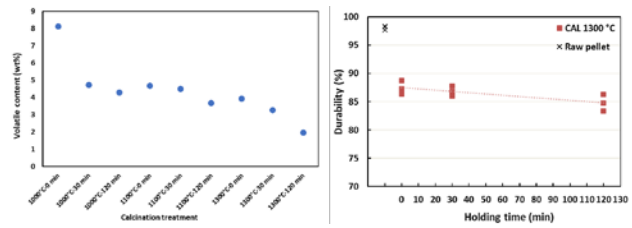


Figure 3. Effect calcination on (a) volatile matter content and (b) mechanical durability of steam exploded pellets

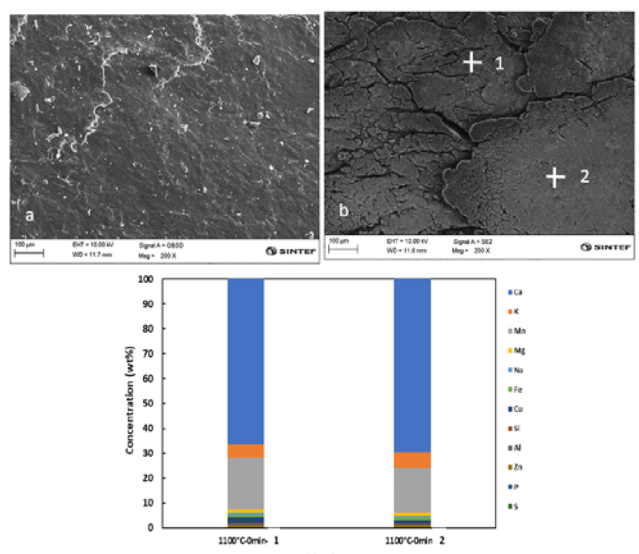


Figure 4. SEM image of (a) surface of raw steam exploded pellet, (b) surface of steam exploded pellet calcinated at 1100°C and (c) EDX analysis on composition of calcinated pellet surface (spot 1 and 2)

Continuation on test of gasification reactivity of different biocarbons in a Macro-TGA

Biocarbon will be exposed to high temperature conditions with presence of different gases, when used in metal production processes. It is therefore necessary to gain better understanding regarding change of biocarbon properties and reactivity of biocarbon under these conditions. Biocarbon produced under different conditions were tested in a Macro-TGA in 50% CO and 50% CO_2 atmosphere with continuous monitoring of weight loss. Figure 5 shows gasification behaviours of different biocarbons as a function of conversion time, which are indicated as reduction of the fixed carbon content at a temperature of 1100 °C. The results show that carbonized pellets react considerably slower in comparison to biocarbon produced from chips. Figure 6 displays a µCT scanning image of a carbonized wood pellet (a, c) and a birch wood chip (b, d) before and after gasification at 1100 °C. Compared to the carbonized wood chip, the carbonized wood pellet has a much denser structure that is even kept after the high temperature gasification test. On the contrary, the carbonized birch wood chip has a clear cellular structure with openings, indicating larger pore volume and surface area in comparison to the carbonized wood pellet. It can partially explain the high gasification reactivity of the carbonized birch wood chip compared to that of the carbonized wood pellet.

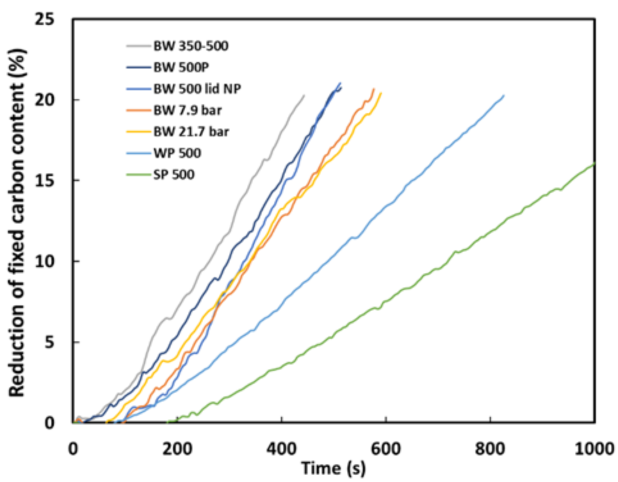


Figure 5. Gasification behaviour of different biocarbon samples in 50% CO and 50% CO_2 atmosphere at 1100 °C

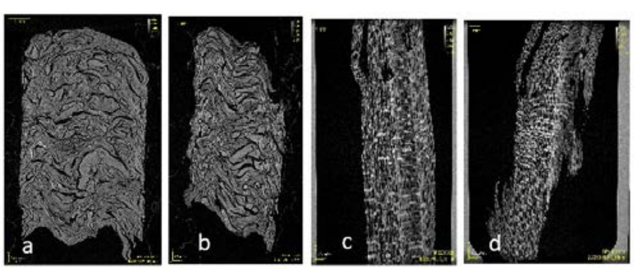


Figure 6. µCT scanning images of carbonized wood pellet and birch wood chip before (a, b) and after (c, d) gasification at 1100 °C

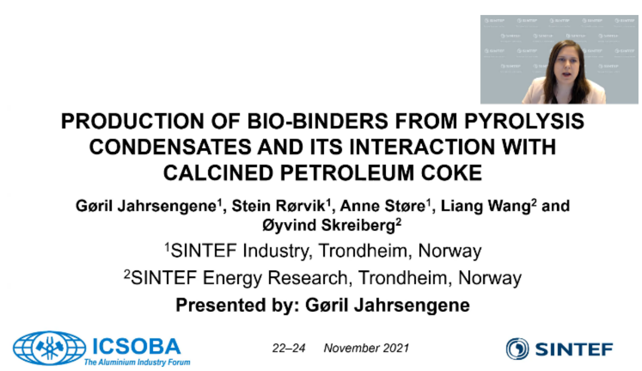
SP3 (Biocarbon end-use) work

Relevant thesis defense

Defense of PhD thesis "Bio-pitch as a potential binder in carbon anodes for aluminum production" by Asem Hussein from Laval University was held in October. Gøril Jahrsengene was one of the opponents. Congratulations to Dr. Asem also with a new job here in Norway, in Elkem Carbon, we hope to continue the good collaborations on biocarbon for metal production in the future!

ICSOBA 2021

The International Committee for Study of Bauxite, Alumina & Aluminium Conference 2021 could unfortunately not be arranged physically in Bahrain this year, but 280 delegates from all over the world connected on a virtual platform 22-24 November. The days consisted of two streams, where the Carbon and Aluminium stream was mainly attended by the SINTEF Industry participants. Interesting and relevant keynote presentations reflecting on the current technologies, and the future of aluminium production, was available for all attendees. In this session Hans Erik Vatne, Senior Vice President, Chief Technology Officer at Norsk Hydro, presented "Moving to CO_2-Neutral Alumina and Aluminium Production at Norsk Hydro" for all the delegates. Among the aspects he mentioned was the use of biocarbon, and BioCarbUp was mentioned by name and also discussed in the Q&A session.
Gøril Jahrsengene acted as session chair during one of the carbon sessions, and also presented the work done in BioCarbUp, "Production of Bio-Binders from Pyrolysis Condensates and its Interaction with Calcined Petroleum Coke" for about 70 delegates (could also be watched on demand). Questions about the aspects of value chain, availability and technological difficulties were asked and answered in the live Q&A session. At the closing of the conference, Gøril and her co-authors Stein Rørvik, Anne Støre, Liang Wang and Øyvind Skreiberg was awarded best paper within the carbon subject. The organizing committee recognized the good and relevant scientific work done, and the clear way it was presented in the paper and during the presentation. Congratulations!

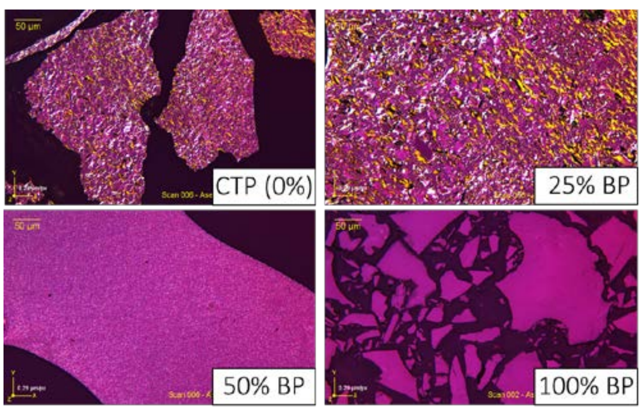


TMS 2022

The plan for TMS Annual meeting 2022 is for it to happen in Anaheim, California, February 27-March 3. We hope for a live conference where the accepted paper "Bio-Binders and its Carbonization and Interaction with Petroleum Coke during Baking" can be presented live by Gøril Jahrsengene on behalf of herself and the co-authors Stein Rørvik, Anne Støre, Liang Wang and Øyvind Skreiberg. Other attendees from SINTEF Industry includes Egil Skybakmoen, Arne Petter Ratvik and Nicholas Smith-Hanssen. Gerrit Surup, the PostDoc from the KPN Reduced CO_2 project, will give a presentation with the title "The interaction of slag and carbon on the electrical properties", which can be of interest to the FeMn industry.

2022 - Collaboration with Canada

Good conversations with Laval University on the aspects of bio-binders have been held all through the project. Some initial work done by Laval on mixing coal tar pitch (CTP) and bio-pitch was continued by SINTEF Industry, and the results showed no/small changes to the structure up 25-50 wt% bio-pitch (see figure below), and this will be further investigated by Gøril at a 4-week visit at Laval in spring of 2022. We look forward to more direct collaborations!



The addition up to 25 wt% of bio-pitch to the traditional CTP does not give any significant changes in the structure

CaNAl Summer School in Trondheim – 14-16 June 2022

The next Summer School through INTPART CaNAl will be hosted by the Norwegian organizers (lead by NTNU) and is planned for 14-16 June 2022 in Trondheim. Visitors will come from Canada from Laval University and the larger Aluminium Research Centre – REGAL. The program is currently under discussion, but the high interest of using biocarbon for aluminium production from both Norwegian and Canadian producers will likely result in several presentations from the biocarbon perspective. The event will be open also for industry partners. More information will come in the new year, and if you have any questions don't hesitate to contact Professor Kristian E. Einarsrud (kristian.e.einarsrud@ntnu.no).

Si-conference 2022

Silicon for the chemical and solar industry conference XVI will be held on 14-16 June 2022 in Trondheim, Norway. The abstract for a paper entitled "Effect of pSiO on SiC production during Si/FeSi process", where Sethulakshmy Jayakumari and Eli Ringdalen are the authors, have been accepted.

BioCarbUp in Light Metals

One BioCarbUp work has been accepted for publication in Light Metals 2022: Electrode Technology for Aluminum Production:
Gøril Jahrsengene, Stein Rørvik, Anne Støre, Liang Wang, Øyvind Skreiberg. Bio-Binders and its Carbonization and Interaction with Petroleum Coke during Baking. The abstract is given below:

"To reduce the carbon footprint in aluminium production, bio-based binders are suggested to replace some or all coal tar pitch in the carbon anodes. In this study, bio-binders based on Norwegian spruce and birch woods were produced in a laboratory set-up, which were studied in terms of wetting properties towards petroleum coke. The binders were mixed with petroleum coke and baked to three different temperatures. Graphitization of the binders were investigated on pure carbonized binders by XRD. Optical light microscopy was used to investigate the structures and interactions between coke and binder after baking. The bio-based binders appeared to adhere well to the coke particles, indicating excellent wetting behaviour during mixing. The optical structure of the carbonized bio-binder seemed to be affected by strain due to shrinkage of the bio-binder around the coke grain boundaries."

BioCarbUp in JAAP

One BioCarbUp connected work has been accepted for publication in Journal of Analytical and Applied Pyrolysis:
Yanqi Xie, Hailong Li, Lena Johansson Westholm, Lara Carvalho, Liang Wang, Eva Thorin, Zhixin Yu, Xinhai Yu, Øyvind Skreiberg. A critical review on production, modification and utilization of biochar. The abstract is given below:

"There has been an increased interest in the production of sustainable biochar in the past years, as biochar show versatile physicochemical properties and therefore can have a wide applicability in diverse fields. Comprehensive studies have been made to characterize biochar produced from various biomass materials, using different production technologies and under different process conditions. However, research is still lacking in correlating biochar properties needed for certain applications with (i) selection of feedstock, (ii) biochar production process and conditions and (iii) biochar upgrading and modification strategies. To produce biochar with the desired properties, there is a need to establish and clarify such correlations, which can be used for further proper selection of feedstock, tuning and optimization of the production process and more efficient utilization of biochar. On the other hand, further elucidation of these correlations is also important for biochar-stakeholder and end-users for predicting physiochemical properties of biochar from certain feedstock and production conditions, assessing potential effects of biochar utilization and clearly address needs towards biochar critical properties. This review summarizes a wide range of literature published on the impact of feedstocks and production processes and reactions conditions on the biochar properties. In addition, this review reports and discusses the most important biochar properties required for the different potential applications. Based on this review, knowledge gaps and perspectives for future research have been identified regarding the characterization and production of biochar. This review has also highlighted the importance of assessing performance of biochar for certain applications."

BioCarbUp at Pacifichem

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

BioCarbUp in ACS Omega

One BioCarbUp connected work has been published in ACS Omega:
Aekjuthon Phounglamcheik, Ricardo Vila, Norbert Kienzl, Liang Wang, Ali Hedayati, Markus Broström, Kerstin Ramser, Klas Engvall, Øyvind Skreiberg, Ryan Robinson, Kentaro Umeki (2021). CO_2 gasification reactivity of char from high-ash biomass. The abstract is given below:

"Biomass char produced from pyrolysis processes is of great interest to be utilized as renewable solid fuels or materials. Forest byproducts and agricultural wastes are low-cost and sustainable biomass feedstocks. These biomasses generally contain high amounts of ash-forming elements, generally leading to high char reactivity. This study elaborates in detail how chemical and physical properties affect CO_2 gasification rates of high-ash biomass char, and it also targets the interactions between these properties. Char produced from pine bark, forest residue, and corncobs (particle size 4−30 mm) were included, and all contained different relative compositions of ash-forming elements. Acid leaching was applied to further investigate the influence of inorganic elements in these biomasses. The char properties relevant to the gasification rate were analyzed, that is, elemental composition, specific surface area, and carbon structure. Gasification rates were measured at an isothermal condition of 800 °C with 20% (vol.) of CO_2 in N_2. The results showed that the inorganic content, particularly K, had a stronger effect on gasification reactivity than specific surface area and aromatic cluster size of the char. At the gasification condition utilized in this study, K could volatilize and mobilize through the char surface, resulting in high gasification reactivity. Meanwhile, the mobilization of Ca did not occur at the low temperature applied, thus resulting in its low catalytic effect. This implies that the dispersion of these inorganic elements through char particles is an important reason behind their catalytic activity. Upon leaching by diluted acetic acid, the K content of these biomasses substantially decreased, while most of the Ca remained in the biomasses. With a low K content in leached biomass char, char reactivity was determined by the active carbon surface area."

BioCarbUp at CUUTE-1

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

BioCarbUp at ICAE 2021

One BioCarbUp work has been presented at International Conference on Applied Energy, 29 Nov - 5 Dec, online:
Liang Wang, Lorenzo Riva, Øyvind Skreiberg, Zsuzsanna Czégény, Pietro Bartocci, Henrik Kofoed Nielsen (2021). Study on Densification of Biocarbon for Metal Production Application.
A corresponding article has been accepted for publication in proceedings.

BioCarbUp at ISFR 2021

One BioCarbUp work has been presented at International Symposium on Feedstock Recycling of Polymeric Materials, 29-30 November 2021, online:
Zsuzsanna Czégény, Bence Babinszki, Zoltán Sebestyén, Emma Jakab, Luca Kőhalmi, Janos Bozi, Liang Wang, Øyvind Skreiberg (2021). Effect of

carbonization conditions on the yield and properties of biocarbon and bio-oil products.

BioCarbUp at ICSOBA 2021

One BioCarbUp work has been presented at 39th Conference of The International Committee for Study of Bauxite, Alumina & Aluminium, 22-24 November 2021, online:

Gøril Jahrsengene, Stein Rørvik, Anne Støre, Liang Wang, Øyvind Skreiberg (2021). Production of Bio-binders from Pyrolysis Condensates and its Interaction with Calcined Petroleum Coke.

A corresponding article has been published in proceedings.

BioCarbUp in ACS Omega

One BioCarbUp work has been published in ACS Omega:

Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2021). Empirical Kinetic Models for the CO_2 Gasification of Biomass Chars. Part 1. Gasification of Wood Chars and Forest Residue Chars. The abstract is given below:

"The gasification kinetics of charcoals and biomass chars is complicated by several factors, including chemical and physical inhomogeneities, the presence of mineral matter, and the irregular geometry of the pore structure. Even the theoretically deduced gasification models can only provide empirical or semiempirical descriptions. In this study, an empirical kinetic model from the earlier works of the authors was adapted for the CO_2 gasification of biomass chars. It is based on a versatile polynomial approximation that helps to describe the dependence of the reaction rate on the progress of the conversion. The applicability of the model was tested by the reevaluation of 24 thermogravimetric analysis (TGA) experiments from earlier publications. The adjustable parameters of the model were determined by the method of least squares by evaluating groups of experiments together. Two evaluation strategies were tested. In the regular evaluations, the same kinetic parameters were employed for all the experiments with a given sample. The use of experiments with modulated and constant reaction rate (CRR) temperature programs made it possible to employ another approach too, when the preexponential factor was allowed to vary from experiment to experiment. The latter approach allows a formal kinetic description of the differences in the thermal deactivation of the samples caused by different thermal histories as well as of some inevitable systematic errors of the TGA experiments. The evaluations were carried out by both approaches, and the results were compared. The evaluations were based on 12 experiments. As a test, each evaluation of the study was repeated with only 8 experiments. The results of the latter test calculations indicated that the information content of the employed experiments is sufficient for the evaluation approaches of this work."

BioCarbUp at SDEWES

Two BioCarbUp works have been presented at 16th Conference on Sustainable Development of Energy, Water and Environment Systems, 10-15 October 2021, Dubrovnik, Croatia:

1) Liang Wang, Lorenzo Riva, Pietro Bartocci, Zsuzsanna Czégény, Øyvind Skreiberg, Henrik Kofoed Nielsen (2021). Study on Densification of Biocarbon for Metal Production Application.

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

BioCarbUp at ISGA-7

One BioCarbUp connected work has been presented at 7th International Symposium on Gasification and its Applications, 27-30 September 2021, online:

Aekjuthon Phounglamcheik, Ricardo Vila, Liang Wang, Norbert Kienzl, Markus Broström, Kerstin Ramser, Øyvind Skreiberg, Kentaro Umeki (2021). Effect of pyrolysis conditions and feedstocks on char gasification reactivity.

BioCarbUp at Infacon XVI

One BioCarbUp work has been presented at Infacon XVI: International Ferro-Alloys Congress, 27-29 September, Trondheim, Norway:

Hamideh Kaffash, Merete Tangstad (2021). The effect of densification on compressive strength of charcoal.

A corresponding article has been published in proceedings.

BioCarbUp in Bioresource Technology

One BioCarbUp work has been published in Bioresource Technology:

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

"Slow pyrolysis of spruce and birch was performed at various heating programs and conditions in a horizontal quartz tube reactor heated by an electric furnace. The effects of feedstock and carbonization conditions on the yield of biocarbon, liquid and gaseous products were studied. The thermal properties, volatile matter (VM) content and the evolution profiles of volatiles from the biocarbons were characterized by thermogravimetry/mass spectrometry. The composition of volatiles was analyzed in detail by pyrolysis–gas chromatography/mass spectrometry. Increased char yield was observed when staged pyrolysis program, low purging flow rate or covered sample holder were applied. Spruce produced more charcoal than birch due to the higher lignin content of softwood. The amount and the evolution profiles of the main gaseous products were similar from spruce and birch biocarbons prepared under the same conditions. The relative amount of aromatic and polyaromatic compounds in VM drastically decreased with increasing carbonization temperature."

Other news

Elkem biocarbon production plant in Canada

Elkem has in an press release announced:
"Elkem has decided to invest in a new biocarbon pilot plant in Canada. The project aims to secure industrial verification of Elkem's technology for renewable biocarbon, with a long-term goal of contributing to climate-neutral metal production. The technology also has potential for application in other industry sectors, contributing to reduced CO_2 emissions. The total investment for the pilot plant amounts to NOK 180 million. The project has received financial support from the Canadian government, the Québec government and the city of Saguenay, reducing Elkem's net investment to NOK 60 million. The plant will be constructed near Elkem's production site in Chicoutimi, Quebec, Canada, with start of construction planned for the second half of 2020. Based on conclusions from the pilot, Elkem will evaluate the basis for a full-scale plant."
The erection of the Elkem plant is now in progress.

Eramet Norway has received financial support from Enova for introducing biocarbon into their metallurgical process in Norway

Enova has granted 62.1 MNOK to Eramet Norway to support introduction of adapted biocarbon targeted at satisfying quality requirements of their Mn-alloy metallurgical process, to replace metallurgical coke currently used as reductant. To meet the qualities of the adapted biocarbon, also possibilities for changes in the metallurgical process itself will be investigated. See press release from Enova here.

Vow ASA has received financial support from Enova for establishing biocarbon production at Follum in Norway

Enova has granted 80.7 MNOK to VoW ASA to support erection of a biocarbon pilot production plant at Follum in Norway. The aim is to produce a biocarbon quality suitable for the metallurgical industry See press release from Enova here.

Elkem signs new agreement for Norwegian biocarbon

Elkem has signed a Letter of Intent (LoI) with Vow ASA's wholly owned subsidiary Vow Industries with the aim of reducing fossil CO_2-emissions from the production of silicon and ferrosilicon products for the global market. See the press release here.

Oplandske Bioenergi with the first commercial biochar production plant in Norway

The Oplandske Bioenergi biochar production plant at Rudshøgda in Norway produces EBC certified biochar and is the first biochar producer in Norway in commercial operation.

Prosess21

Prosess21 is a forum 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. Prosess21 provided their input to the work with a Report to the Storting (white paper) regarding how to reach the national climate goals for 2030. An interesting report, with respect to possible future use and priorities regarding biomass based materials in the Norwegian process industry, Biobasert Prosessindustri, is now finalized by one of the Prosess21 expert groups, as well as Ny prosessteknologi med redusert karbonavtrykk inkl. CCU. The Prosess21 main report, summarises the Prosess21 work.
For more info about Prosess21:
https://www.prosess21.no/

PhD thesis on Bio-coal for the Sustainable Industry

Aekjuthon Phounglamcheik, a PhD student at Luleå University in Sweden, defended his PhD thesis 24 September 2021. He was in his work also collaborating with BioCarbUp. The thesis is available here.

PhD thesis on Production and application of sustainable metallurgical biochar pellets

Lorenzo Riva, who was awarded the Elkem student prize for 2019 for his work within pyrolysis and pelletization of metallurgical biochar, and his networking abilities, defended his PhD thesis 7 September 2020. He was in his work also collaborating with BioCarbUp. The thesis is available here.

Norsk Biokullnettverk

The "Norwegian Biochar Network" was founded in 2019. Its purpose is to gather actors from the biochar value chains in Norway. The network aims to promote biochar as an important part of the circular economy, and works towards Norwegian leadership in value creation connected to production and utilization of biochar. SINTEF Energy Research is a member in the network, and Øyvind Skreiberg is a member of its board. Also the BioCarbUp industry partners Elkem and Eramet Norway are members in the network. The network has now been in operation for more than two years and has attracted great interest and many members. As a part of the network activities, seminars, workshops and webinars have been arranged on different biochar topics and for different industries (e.g. the metallurgical industry), and the network also are active in making the biochar voice heard in the society and towards authorities. The most recent dissemination effort was a parallel session on biochar during Bioenergidagene 2021, where Øyvind Skreiberg gave a presentation on the topic of the biocarbon value chain for metallurgical industry. All in all, the foundation of the network has been a timely one, serving its purpose. For more info about the network: https://www.biokull.info/ and the news page here. See also their recent activity report here.

Nordic Biochar Network

The Nordic Biochar Network was founded in 2019. It is a joint initiative of researchers in the Nordic countries to increase and spread knowledge about biochar. Research Scientist Kathrin Weber from SINTEF Energy Research was the main initiator of the Nordic Biochar Network. As a part of the network activities, a conference and webinars have been arranged. For more info about the network: https://www.nordicbiochar.org/

International Biochar Initiative

In addition to the Norwegian Biochar Network and the Nordic Biochar Network, the International Biochar Initiative (IBI) is a source of extensive information connected to the biochar field. Its mission is to provide a platform for fostering stakeholder collaboration, good industry practices, and environmental and ethical standards to support biochar systems that are safe and economically viable. The members of the Norwegian Biochar Network also become members of the international Biochar Initiative. IBI news are available here.

Recent events

Norsk Biokullnettverk seminar for metallurgical industry, 21 January 2021, Arendal, Norway. + virtual

International Symposium on Functional Biomass-derived Carbon Materials (GreenCarbon 2020). 9-11 March 2021, Zaragoza, Spain. e-conference
http://greencarbon-etn.eu/greencarbon2020/

TMS 2021 Annual Meeting & Exhibition, 15-18 March 2021. e-conference
https://www.tms.org/tms2021

International eConference on Analytical and Applied Pyrolysis (ePYRO 2021), 12-13 April 2021. e-conference
http://www.pyro2020.org/

29th European Biomass Conference & Exhibition, 26-29 April 2021, Marseille, France. e-conference
http://www.eubce.com/

INFACON XVI (The 16th International Ferro-Alloys Conference) - 26-29 September 2021, Trondheim, Norway. hybrid conference
https://www.sintef.no/projectweb/infacon-2021/

ICSOBA 2021, 22-24 November. e-conference
https://icsoba.org/upcoming-icsoba-event-2021/

Pacifichem 2021, 16-21 December. e-conference
https://pacifichem.org/

Upcoming events

TMS 2022 Annual Meeting & Exhibition, 27 February – 3 March 2022, California.
https://www.tms.org/AnnualMeeting/TMS2022

30th European Biomass Conference & Exhibition, 9-12 May 2022, Marseille, France. + e-conference
http://www.eubce.com/

23rd International Conference on Analytical and Applied Pyrolysis (PYRO 2022), 15-20 May 2022, Ghent, Belgium.
https://na.eventscloud.com/website/21947/

IConBM 2022, 5-8 June, Naples, Italy.
https://www.aidic.it/iconbm2022/

Silicon for the Chemical and Solar Industry XVI, 14-16 June 2022, Trondheim, Norway.
https://www.ntnu.edu/si-conference

39th International Symposium on Combustion, 24-29 July 2022, Vancouver, Canada.
http://www.combustionsymposia.org/2022/

Links (click on the links or logos to get there)

BioCarb+
KPN reduced CO_2
Prosess21
SKOG22
Energi21
Norsk Biokullnettverk
Nordic Biochar Network
International Biochar Initiative

Project information and past achievements

About the project

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

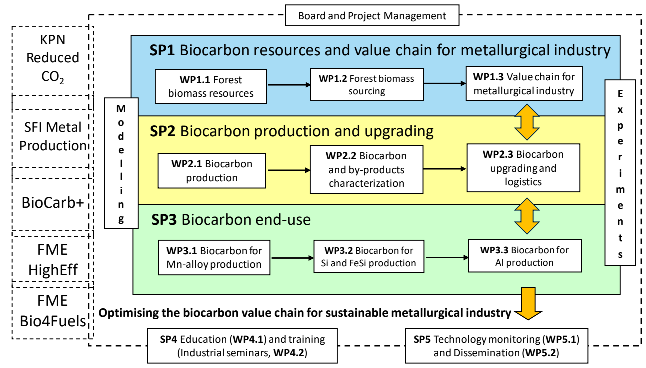
- **Production of biocarbon with sufficient quality** satisfying the end user quality requirements while ensuring optimum utilisation of the by-products
- **Optimised sourcing of Norwegian forest resources** for biocarbon production towards the specific metallurgical processes
- **Maximising the energy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

The sub-objectives are:

- 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

The anticipated results of the project are 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.

The Work Breakdown Structure of BioCarbUp is:



BioCarbUP management and work break down structure and project links and information flow.
BioCarb+: Enabling the biocarbon value chain for energy, http://www.sintef.no/biocarb
SFI Metal Production, https://www.ntnu.edu/metpro
FME HighEFF: Centre for an Energy Efficient and Competitive Industry for the Future, http://www.higheff.no
KPN Reduced CO_2 emissions from metal production, https://www.sintef.no/en/projects/reduced-co2-reduced-co2-emissions-in-metal-production/
FME Bio4Fuels, https://www.nmbu.no/bio4fuels

BioCarbUp will run for four years (2019-2022) and has a total cash budget of 25 million NOK, which is 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 covers all the necessary aspects, and includes large and central industrial players in the metallurgical and biomass utilization areas in Norway, complemented by recognized international research institutions.

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

The industrial partners contribute 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 is very strong, bringing together leading research organisations within the field and major industrial players.

Project background

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 society in 2050. For biomass, there is an expectation of total biomass feedstock utilisation.

The metallurgical industry in Norway seeks 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 lay 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 must be optimized to remove economic constraints, satisfy reductant quality demands, and develop predictable (amount, quality and price), long-term biomass resource demand.

This project responds to the national strategies and the goals of the metallurgical industry by analyzing and optimizing the BC value chain to produce suitable and affordable reductants in a sustainable manner. Producing BC, a renewable material from biomass resources, will 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, is the most suitable candidate for reductant feedstock.

The overall objective of this project is to optimise the biocarbon value chain for the metallurgical industry.

Project overview

The project is divided into 5 subprojects (SP), each subproject is 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 are 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 are 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 is 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 will develop fundamental competence about effect on specific metallurgical processes of changes in properties of carbon sources. Sources currently in use will be compared with bio-based carbon sources.
SP3 leader: Research Scientist Gøril Jahrsengene, SINTEF Industry

Education and training - SP4

The major objective of SP4 is to strengthen the education within this field through MSc and PhD students, and a postdoc candidate. The objective is also to increase the competence level in the industry. The long-term goal is competence 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 are to monitor the latest research and technological developments and to disseminate research results.
SP5 leader: Chief Scientist Øyvind Skreiberg, SINTEF Energy Research, who also is the BioCarbUp project leader

Earlier progress

In **2020** the focus on studies connected to the resource base in Norway for biocarbon production continued, carbonization experiments continued in different experimental setups and the biocarbons and by-products were characterized. The characterization included biocarbon CO_2 reactivity testing, and a summer job student was working at SINTEF Energy Research connected to this topic and kinetics. Characterization methods and critical biocarbon characteristics with respect to the specific biocarbon end-uses were evaluated and there was a focus on how to improve biocarbon characteristics by tuning biocarbon production processes and by biocarbon upgrading. The latter is also investigated by the BioCarbUp postdoc candidate. The BioCarbUp PhD student started, focusing on modelling related to the biocarbon production process. In general, the scientific activities were progressing rather well considering that the Covid-19 situation inflicted on the ability to carry out experimental activities, where additional HSE regulations must be followed due to the pandemic.

In **2019** the focus was on start-up of the project, studies connected to the resource base in Norway for biocarbon production, planning and execution of carbonisation experiments, characterisation of biocarbon, start-up of the postdoc work and dissemination from the project.

Earlier publications

BioCarbUp at EUBCE 2021

Two BioCarbUp works have been presented at EUBCE 2021, 26-29 April 2021, online:

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

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

BioCarbUp at ePyro2021

Two BioCarbUp works have been presented at ePyro2021, 12-13 April 2021, online:

1) Øyvind Skreiberg, Liang Wang, Zsuzsanna Czégény, Scott Turn (2021). Tuning the pyrolysis process in the direction of satisfying quality demands of metallurgical industries.

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

BioCarbUp at BSAEH-2021

One BioCarbUp work has been presented at International Conference on Biotechnology for Sustainable Agriculture, Environment and Health, 4-8 April 2021, online:

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

BioCarbUp at 38th International Symposium on Combustion

One BioCarbUp work has been presented at 38th International Symposium on Combustion, 24-29 January 2021, Adelaide, Australia:

Boyao Wang, Jingyuan Zhang, Terese Løvås, Tian Li (2021). CFD-DEM modeling of biomass pyrolysis in a fixed bed reactor.

BioCarbUp in Processes

One BioCarbUp work has been published in Processes:

Hamideh Kaffash, Gerrit Ralf Surup, Merete Tangstad (2021). Densification of Biocarbon and Its Effect on CO_2 Reactivity. The abstract is given below.

"Charcoal is an interesting reducing agent because it is produced from biomass which is renewable and does not contribute to global warming, provided that there is a balance between the felling of timber and growth of trees. Biocarbon is a promising alternative to fossil reductants for reducing greenhouse gas emissions and increasing sustainability of the metallurgical industry. In comparison to conventional reductants (i.e., petroleum coke, coal and metallurgical coke), charcoal has a low density, low mechanical properties and high CO_2 reactivity, which are undesirable in ferroalloy production. Densification is an efficient way to upgrade biocarbon and improve its undesirable properties. In this study, the deposition of carbon from methane on three types of charcoal has been investigated at 1100 °C. CO_2 reactivity, porosity and density of untreated and densified charcoal were measured, and results were compared to metallurgical coke. Surface morphology of the charcoal samples was investigated by using scanning electron microscopy (SEM). SEM confirmed the presence of a deposited carbon layer on the charcoal. It was found that the CO_2 reactivity and porosity of charcoals decreased during the densification process, approaching that of fossil fuel reductants. However, the CO_2 reactivity kept higher than that of metallurgical coke."

BioCarbUp in Energy

One BioCarbUp connected work has been published in Energy:
Lorenzo Riva, Liang Wang, Giulia Ravenni, Pietro Bartocci, Therese Videm Buø, Øyvind Skreiberg, Francesco Fantozzi, Henrik Kofoed Nielsen (2021). Considerations on factors affecting biocarbon densification behavior based on a multiparameter model. The abstract is given below.

"The optimization of upscaled biochar pelleting is limited by lack of knowledge regarding the effects of process parameters. A multiparameter model, coupled to a single pellet press unit, was for the first time applied to biochar production to predict the upscaled biochar pelleting process behavior. The model permits to estimate in a time and cost-effective way how the die friction forces, quantified through the
pellet exiting pressure, are affected by the key process parameters. It was observed that to achieve acceptably low exiting pressures (in the order of 100 MPa), it was critical to produce biochar at high temperatures (e.g. 600 °C). Addition of water as a binder is also beneficial, while pelletization temperature does not significantly affect the exiting pressure. Furthermore, when pyrolysis oil was used as a binder, lower exiting pressures were measured. Biochar returned higher exiting pressure values compared with untreated wood, but lower compared with torrefied wood. Moreover, the correlation between density and compressive strength was also examined. It was found that the exiting pressure trend is a good indicator to estimate the mechanical quality of the pellets."

BioCarbUp at MIT A+B Applied Energy Symposium

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

BioCarbUp at EUBCE 2020

One BioCarbUp work was presented at the 28th European Biomass Conference & Exhibition, originally planned for 27-30 April 2020, Marseille, France, but which was changed to an e-conference 6-9 July due to Covid-19:
Liang Wang, Lorenzo Riva, Øyvind Skreiberg, Pietro Bartocci, Henrik Kofoed Nilsen, Francesco Fantozzi (2020). Effect of Pyrolysis Conditions and Use of Condensates as Binder on Densification of Biocarbon.

BioCarbUp in Energy & Fuels

One BioCarbUp work has been published in Energy & Fuels:
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2020). Empirical Kinetic Models for the Combustion of Charcoals and Biomasses in the Kinetic Regime. The abstract is given below.

"An empirical kinetic model was proposed in 2019 and tested extensively on biomass pyrolysis (Várhegyi, G., Energy Fuels 2019, 33, 2348−2358). The model was based on an isoconversional kinetic equation. The functions in the kinetic equation were approximated by mathematical formulas with adjustable parameters, and the parameters were determined by the method of least squares. This procedure ensures that the data calculated from the model would be close to the experimental data. In the present work, this way of modeling was adapted for the combustion of charcoals and lignocellulosic biomasses. The performance of the model was tested by the reevaluation of TGA experiments from earlier publications. In total, 18 experiments belonged to a study of charcoals, while 20 experiments were carried out on wheat straw and willow samples. The corresponding temperature programs included linear, modulated, stepwise, and constant reaction rate (CRR) temperature–time functions. The adjustable parameters of the model were determined by the method of least squares by evaluating groups of experiments together. The procedure aimed at finding best-fitting models for the derivative of the measured reacted fraction. The activation energy, E, was regarded as constant for the whole process. The change of the reactivity during the progress of the reaction was described by the rest of the isoconversional kinetic equation. Model variants with different numbers of adjustable parameters resulted in practically identical E values. It was possible to determine common E values for different samples with only a slight worsening of the fit quality. This procedure allowed an easy comparison of the reactivities of the samples as functions of the reacted fraction."

BioCarbUp in Energy & Fuels

One BioCarbUp associated work has been published in Energy & Fuels:
Liang Wang, Lorenzo Riva, Øyvind Skreiberg, Roger Khalil, Pietro Bartocci, Qing Yang, Haiping Yang, Xuebin Wang, Dengyu Chen, Magnus Rudolfsson, Henrik Kofoed Nielsen (2020). Effect of Torrefaction

on Properties of Pellets Produced from Woody Biomass. The abstract is given below.

"Torrefaction has been recognized as a promising strategy to improve handling and storage properties of wood-based pellets, thus producing a uniform-quality commodity with high energy density and hydrophobicity. In this work, pellets produced from spruce stem wood, bark, and forest residues were torrefied in a bench-scale tubular reactor at 225 and 275 °C with two residence times (30 and 60 min). The effects of torrefaction on general properties, grindability, mechanical properties, hydrophobicity, and microstructure of the studied pellets were investigated. The increase of torrefaction severity reduced mass yields, but the heating values and the fixed carbon content of the torrefied pellets considerably increased. The grindability of raw pellets was substantially improved after torrefaction treatment. The energy required for grinding torrefied pellets is less than 50% of the energy needed for grinding the untreated pellets. In comparison to untreated pellets, the particles from ground torrefied pellets have clearly smaller sizes in a narrower size range. The increase of torrefaction severity improved hydrophobicity of the pellets, which have high resistance to water uptake and maintain their integrity after immersion testing. Upon torrefaction treatment, the durability and tensile strength of the pellets slightly decreased. Scanning electron microscopy analysis results show that particles from wood pellets torrefied at 275 °C lost their fibrous structure with an evident decrease of length/diameter ratios compared to untreated wood pellets. The particles from ground torrefied pellets are more uniform in terms of shape and size. Torrefaction can considerably improve grindability and uniformity of wood-based pellets and make them more acceptable in pulverized fuel applications."

BioCarbUp in Energy & Fuels

One BioCarbUp associated work has been published in Energy & Fuels:
Aekjuthon Phounglamcheik, Liang Wang, Henrik Romar, Norbert Kienzl, Markus Broström, Kerstin Ramser, Øyvind Skreiberg, Kentaro Umeki (2020). Effects of Pyrolysis Conditions and Feedstocks on the Properties and Gasification Reactivity of Charcoal from Woodchips. The abstract is given below.

"Pyrolysis conditions in charcoal production affect yields, properties, and further use of charcoal. Reactivity is a critical property when using charcoal as an alternative to fossil coal and coke, as fuel or reductant, in different industrial processes. This work aimed to obtain a holistic understanding of the effects of pyrolysis conditions on the reactivity of charcoal. Notably, this study focuses on the complex effects that appear when producing charcoal from large biomass particles in comparison with the literature on pulverized biomass. Charcoals were produced from woodchips under a variety of pyrolysis conditions (heating rate, temperature, reaction gas, type of biomass, and bio-oil embedding). Gasification reactivity of produced charcoal was determined through a thermogravimetric analysis at an isothermal condition of 850 °C and 20% of CO_2. The charcoals were characterized for the elemental composition, specific surface area, pore volume and distribution, Raman spectroscopy, and inductively coupled plasma optical emission spectrometry. The analysis results were used to elucidate the relationship between the pyrolysis conditions and the reactivity. Heating rate and temperature were the most influential pyrolysis parameters affecting charcoal reactivity, followed by reaction gas and bio-oil embedding. The effects of these pyrolysis conditions on charcoal reactivity could primarily be explained by the difference in meso- and macropore volume, and the size and structure order of aromatic clusters. The lower reactivity of slow pyrolysis charcoals also coincided with its lower catalytic inorganic content. The reactivity difference between spruce and birch charcoals appears to be mainly caused by the difference in catalytically active inorganic elements. Contrary to pyrolysis of pulverized biomass, low heating rate produced higher specific surface area compared with high heating rate. Furthermore, the porous structure and the reactivity of charcoal produced from woodchips were influenced when the secondary char formation was promoted, which cannot be observed in pyrolysis of pulverized biomass."

BioCarbUp at TMS 2020

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

A corresponding article has been published in Light Metals 2020, pp. 1338-1347. The abstract is given below.

"Carbon anodes for aluminium production are produced from calcined petroleum coke (CPC), recycled anode butts and coal tar pitch (CTP). The CO_2 produced during anode consumption contributes to a substantial amount of the CO_2 footprint of this industrial process. Charcoal from wood has been suggested to partly replace coke in anodes but high porosity, low electrical resistivity and high ash content contributes negatively to final anode properties. In this work, charcoal from Siberian larch and spruce was produced by heat treatment to 800, 1200 and 1400 ℃ and acid-washed with H_2SO_4. Acid-washing resulted in reduced metal impurity and the porosity decreased with increasing heat treatment. Pilot anodes were made from CTP, CPC with some additions of spruce and larch charcoal. Another set of pilot anodes were produced using a green binder. Compared to reference anodes, the CO_2 reactivity of anodes containing larch was less affected compared to anodes containing spruce. The green binder was found to be highly detrimental for the anodes' CO_2 reactivity properties. Electrochemical consumption increased for anodes containing both green binder, larch and spruce compared to the reference anode."

BioCarbUp in Journal of Thermal Analysis and Calorimetry

One BioCarbUp work has been published in Journal of Thermal Analysis and Calorimetry:
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2019). Non-isothermal kinetics: Best fitting empirical models instead of model-free methods. The abstract is given below.

"The isoconversional (or model-free) methods cannot provide meaningful kinetic description for most samples in thermal analysis. Nevertheless, they can serve as empirical models. A usable empirical model should describe well the observed data and should be suitable for predictions, too. For this purpose, the functions in the isoconversional kinetic equation were parametrized, and the parameters were determined by the method of least squares. This procedure ensures that the data calculated from the model would be close to the experimental data. The present work supplemented a preceding work of Várhegyi (Energy and Fuels 33:2348–2358, 2019) by further considerations and by various evaluations on the TGA curves of a wood sample. The prediction capabilities of the models were also tested. It was found that an evaluation based on three experiments with constant heating rates could predict well two further experiments with stepwise temperature programs. Furthermore, a modification of the model was proposed and examined. The aim of this modification was to improve the fit quality without increasing the number of parameters in the least-squares procedure."

BioCarbUp in Applied Energy

One BioCarbUp associated work has been published in Applied Energy:
Lorenzo Riva, Henrik Kofoed Nielsen, Øyvind Skreiberg, Liang Wang, Pietro Bartocci, Marco Barbanera, Gianni Bidini, Francesco Fantozzi (2019). Analysis of optimal temperature, pressure and binder quantity for the production of biocarbon pellet to be used as a substitute for coke. The abstract is given below.

"In order to contribute to the decarbonization of the economy, efficient alternatives to coal and coke should be found not only in the power sector but also in the industrial sectors (like steel, silicon and manganese production) in which coal and coke are used as a reductant and for steel production also as a fuel. To this aim many research works have been focused on the development of a coke substitute based on woody biomass and known as "biocarbon". There are still barriers to overcome, among them: the biocarbon low density, poor mechanical strength and high reactivity. In this paper a new biocarbon production methodology is proposed, based on: pyrolysis at 600 °C, densification (using pyrolysis oil as binder), reheating of the obtained pellet. Response surface methodology with a Box-Behnken experimental design was utilized to evaluate the effects of the process conditions on the pellet's quality. Responses showed that densification was mainly affected by oil content and pelleting temperature, while pelleting pressure had a minor influence. The pelleting process has been finally optimized using Derringer's desired function methodology. Optimal pelletizing conditions are: temperature equal to 60 °C, pressure equal to 116.7 MPa, oil content concentration of 33.9 wt%. These results are relevant for metal production industries at a global level. The identified optimal parameters of the new biocarbon production process can contribute to replace coke with sustainable fuels and probably reduce great part of the related greenhouse gases emissions."

BioCarbUp at JTACC 2019

One BioCarbUp work was presented at 2nd Journal of Thermal Analysis and Calorimetry Conference (JTACC), 8-21 June 2019, Budapest, Hungary:
Gábor Várhegyi, Liang Wang, Øyvind Skreiberg (2019). Non-isothermal kinetics: best fitting empirical models instead of model-free methods.
A corresponding article has been published in Journal of Thermal Analysis and Calorimetry.

BioCarbUp at ISFR 2019

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

BioCarbUp in EERA Bioenergy Newsletter

An article entitled "Optimising the biocarbon value chain for a sustainable metallurgical industry" presented BioCarbUp in an EERA (European Energy Research Alliance) Bioenergy newsletter.

Publication list

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

Yanqi Xie, Hailong Li, Lena Johansson Westholm, Lara Carvalho, Liang Wang, Eva Thorin, Zhixin Yu, Xinhai Yu, Øyvind Skreiberg. A critical review on production, modification and utilization of biochar. Accepted for publication in Journal of Analytical and Applied Pyrolysis.

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

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

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.

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

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

Gøril Jahrsengene, Stein Rørvik, Anne Støre, Liang Wang, Øyvind Skreiberg (2021). Production of Bio-binders from Pyrolysis Condensates and its Interaction with Calcined Petroleum Coke. ICSOBA 2021, 22-24 November 2021, online. A corresponding article has been published in proceedings.

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

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

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

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

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

Hamideh Kaffash, Merete Tangstad (2021). The effect of densification on compressive strength of charcoal. Infacon XVI: International Ferro-Alloys Congress, 27-29 September, Trondheim, Norway. A corresponding article has been published in proceedings.

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

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

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

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

Boyao Wang, Tian Li, Terese Løvås, Liang Wang, Øyvind Skreiberg (2021). CFD-DEM modelling of biomass pyrolysis

using multi-component kinetics mechanism. ePyro2021, 12-13 April, online.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Øyvind Skreiberg (2019). Optimising the biocarbon value chain for sustainable metallurgical industry. Eramet metallurgical meeting, 4 September 2019, Trondheim.

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

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

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

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

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

Polymeric Materials (ISFR), 26-29 May 2019, Budapest, Hungary.

Øyvind Skreiberg (2019). Optimising the biocarbon value chain for sustainable metallurgical industry. SFI Metal Production 2019 Spring Meeting, 24-25 April 2019, Trondheim, Norway.

Øyvind Skreiberg, Liang Wang (2019). Biocarbon activities at SINTEF Energy Research. KPN Reduced CO_2 workshop, 1 April 2019, Trondheim, Norway.