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Biochar for Industry

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2 Introduction

This project was carried out within the framework of the program Energy Model Region (3rd call, “Vorzeigeregion Energie”). In total 4 highly qualified partners from Austria (3 partners) and Sweden (1 partner) participated, whereby a significant added value compared to a national project could be achieved. The consortium consisted of the following partners:
Austria:

- BIOS BIOENERGIESYSTEME GmbH (BIOS)
- Montanuniversität Leoben, Department of Metallurgy, Chair of Nonferrous Metallurgy (MUL)
- POLYTECHNIK Luft- und Feuerungstechnik GmbH (Polytechnik)

Sweden:

- Catator AB, Sweden (CAT)

2.1 Background

The metallurgical industry is responsible for a considerable share of the world’s CO2 emissions, thus appropriate mitigation strategies are urgently needed. One feasible option is the substitution of fossil carbon by biochar. To facilitate this, an already existing biomass pyrolysis reactor concept shall be adapted in terms of process settings and control to produce biochar, which is suitable for that purpose, i.e. complies with the demands of the metallurgical industry in terms of chemical composition and physical properties. To reach also economic compliance, the project focuses on (i) the application of low-cost feedstocks such as low-quality fallen timber and beetle wood, which are available in sufficient amounts in Austria and (ii) the development of a novel pyrolysis gas utilization route based on a combined thermal and catalytic tar reforming to allow a direct utilization in a gas engine. The additional income from electricity and heat sales shall facilitate a competitive biochar price. Therefore, the new process shall be attractive for both, owners and operators of heating and CHP plants who are willing to turn to an economically attractive bio-refinery approach and industries who want to apply the biochar.

2.2 Task

The main aim of the BC4I project is the development of a highly efficient slow pyrolysis-based process, which produces biochar as a main product as well as electricity and heat as added-value products from a broad range of different biomass fuels. A novel pyrolysis gas (PG) upgrading concept to be developed (combined thermal and catalytic cracking of tars) shall make the PG suitable for application in gas engines. In overall with this concept an efficiency of energy conversion from the biomass feedstock to all products of more than 90% shall be reached.
The BC4I process shall facilitate an adjustment of the biochar qualities to the demands of the metal industry (e.g. reactivity, chemical composition, etc.). Moreover, the utilization of rather cheap waste materials as feedstock and the income generated from the valorization of the PG by electricity and heat generation shall result in a, compared to fossil carbon, competitive biochar price.

BC4I shall boost Austria's technology leadership regarding efficient and sustainable regional production of biochar, green electricity and heat and thus has great potential to increase the competitiveness of the companies involved. Following, through BC4I increased regional added value shall be gained and at the same time it shall help to secure Austria as a business location.
An industrial advisory board has been installed to secure direct information exchange with industry regarding application options and related biochar quality demands as well as to assure that all relevant industrial (technical and economic) framework conditions are considered.

2.3 Focal points of the project

1. Development of the pyrolysis process and its control to optimize the biochar quality with respect to the demands of the metal industry and in parallel to achieve an almost dust free PG
2. CFD supported development and optimization of a combined thermal and catalytic PG reformer to achieve an almost tar-free pyrolysis gas for direct utilization in a gas engine.
3. Application of a novel precious metal-based catalyst specially adapted to the needs of tar reforming in PG without soot formation.
4. Development of a highly efficient overall process based on an optimized cascaded utilization of the energy from the gas burner in the reformer (high temperature) and the pyrolysis reactor (moderate temperature) to minimize PG combustion and thus maximize the share of PG utilized in the gas engine.
5. Performance of test runs with accompanying measurements and analyses with a prototype testing plant (pyrolysis reactor, gas burner and gas reformer) to validate and calibrate the simulation models used, to gain experimental data and to evaluate/optimize the individual components and the process control.
6. Detailed characterization and subsequent test and evaluation of the biochar produced for the application in the metallurgical industry covering lab-scale reactor tests.
7. Ecological and economic evaluation of the new technology and of the substitution of fossil carbon by biochar in industry.
8. Development of application concepts in the metallurgical industry with a key focus on framework conditions in Austria.

2.4 Placement in the Programme

1. Technology development: “Development and model use of local energy and energy-related transport technologies for the large-scale field testing of intelligent system solutions in live operation” → the novel BC4I process shall contribute to an increased penetration of renewable energy sources in the industrial energy mix. Moreover, biochar can be easily transported and stored and therefore can also be seen as an intermediate energy carrier (or storage) with comparably high energy density.
2. Market development: “Strengthening and developing Austria as a lead market for innovative energy and energy-related transport technologies and services” → Attractive biochar prices shall

be achieved by (i) using regionally available low-cost biomass feedstocks and (ii) a novel highly efficient production process. The regionally produced biochar shall, under consideration of future taxes resp. certificate prices for CO2 emissions, be an economically interesting alternative to fossil fuels. Consequently, the whole value chain leading from the feedstock over the conversion technology development and implementation to the biochar utilisation is “made in Austria”.

3. Acceptance: “Involvement and active participation of users” → BC4I shall boost Austria's technology leadership regarding efficient and sustainable regional production of biochar, green electricity and heat and thus has great potential to increase the competitiveness of the companies involved. Following, through BC4I increased regional added value shall be gained and at the same time it shall help to secure Austria as a business location. An industrial advisory board was installed to secure direct information exchange with industry regarding application options and related biochar quality demands as well as to assure that all relevant industrial (technical and economic) framework conditions are considered.

2.5 Methods used

The work to be performed was based on system and component simulations with CFD models under consideration of newly developed innovative modelling tools, experimental work on the pyrolysis process and the gas upgrading at prototypes, lab-experiments with the biochar produced to investigate its suitability for the metallurgical industry as well as accompanying techno-economic process evaluations. An industrial advisory board ensured that all relevant technical, economic and strategic constraints were considered appropriately.

2.6 Structure of the work

The work within this project was divided into 8 work packages (WPs):
WP1, Project management, dealt with the overall management of the project (controlling, milestone control), the preparation of reports, communication with NEFI and the funding body, information exchange with the industrial advisory board and dissemination activities.
WP2, Basic system design, focussed on the definition of input material properties and interfaces, basic concepts for the different system units including the thermal/catalytic tar reformer and the overall plant.
Within WP3, Adjustment of the pyrolysis reactor control, the design for a continuous pyrolysis reactor including the adapted reactor control was developed using CFD modelling. Moreover, the set of quality criteria for biochar applications in metallurgical processes was defined.
WP4, Development of the novel pyrolysis gas reformer and its integration, included the CFD and kinetic modelling of tar conversion and soot formation in the tar reformer, the definition and pre-testing of suitable catalyst options and the integration of the new tar reforming process in the overall plant concept.
WP5, Design, construction and installation of a prototype, focussed on the construction and installation of the testing plant at the premises of Polytechnik.
WP6, Performance and evaluation of test runs and stepwise optimisation, included the performance and evaluation of the test runs with the testing plant and the step-by-step optimisation of the plant.

Within WP7, Characterisation and evaluation of the biochar for metallurgical applications, the biochars produced were characterized, their suitability for certain metallurgical processes were evaluated in various lab-scale tests and recommendations for the application of biochar in the metallurgical industry were worked out.
WP8, Techno-economic and ecological evaluation, used the results gained from the other work packages to perform a detailed ecological assessment and techno-economic analysis as well as different application case studies.
Subsequently, an overview regarding the work performed and the results achieved within the WPs is given.

3 Content presentation

3.1 WP1: Project management and dissemination

Efficient information and data exchange procedures could be maintained in the reporting period. To control and adjust the work to be performed and the contents and timing of information exchange, detailed work plans for the work in the different WPs and related lists of actions have been generated for each partner meeting. Their proper execution has regularly been checked by BIOS. Communication was based on:

- Regular project coordination meetings as a central event for project coordination and information exchange (two partner meetings per year where also the members of the advisory board, see below, were attending)
- Day to day communication by email and phone
- MS-Teams and phone meetings of different partner groups to discuss specific items
- Bilateral meetings of partners and meetings in smaller groups (i.e. technical meetings) to discuss specific issues.

The industrial advisory board has been installed at the beginning of the project. Members of the advisory board were:

- Ecobat Resources Austria GmbH (former BMG Metall und Recycling GmbH (Austria))
- Stahl- und Walzwerk Marienhütte GmbH (Austria)
- TIROLER ROHRE GmbH (Austria)
- Befesa Steel Services GmbH (Spain)

The project consortium cooperated with the NEFI cluster coordinator regarding information about the project in newsletters, participation of NEFI workshops and the NEFI homepage (https://www.nefi.at/bc4i-biochar-for-industry/). Moreover, information regarding the project is also presented on the homepage of the Austrian Research Promotion Agency (FFG, https://projekte.ffg.at/projekt/3849162), the Austrian Climate and Energy Fund (Klima+Energie-Fonds; https://www.klimafonds.gv.at/), the homepage of the funding program (Vorzeigeregion Energie, https://www.vorzeigeregion-energie.at/vorzeigprojekte/biochar-for-industry/) and in the issue 1/2024 of the “energy innovation Austria” magazine of the Austrian Federal Ministry for climate action,

environment, energy, mobility, innovation and technology (https://www.energy-innovation-austria.at/wp-content/uploads/2024/02/eia_01_24_deutsch_fin.pdf).
In addition, several scientific publications have been published within the course of the project. The complete list can be found in Chapter 6.

3.2 WP2: Basic system design

The BC4I project primarily focuses on the development and implementation of a novel tar reforming reactor. For a meaningful test of the tar reforming reactor, a pyrolysis gas flow that is as constant as possible is required. To enable a continuous operation at the pyrolysis reactor for the test of the tar reforming reactor, the use of a continuous process would be advantageous.
Based on the arguments above, it was decided by all partners to provide a continuously operating pyrolysis process for the testing plant at Polytechnik to create a good and meaningful basis for the development and tests of the tar reforming reactor. Moreover, this continuously operating reactor seems also very interesting for future large-scale applications of Polytechnik which is an additional positive synergy.

Consequently, a basic concept for a new testing plant and for a real-scale plant, both accompanied with mass and energy balances, have been developed.

3.2.1 Concept and balance of the new testing plant at Polytechnik

With the aim of developing a continuous pyrolysis process for the new testing plant at Polytechnik, different variants of pyrolysis gas generation have been investigated (pyrolysis reactor heated by direct heating by pyrolysis gas; pyrolysis reactor with indirect wall heating via hot flue gas from the PG burner passing along the outer reactor walls).
The pyrolysis reactor with wall heating by hot flue gas from the PG burner proved to be advantageous and has thus been chosen as the concept for the new testing plant at POLY.
Furthermore, preliminary investigations based on kinetic calculations of tar reforming have shown that pyrolysis gas reforming by partial oxidation (POX) in combination with thermal and catalytic tar reforming could lead to better tar degradation rates and lower soot formation. For this reason, the pyrolysis reactor was coupled with a tar conversion zone comprising a thermal tar reforming stage, optional partial oxidation and a tar reforming catalyst at the new testing plant to be able to perform tests flexibly.
The framework conditions for the mass and energy balances are based on data obtained in previous R&D projects. Table 1 and Table 2 show the composition of the feedstock (beech) and the charcoal, respectively, as used in the calculations (analyses based on results of previous R&D projects).
According to experiences from the operation with the existing test plant at Polytechnik (from a previous R&D project), it was considered that the charcoal output corresponds to about 30 to 32% of the biomass input (related to d.b.).
The biomass feed rate of 30 kg w.b./h was selected for balancing the testing plant. This size is based on the results of the detailed CFD simulations performed within WP3 and enables POLY to use components of the existing pyrolysis testing plant for the new technology.

Table 1: Chemical composition of the feedstock considered in the mass and energy balances
Explanations: w.b. … wet basis; d.b. … dry basis; biomass used: beech

Biomass type	wood chips beech	
Biomass water content	wt% w.b.	10.73
C	wt% d.b	48.65
H	wt% d.b	6.02
N	wt% d.b	0.11
S	wt% d.b	0.01
O	wt% d.b	44.63
AC	wt% d.b	0.58
Gross calorific value	MJ/kg d.b.	19.47

Table 2: Chemical composition of the charcoal considered in the mass and energy balances
Explanations: w.b. … wet basis; d.b. … dry basis; AC … ash content

Charcoal		
C	wt% d.b	85.50
H	wt% d.b	3.10
N	wt% d.b	0.30
S	wt% d.b	0.01
O	wt% d.b	9.27
AC	wt% d.b	1.81
Gross calorific value	MJ/kg d.b.	32.50

The pyrolysis gas composition (N2, H2, H2O, CO, CO2, CH4 and tars) was pre-defined based on tests and analyses within previous R&D projects. The composition of the tars and hydrocarbons was approximately defined based on detailed 1D simulations performed in parallel.
For an approximate calculation of the reactions to be expected in the thermal conversion zone, a 1D-model developed by BIOS was used with detailed reaction kinetics concerning tar and soot formation. Based on the PG compositions resulting from the reactions in the thermal tar conversion zone, the cp values and enthalpies of the PG could be calculated via the material data of the individual components.
The general concept of the newly developed process is shown in (see also Figure 1.
The basic concept of the testing plant features no gas engine and a propane gas burner to provide energy for the reactor heating (to enable a more flexible operation of the plant):

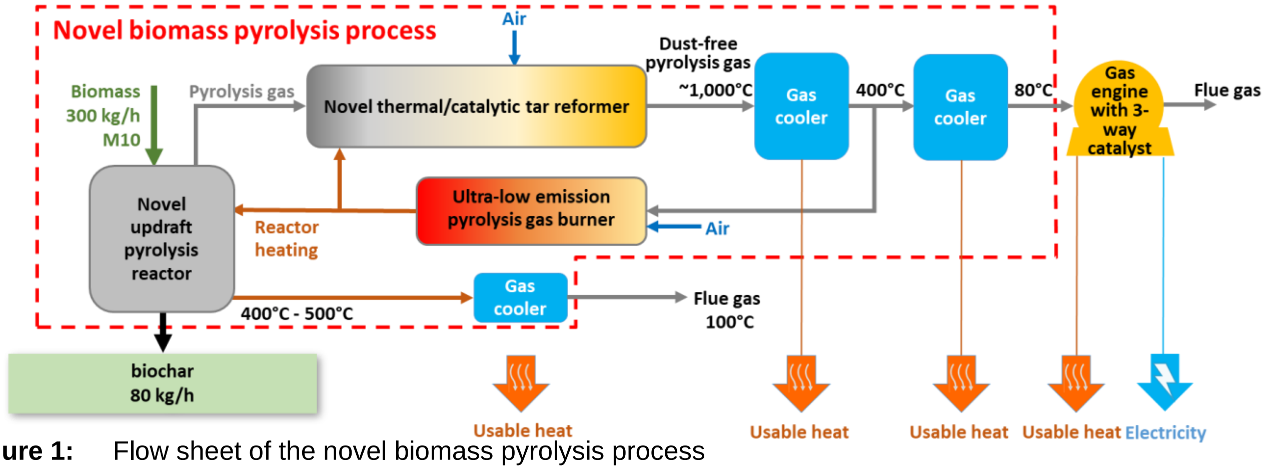

Figure 1: Flow sheet of the novel biomass pyrolysis process

Explanations: NCV…net calorific value; assumption: gas engine electric efficiency 40%, gas engine thermal efficiency 45%, biomass feed with 11 wt% moisture content

Based on the results of the balance, about 30 wt% of the dry basis of the biomass feed is converted to biochar (8 kg/h). This represents, based on NCV, >50% of the fuel power. As the testing plant does not feature any energy-related pyrolysis gas utilisation (the gas is burned in the pyrolysis gas burner and cooled off in an evaporative cooler), while the heating of the pyrolysis reactor and thermal conversion zone is provided by a propane gas burner, the energy balance over the complete testing plant is not shown as it is not representative for the technology in industrial scale. For the results of the energy balance of a real scale plant, see section 3.2.2

The results obtained define the relevant interfaces and requirements for the individual components in terms of size and material specifications that form the basis for the book of specifications for the testing plant as well as for the CFD-aided development of the pyrolysis reactor and the development of the control concept for the testing plant within WP3 and the development of the novel PG reformer and its integration (including the adaptation of the gas burner) within WP4.

3.2.2 Basic concept, mass and energy balances for a real-scale plant

The BC4I project application describes a quasi-continuous process based on batch pyrolysis reactors coupled with a continuously operating gas burner. For a possible real-scale plant with a biomass feed of about 2,085 kg/h (wet basis) which corresponds to a biochar production volume of about 600 kg/h (corresponding to approx. 4,500 - 5,000 t/a), a concept and associated mass and energy balances have also been prepared.

The basic concept of the real-scale plant comprises the following main components:

- Pyrolysis reactor with wall heating
- Thermal tar reforming reactor with wall heating
- Pyrolysis gas burner to supply sufficient heat for the pyrolysis reactor
- Gas engine to utilise the main share of the pyrolysis gas
- Efficient heat recovery over all process units

The results of the energy balance from the real-scale plant concept are summarised in Figure 2. The total efficiency of the process is well above 90%. Additional electricity production and high overall efficiency shall considerably contribute to an improved economic performance and thus competitive biochar process based on the new technology.

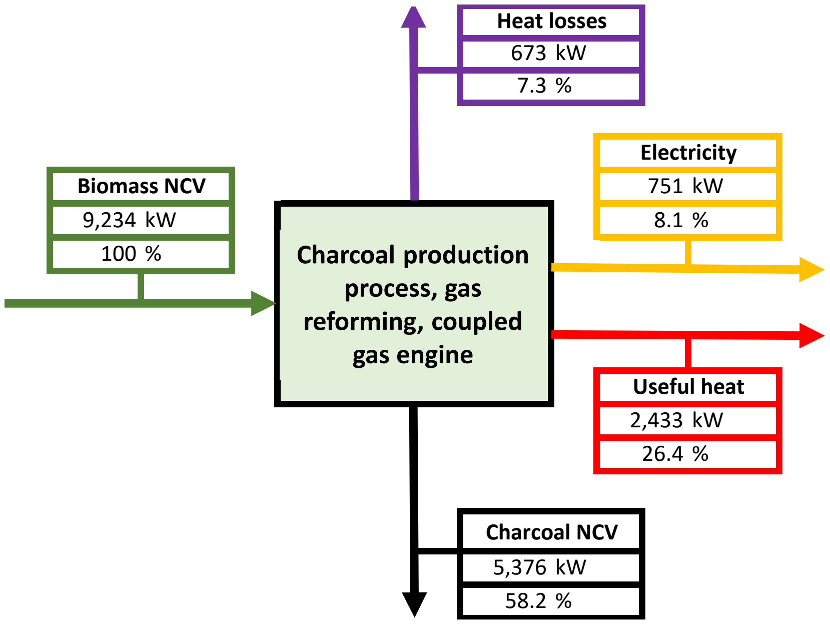

Figure 2: Energy balance for the basic concept of a real scale plant
Explanations: NCV…net calorific value; assumption: gas engine electric efficiency 40%, gas engine thermal efficiency 45%, biomass feed with 11 wt% moisture content

The energy balance of the real-scale plant results in a chemical power of the pyrolysis gas (NCV) of 1,877 kW that can be used for electricity production. Assuming an electric efficiency of the gas engine of 40%, this results in an electric power production of around 750 kW.

3.2.3 Basic concept of the tar reforming catalyst

The aim of the project is to use pyrolysis gas in an Internal Combustion Engine (ICE) application. Tar components will cause durability problems in the engine due to deposits, so it is important to minimise the tar concentration upstream the engine. Tar reforming will be used as a method to reduce the concentration of tar components.

Wood pyrolysis result in formation of primary, secondary and ternary tars with increasing complexity and soot appearance, see Figure 3 In addition, a synthesis gas comprising H_2, CO, CO_2, H_2O, N_2 and light hydrocarbons is formed. Complicated non-catalytic reactions between tars and synthesis gas will occur in the gas phase and heavy tar components might also form soot particulates (polyaromatic compounds) during decomposition. Some inorganic dust might also be found (originates from inorganic compounds) in the fuel (wood).

Tar decomposition is extremely challenging from a theoretical perspective and characterised by an extensive complexity since tars comprise a complex mix of polyaromatic and heterocyclic hydrocarbons, which can be decomposed via reforming and/or hydrogenation by a suitable catalyst. Wood also contains sulphur as a natural ingredient, which results in H_2S-levels ranging from about 5 to 50 ppm(v/v)

in the gas stream. Dust and tar cause fouling on surfaces including the catalyst and H_2S will give rise to catalyst poisoning via competitive adsorption and sulphide formation.
There are several literature studies that describe the possibility to use different bed materials, such as dolomite, magnesite, olivine etc. for tar reforming. However, these types of materials have limited efficiency and low capacity (need to use a large bulk of material). The aim of the project is to investigate various precious metal (PM) catalysts as candidates in tar reforming under realistic process conditions. The different PM catalysts will be based on a high-temperature stable wash coat with low surface acidity and high oxygen conduction and most probably including platinum and/or rhodium as active catalyst materials.
Based on results obtained within WP2 the following basic requirements for the operation of the catalyst can be defined:

- Operation temperature – probably in the range of 850-950 °C
- The quality of the biomass (i.e. amount of sulphur and other trace elements which can deactivate the catalyst) needs considerations (especially related to the S content)
- Dust in the gas should be minimised– dust may settle on the catalyst surface and give rise to a diffusion boundary layer
- Amount of steam present; steam is mandatory in steam reforming
- Gas velocity – too low superficial velocity will decrease the external mass-transfer to the catalyst; gas velocities in the free cross section of the catalyst should be in the range of 3 m/s at least.

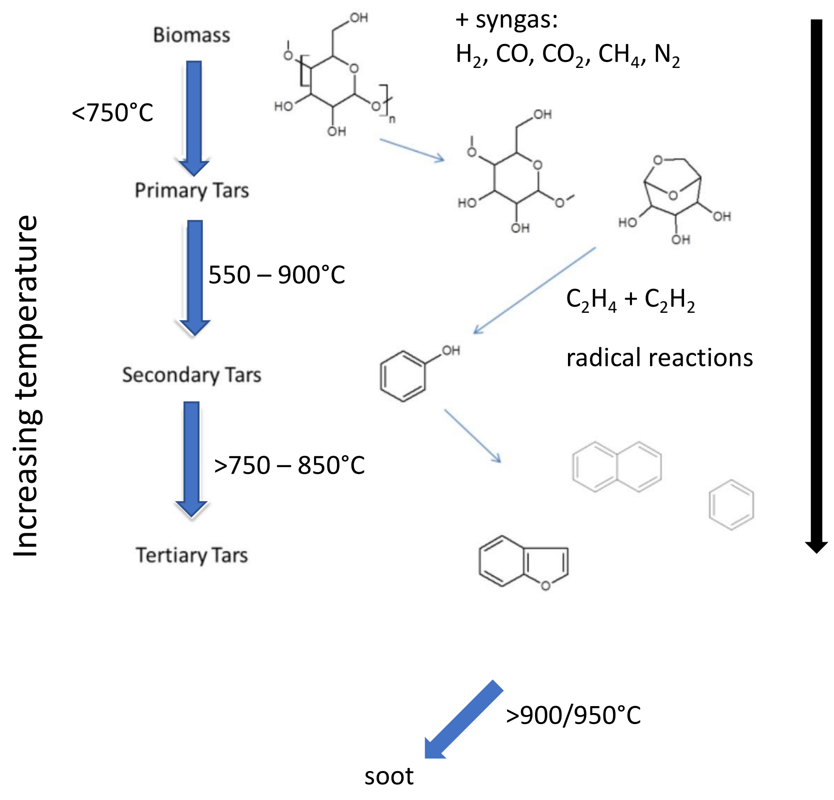

Figure 3: Principal complexity of tar generation during pyrolysis

A detailed investigation of different catalyst recipes at different operating conditions has been carried out during WP4 (see related section)

3.3 WP3: Adjustment of the pyrolysis reactor control

3.3.1 Definition of biochar quality

Development of a usability matrix:

Previous work on the topic of biomass utilization in metallurgy, as well as data from literature, show that biochar from biomass has different properties compared to conventionally used carbon carriers (fossil carbon). Therefore, the biochar properties need careful examination regarding its usability in the metallurgical industry. For example, the use in a Waelz process requires a lower reactivity to ensure that carbon is available at the right place and time in the Waelz furnace. Whereas, in a shaft furnace, carbon carriers must feature an adequate compressive strength to withstand the load of the charged material and to ensure a proper gas flow through the furnace.

To provide an overview of the requirements for an alternative carbon carrier and the properties of the available biochar, the partners involved in the project as well as the advisory board have been asked about the following properties for the application of carbon carriers in their aggregates:

- Compressive strength
- Reactivity
- Moisture content
- Impurities
    - Volatile
    - Non-volatile
- Grain size

In addition, a questionnaire was sent to the industrial partners to define the potential applications of biochar as precisely as possible. The replies from the contacted companies show a rather wide range of individual properties depending on the actual use of carbon in their facilities. The replies are summarized in Table 3 and show that the main chemical properties can be fulfilled by biochar from beech and spruce.

Table 3: Comparison of required carbon carrier properties with typical biochar properties

Explanations: typical range … summary of the replies from the contacted companies; typical properties of biochar … range of measurements at MUL and BIOS from different biochar qualities (spruce and beech)

Parameter		typical range	typical properties of biochar
Required carbon content	[wt%]	80 +	80 - 90
Volatile Matter	[wt%]	1 - 7	1.3 - 12.3
Ash content	[wt%]	up to 10	< 1 - 14
Sulphur content	[wt%]	up to 1.3	0.01 - 0.07
Grain size	[mm]	up to 10 mm (250 mm)	milling/grinding possible
Max. quantity per annum		1,000 to 90,000 t per year	

The results of the work performed were compiled in a matrix that summarises the required biochar properties for different metallurgical applications (see Figure 4) and provides a set of quality criteria for biochar application in in these processes.

characteristics/parameters	unit	aggregates/applications: Company 1, waelz process			Company 2, carburizing agent		
carbon content	[%]	90	-		98	-	
volatile matter	[%]	not relevant				-	1
ash content	[%]	not relevant				-	0.3
ash basicity	[CaO/SiO2]	0.9	-	1 (SiO2 shouldn´t be too high)	not relevant		
sulphur content	[%]		-	1		-	1.3
nitrogen content	[%]	not relevant				-	0.8

characteristics/parameters	unit	charcoal from biomass	
carbon content	[%]	-	90
volatile matter	[%]	-	1.3
ash content	[%]	-	8.7
ash basicity	[CaO/SiO2]	-	
sulphur content	[%]	-	0.03
nitrogen content	[%]	-	0.67

Figure 4: Extract from the matrix created for the use of biochar in metallurgical aggregates
Explanations: Biochar properties shown are based on biochar from beech

The matrix allows the input of essential requirements for different processes and the analysis and data of the pyrolyzed biomass. The entered data is compared, and the results are color-coded, making it easy to identify which parameters of the biochar meet the requirements and which do not. In addition to the contents of carbon, volatile, ash, sulphur, etc., the matrix also includes data on reactivity and annual quantities required, for example.
These quality criteria were used to check the suitability of the biochar produced in the testing plant and for future considerations regarding the design and control of a large-scale demonstration plant.

3.3.2 Potential applications for the use of biochar:

In addition to the companies involved in the project, research was done to find out which other Austrian companies in the field of metallurgy see a theoretical potential for the use of biochar. The results are listed below.
Possible biochar applications (companies):

- Breitenfeld Edelstahl (about 1,000 t per year)
- Böhler Edelstahl (about 1,000 t per year)
- Georg Fischer (about 3,000 t per year)
- voestalpine Linz (about 1.3 mio t per year)
- voestalpine Donawitz (about 360,000 t per year)
- Montanwerke Brixxlegg (about 3,500 t per year)
- Tiroler Rohre GmbH (about 7,000 t per year)

The numbers listed above show that a large application potential is given, even if biochar can only partly substitute fossil carbon. There is further particular potential in the foundry industry, where carbon is used, for example, as a carburizing agent in grey and malleable cast iron. The literature refers here to an average of 1 to 1.5 % of the iron production.

3.3.3 CFD aided design of the pyrolysis reactor

The work related to Task 3.2 (CFD simulations of the pyrolysis reactor to adjust the process conditions to the feedstock/biochar quality needed) was performed in two steps.
Step 1 dealt with the development of a basic concept for a continuously operating pyrolysis reactor for biochar production for a first testing plant.
Step 2: Based on the results and the derived pre-optimised design from step 1, the steady-state pyrolysis process has been simulated in detail within the second step using a DPM-based (DPM: Discrete Phase Model) particulate model in combination with a detailed gas phase reaction mechanism which was specially developed for gas phase conversion of biomass.

Ad Step1:

The underlying CFD work focused on the optimisation of the flue gas flow around the pyrolysis reactor and the heat transfer from the heating jacket of the reactor to the biomass bed, as well as the heat losses to the environment.
For this purpose, a simplified bed model has been used for the simulations. A constant temperature profile was created for the simulation, which was considered as an approximation for the radiant heat transfer, as well as for the convective heat transfer between the bed and the reactor wall. The conduction within the biomass bed and in the gas was neglected, as experience has shown that it has minor contributions to the overall heat transfer.
The preliminary design of the reactor was based on basic findings from the CFD simulations and test runs in a previous R&D project of BIOS and Polytechnik. The reactor inner diameter of the preliminary design was designed for a pyrolysis gas velocity below 0.5 m/s, at a feed mass flow of 25kg w.b./h of wood chips.

Within this step, a CFD-based sensitivity study with the following focal points was carried out:

- The investigation of the influence on the flow through the flue gas jacket and the responding heat transfer to the pyrolysis reactor by varying the gap width of the flue gas jacket.
- A first evaluation of the influence on heat fluxes, surface temperatures and the flow in the heating jacket, by varying flue gas inlet temperatures to the reactor.

The flue gas is fed in the channel tangentially to induce a swirling flow which improves the heat transfer. The version with the best heat transfer to the reactor wall with an acceptable pressure drop was selected for further simulations

Ad Step2:

The results from the second step were used to draw conclusions about the progress of the carbonisation process along the reactor height, from which further optimisation steps concerning the heat transfer to the reactor, the flue gas temperature and the residence time of the particles in the reactor could be derived. Moreover, the thermal tar conversion zone atop the pyrolysis reactor was evaluated within the CFD simulations.
Based on the pre-optimised variant from step 1, different variants with different reactor heights, insulation thickness and operating temperatures were investigated.
A pre-evaluation of the different variants was performed using a simplified discrete phase 3D model for modelling the biomass bed and a simplified gas conversion model.

Based on the simulations results, an optimised variant in terms of reactor height (pyrolysis reactor and thermal conversion zone) and biomass and flue gas throughputs was selected. Since the CFD results of the preliminary variants showed that the reactor still has additional capacity for the selected biomass input, the biomass input was increased by 20% for the optimised variant (30 kg/h). Following, this variant of the reactor has been simulated with a detailed DPM-based pyrolysis model according to Ranzi et al. in combination with a detailed gas phase reaction mechanism which was specially developed for gas phase conversion of biomass (POLIMI-BIO mechanism - 134 species, 4169 chemical reactions). The combination of the detailed models is novel and to the knowledge of the authors, it is the first simulation world-wide for a fixed bed pyrolysis reactor with detailed reaction kinetics and a detailed gas/tar conversion considered. Due to the complex mechanisms and the resulting high computational effort, the simulation had to be carried out as a 2D rotational symmetric simulation. Nevertheless, the computational efforts have been very high, but the simulations have been completed successfully.
As a result of the simulations, a detailed insight into the pyrolysis process has been provided.
Relevant results of the simulation are discussed below.

Due to the lower gas temperatures of the detailed simulation at the fuel bed surface, and the better description of the gas composition the prediction of the gas velocity at the bed surface is more accurate. According to simulation, the pyrolysis gas leaves the bed surface with an average velocity of < 0.5 m/s. The low gas velocities enable low particle entrainment from the bed which is very important for the operation of the catalytic converter inside the conversion zone and the downstream use in a gas engine.
The particle residence time inside the heated zone of the reactor is within a range of 50 to 60 minutes for the detailed 2D simulation model.
The average C content of the biochar reaches a range between 85 and 90 wt.%.
The minimum char temperature in the area between the end of the carbonisation process, and the level of flue gas outlet (hottest area in the reactor) is within a range of 450 to 500°C, which is sufficient for the degradation of PAHs.
The detailed pyrolysis model results in a charcoal yield (about 30% of the dry biomass input) close to the values usual for batch reactors at comparable temperatures (30 to 32%).
The maximum surface temperature of the walls inside the flue gas jacket (at flue gas entry) is about 900°C according to the detailed simulation. This temperature must be considered for the material selection in connection with the oxidising atmosphere in the flue gas duct and the reducing conditions on the pyrolysis gas side.
The pyrolysis gas reaches a temperature above 800°C at the exit of the simulation domain (at the end of the thermal conversion zone).
At the exit from the fuel bed, the tar content in the pyrolysis gas at bed outlet is about 25 wt% or approx. 280 to 300 g/Nm³ w.b.. Due to the long thermal conversion zone, the tars are thermally cracked and thus decrease to approx. 2 to 3 wt% at the exit of the reactor (tar conversion about 90%), which is an advantage for the operation of the subsequent catalytic conversion zone (enables an improved overall tar conversion). Most of the tars get decomposed and a certain amount of benzene, which is a very stable tar compound, forms (together with some other tertiary tars). Therefore, the concentrations of the main tar species released from the fuel bed decrease while the concentration of benzene increases over the height of the thermal gas reforming zone.

The composition of the gas and its heating value seem plausible in comparison to gas analyses available from batch reactor measurement of comparable operating conditions and were used as input parameters for the simulation of the gas reformer (see WP4).

Conclusions
The simulation results showed that the optimised variant is sufficiently dimensioned for the biomass and flue gas throughputs investigated. The detailed simulation enabled a more precise prediction of the pyrolysis gas composition, its heat transfer and its residence time in the gas-heat-up-section, which in a next step was used for the design of the pyrolysis gas reformer which is connected to the pyrolysis reactor.
Wall temperatures of about 900°C must be considered for the material selection in connection with the oxidising atmosphere in the flue gas duct and the reducing conditions on the pyrolysis gas side. Large temperature gradients around the flue gas entry must also be considered regarding thermal stress.

3.3.4 Development of a process control concept for the testing plant

Based on the results of the CFD-aided optimisation of the pyrolysis reactor described above and the results of the design and adaption of the other main components (see WP4) a control concept for the testing plant has been developed by POLY and BIOS.
The process control shall ensure optimal process conditions with respect to temperatures, mass flows and temperature of all relevant plant components. The development of the process control concept was supported by the CFD simulations performed.
The control concept developed comprises the following main control loops:

- Biomass feed control
- Biochar discharge control
- Control of the biochar airlock (double airlock system)
- Temperature control of the biochar in the discharge channel and the biochar conveyor
- Temperature control of the pyrolysis zone and the thermal tar conversion reactor
- Pyrolysis gas temperature control (thermal conversion zone, catalyst)
- Pyrolysis gas temperature control at pyrolysis gas burner inlet (gas cooler upstream pyrolysis gas)
- Pyrolysis gas burner control (temperature control, air staging)
- Control of the under pressure (flue gas fan control)
- Flue gas recirculation control
- Control of the flue gas temperature upstream flue gas fan (flue gas cooler)

As the pyrolysis process shall be performed without the presence of O_2, the discharge system to the biochar storage container needs to be airtight. This shall be achieved with a double airlock to be installed at the end of the grate. Downstream the airlock a biochar conveyor transports the biochar to the storage container. To avoid self-ignition, the biochar needs to be cooled well below 100°C.
The pyrolysis reactor and the thermal tar reactor shall be heated directly with a propane gas burner (the burner at the existing test facility could be used for this purpose). To ensure constant experimental conditions, the burner should be operated at constant power. The target inlet temperature into the

reactor (approx. 950°C) can be adjusted by mixing with air. The process can be influenced by the selected flow rate (burner power) and the flue gas inlet temperature into the reactor.
The control concept will be further adapted and fine-tuned during the detailed design of the testing plant performed in WP5.

3.4 WP4: Development of the novel pyrolysis gas reformer and its integration

3.4.1 CFD-aided development of the gas reformer and system integration

The work focussed on the design of a thermally and catalytically acting pyrolysis gas reformer (gas conversion zone) and builds on the simulation work performed for the design of a test facility for a continuously operating pyrolysis reactor (see WP3).
Based on the gas composition achieved from the detailed bed simulation (see WP3), a gas conversion zone including optional partial oxidation zones and a catalytic converter has been designed and optimised by CFD simulations. The focus was on the geometrical design of the conversion zone, as well as the geometrical pre-definition of the catalytic converter regarding its dimensions and the number of meshes (in close coordination with Catator).
The simulation results showed that based on the tar content at the inlet of the conversion zone (outlet of the thermal conversion zone, discussed in WP3), a tar reduction > 99% should be achievable.

3.4.2 CFD-aided adaptation of the pyrolysis gas burner

This work focused on the CFD-based adaptation of a pyrolysis gas burner concept for the combustion of pyrolysis gas out of a previous R&D project. The adaption of this burner is necessary to adjust it to the framework conditions of the new technology developed and to the testing plant. The original burner concept featured three combustion zones (primary, secondary and tertiary combustion zone) with flue gas recirculation for temperature control. The staged combustion combined with moderate temperatures enable a full burnout and low NOx emissions. However, the existing concept has occasionally led to ignition problems during operation, which needed to be addressed.
The work dealt with the modification of the nozzle design to the requirements of the pre-oxidised product gas from the stationary pyrolysis reactor that has been developed (see WP3 and above) and the optimisation of the burner concept for good pyrolysis gas burnout and stable operation with a defined band width of gas compositions.
Based on an existing pyrolysis gas burner design, optimisation measures regarding the nozzle design and the position of the flue gas recirculation nozzles have been performed.
Following, the modified burner concept has been CFD-simulated.
The changes made in terms of nozzle design and position of the recirculation nozzles showed a complete burnout of the PG gas (CO < 10 mg/Nm^3 @ 3 Vol% O2) at low NOx levels.

3.4.3 Catalyst development - overview

Based on the findings described in WP2, different selected catalyst alternatives have been studied in a small test reactor at Catator, using an expected gas composition at this section of the tar conversion zone and H_2S levels between 0 and 50 ppm. The catalysts investigated are based on wire-meshes that are coated with a washcoat (to provide sufficient specific surface area and pore size) and catalytically active metals.

Different tar compounds have been added to the gas environment, under different gas loads and in a relevant temperature span.
The objectives of the laboratory studies were:

- To investigate various catalyst candidates in tar reforming under realistic process conditions with one or several selected tar components
- To investigate the impact of H_2S on the catalyst activity
- To investigate effects of diffusion limitation, H_2S-content and fouling by mathematical models
- To suggest a suitable catalyst candidate and optimum process conditions

Based on the results obtained the following conclusions can be derived:

- Sulphur compounds present in the synthesis gas will impact the observable activity significantly
- Pt seems to be a suitable active metal due to its higher S tolerance
- Dust (soot) layers will add pore diffusion resistance to the system (worse results in an atmosphere containing particulate matter)
- Catalysts should be operated in the range of 850 to 950°C with up to 20 ppm (v/v) H2S

In addition to tests at Catator, comprehensive test series with pre-selected catalysts have been performed at BIOS. The series focused on the optimization of the pre-selected catalyst recipes.
A suitable lab-reactor has been developed and set-up by BIOS. The test run set-up is shown in Figure 5. The main components are the gas mixing station with gas bottles and mass flow controllers, a humidifier, an injection unit for benzene/naphthalene, a lab-reactor with a reactor tube made of temperature-resistant stainless steel and auxiliary equipment like thermocouples, valves, sampling points for gas measurements and heat tracing for pipes. Gas measurement was done by NDIR (CO/CO_2), TCD (H_2), FID (sum of hydrocarbons) and FTIR (benzene, naphthalene and other hydrocarbons).
The results from the tests performed at the lab-scale reactor were compared with results from high temperature equilibrium calculations (HTEC).
Without H_2S in the gas the concentrations of the main gas components are close to equilibrium according to HTEC and follow the expected trend over the temperature range evaluated.
The results show that the tar conversion efficiency decreases with increasing tar load of the gas. Following, a reduction of the tar load by primary measures (thermal tar conversion prior to catalytic conversion) is of relevance. Tar concentrations below 6,000 ppm shall be the target.
Catalysts are significantly affected by the presence of H_2S. Loss of catalyst performance is of similar magnitude, when the H_2S concentration is increased from 0 to 6 ppm and from 6 to 25 ppm respectively. Deterioration of catalyst performance due to H_2S is most pronounced in the temperature range below 900°C.
Based on the findings from the test runs at the lab-scale reactor at BIOS a suitable catalyst for the test runs has been defined:

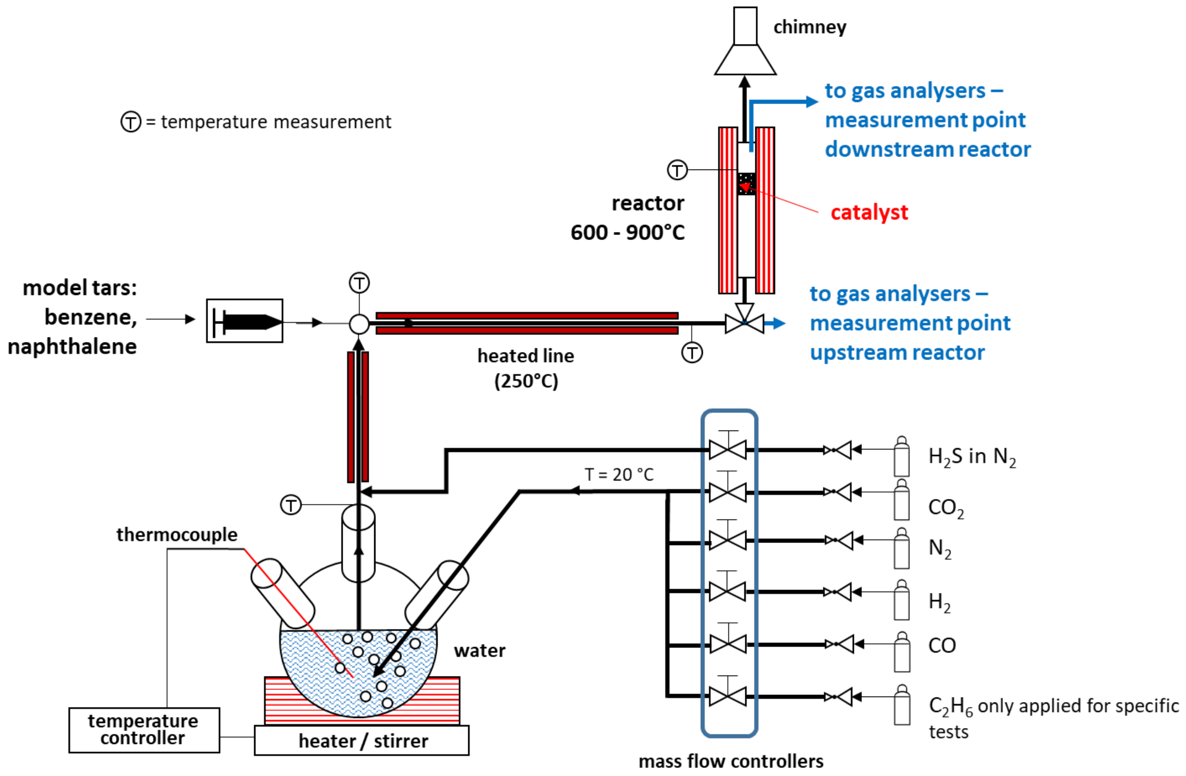

Figure 5: Test run set-up for the catalyst tests in a lab-scale reactor at BIOS

3.4.4 Catalyst tests in a lab-scale gasifier at BIOS

To gain additional information about the tar reforming efficiency under real gas conditions, catalyst tests in an appropriately adopted lab-scale gasifier were performed at BIOS. Figure 6 shows the lab-scale gasifier during the start-up phase. The installation was performed by Polytechnik, cold and warm start-up were performed by BIOS and Polytechnik. The test runs have been performed by BIOS.

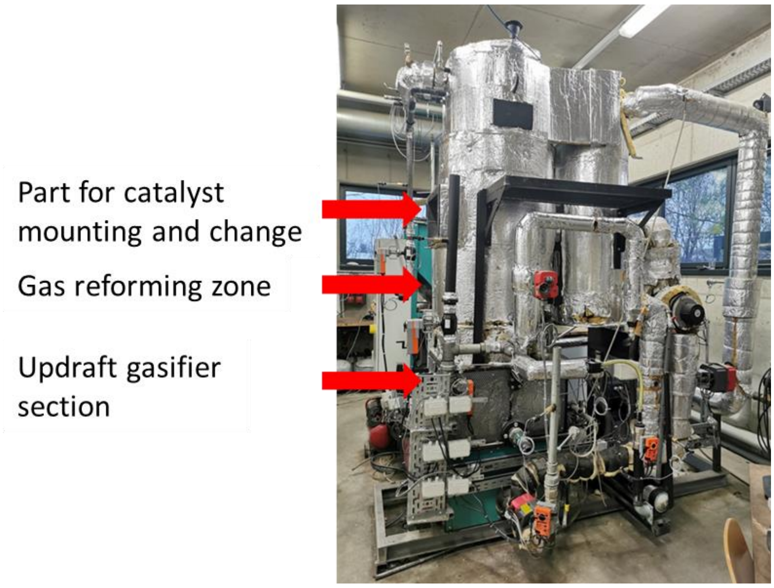

Figure 6: Appropriately adopted lab-scale gasifier at BIOS for catalyst tests

3.5 WP5: Design, construction and installation of a prototype

3.5.1 Unit design

Based on the results of WP2, WP3 and WP4 the overall process control concept and process flow sheet (updated with results from WP3 and WP4) as well as the design and specification of the main components of the testing plant have been defined and formed the basis for the detailed design of the individual components.
The testing plant including all new components was designed in detail, constructed and built by partner Polytechnik. BIOS supported Polytechnik in the process. Following, a short overview of the main components is given.

Feeding system: Fuel feeding is provided by conveying and feeding screws.
Char discharge system: The concept for the biochar discharge consists of several horizontal discharge screws and rotary valves and a flexible connecting piece and a container. The char discharge system must be tight to avoid the input of any false air into the discharge system and the pyrolysis reactor, as the oxygen in the air would react immediately with the charcoal and or the pyrolysis gas. The cooling of the charcoal is provided by natural convection (see WP4).
Pyrolysis reactor and tar conversion zone: The design of the pyrolysis reactor and the thermal conversion zone was based on the results of the CFD simulations (optimised variant). To allow for a smooth construction and installation, some changes had to be made to the original design, but the main remained the same.
The reactor featured several measuring points for continuous (temperature, pressure, volume flow) and discontinuous measurements (gas measurements).
Pyrolysis gas cooler: the pyrolysis gas cooler was designed as a fire tube boiler.
Pyrolysis gas burner and flue gas cooler: The pyrolysis gas burner was constructed based on the recommendations derived from the CFD simulations performed see WP4).

3.5.2 Construction and installation

The installation of the plant components took about 2 months. Following the installation of the plant components, the electric installation and the installation of the insulation were carried out. In parallel the control system was implemented. After completion of the cold start-up (check of all mechanical and electrical connections, signal tests, tightness checks etc.), the first phase of the hot start-up took place. Within this phase, the refractory was dried by operating the two propane gas burners of the plant (burner for the reactor heating and start-up burner of the pyrolysis gas burner).
After the drying of the refractory lining, the pyrolysis reactor/thermal conversion zone and the pyrolysis gas burner were heated up with the two propane gas burners. Following, the hot start-up (first tests with fuel) was initiated.
Figure 7 shows some of the main components of the installed prototype testing plant.

Figure 7: Prototype testing plant – selected plant components installed
Explanations: left … pyrolysis reactor and thermal conversion zone with fuel feeding system, right … pyrolysis gas burner with pyrolysis gas cooler in the back

3.6 WP6: Performance and evaluation of test runs and stepwise optimisation

Within WP6, BIOS and POLY performed intensive test runs at the prototype testing plant at POLY. During the test runs, the testing plant was operated with beech chips.
Practical data and experience regarding the operation of the individual key components (especially the reactor control and the PG reformer) could be obtained and performance data have been evaluated. In addition, an appropriate stepwise optimisation of the reactor control and the tar reformer took place.
The first hot start-up of the plant with fuel was in August 2023, several test runs followed until the end of the testing campaign in January 2024. The first months of the testing campaign were used to improve and optimise plant performance followed by test runs with the full measuring and monitoring program. Despite the efforts to improve the system, problems with the tightness of the heating jacket of the pyrolysis/thermal conversion zone reactor prevailed, leading to an unwanted false air inlet in den thermal conversion zone.
Apart from measuring and recording all operating data (volume flows, temperatures, pressures etc.), the feedstock and the biochar produced were analysed (elemental composition, water content, ash content. Volatiles (biochar only)) and detailed product gas measurements as well as flue gas measurements downstream gas burner were performed.

3.6.1 Relevant test run results

Pyrolysis reactor and biochar production
In all test runs, pre-dried beech chips with a particle size between 20 and 63 mm have been used (see Figure 8). The water content was below 10%.

Figure 8: Beech chips used during the test runs

The chemical composition of the fuel used is shown in Table 4.

The wet chemical analysis showed typical values for beech. Compared to the reference, the ash content is slightly higher, hence also the contents of most of the ash forming elements are somewhat elevated. Despite the unfavorable conditions in the pyrolysis reactor and especially thermal conversion zone (false air inlet, entry of flue gas from the heating jacket) that also led to a reduced biochar yield and a lack of a reliable level control, biochar with good quality (C- contents in the range of 85 to 90%) could be produced.

Table 4: Composition of beech used during the test runs compared with database values

Explanations: The reference values shown are based on four analyses of beech samples from the BIOS internal biomass fuel database.

		Beech wk41/23	Beech wk06/24	Beech wk08/24	Beech ref. (database values)	
Lab-#		14488	14514	14523	mean	s
Moisture content	wt% wet	6.1	3.9	3.9	8.6	4.3
Ash content	wt% dry	0.8	0.8	0.8	0.7	0.1
Ash content corr.	wt% dry	0.6	0.6	0.6	0.5	0.1
GCV	MJ/kg dry	20.0	20.0	19.9	19.5	0.1
NCV	MJ/kg wet	17.4	17.8	17.7	16.4	0.9
Volatiles	wt% dry					
C	wt% dry	49.60	49.00	49.00	48.78	0.15
H	wt% dry	6.10	6.30	6.20	6.05	0.08
N	wt% dry	0.08	0.10	0.10	0.11	0.02
S	mg/kg dry	200.5	119.0	109.0	105.5	16.5
Cl	mg/kg dry	<50	50.0	35.0	36.0	5.6
Ca	mg/kg dry	945.0	1,450.0	1,450.0	1,170.0	276.5
Si	mg/kg dry	724.5	140.0	120.0	121.0	19.1
Mg	mg/kg dry	495.0	475.0	400.0	341.3	88.4
Al	mg/kg dry	60.3	30.9	21.9	13.7	6.3
Na	mg/kg dry	145.0	<20	<20	7.8	4.8
K	mg/kg dry	1,350.0	1,250.0	1,200.0	1,392.5	258.6
Fe	mg/kg dry	98.0	55.7	33.8	7.7	3.7
P	mg/kg dry	59.7	88.0	70.2	94.1	8.8
Zn	mg/kg dry	<5	<10	<10	2.7	0.3

Tar conversion zone

Pyrolysis gas measurements were performed to evaluate the performance of the tar conversion zone. The results showed that gaseous hydrocarbons such as ethane and propene as well as tar components such as benzene and naphthalene are almost completely reduced in the tar conversion zone. The high benzene conversion is of specific interest as benzene is considered as the most stable tar component. The results of the gravimetric tar measurements confirm these values (see Figure 9). Despite the higher PG gas flow and thus shorter residence times in the tar conversion zone, a tar conversion of >99% (based on the tar load at fuel bed exit) could be achieved.

The tar contents downstream the tar conversion zone are in an acceptable range for gas engines.

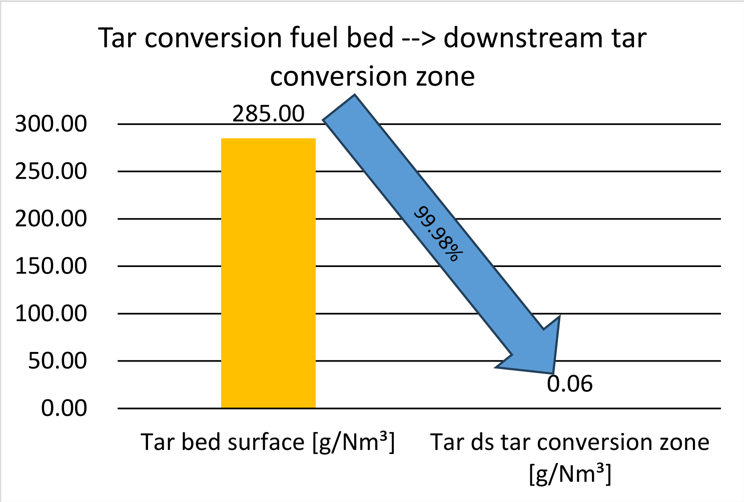

Figure 9: Tar conversion from the fuel bed to the end of the tar conversion zone

Gas burner and emissions

The flue gas analysis downstream PG burner showed an almost complete flue gas burnout at low O2 contents in the flue gas (CO < 10 mg/Nm³ @ 6 vol% O2 in dry flue gas) and moderate NOx emissions (around 225 mg/Nm³ @ 6 vol% O2 in dry flue gas). A lambda of about 0.9 should be achieved in the secondary combustion zone to provide good conditions for NOx reduction.

Considering the release rate of N from the fuel (approx. 25%) as well as the NOx emissions (approx. 200-230 mg/Nm³ @ 6 vol% O2 in dry flue gas) and flue gas volume flow measured, about 75 to 80 wt% of N that is released to the pyrolysis gas are converted to NOx. Concluding, an efficient NOx reduction is possible due to N embedding in the biochar and staged pyrolysis gas combustion in the Low-NOx burner- in total less than 20% of the fuel N get converted to NOx.

3.7 WP7: Characterisation and evaluation of the biochar for metallurgical applications

3.7.1 Compilation of a biochar database

To investigate different types of biochar and utilise information from previous biomass pyrolysis activities, a database was created. The project partners, namely MUL and BIOS, have entered the data available, regarding biochars produced from different biomass feedstocks. The database includes important information concerning biochar characterization like:

- chemical analysis,
- fixed carbon and volatiles,
- reactivity and
- specific surface area.

Furthermore, the information on biochar production, as provided by the manufacturer, is also listed. As shown in detail in Figure 10, the database also includes information on the type of biomass, the pyrolysis unit used, the biochar yield and treatment temperature and time.
The aim of this assembling is to provide an easily accessible and clear overview of the various types of biochar and their properties. Combined with the biochar quality criteria matrix, this data creates a comprehensive tool for evaluating biomass and biochar for metallurgical industry.

BIOCHAR																
Source	type of biomass	pyrolysis unit	max. temperature [°C]	time [h]	C [%]	H [%]	N [%]	S [%]	volatiles [%]	ash [%]	C_{fix} [%]	H_2O [%]	biochar yield [%]	CRI [%]	B.E.T. [m²/g]	test gas
MUL	Pinustaeda	twin screw reactor	750	-	89.40	1.74	0.18	<0,03	1.80	2.06	90.40	5.70	23.16	39.30	436.50	CO_2
			800	-	91.20	1.40	0.20	<0,03	1.60	1.45	94.05	2.90	23.00	31.70	505.50	CO_2
			850	-	86.40	1.20	0.18	<0,03	0.70	7.75	87.85	3.70	22.21	29.15	527.00	CO_2
MUL	Eucalyptustereticornis	twin screw reactor	750	-	87.40	1.72	0.14	<0,03	1.67	2.73	89.50	6.10	25.21	30.00	460.00	CO_2
			800	-	85.70	1.69	0.13	<0,03	2.50	3.40	88.05	6.10	24.65	27.90	481.00	CO_2
			850	-	90.50	1.26	0.20	<0,03	1.75	1.90	93.35	3.00	24.33	27.00	504.50	CO_2

Figure 10: Extract of the biochar database

3.7.2 Biochar characterisation

The properties of biochar strongly depend on the source products and the pyrolysis process. Various types of biochar were evaluated and compared with fossil C carriers at MUL during the project. Some examples for analyses performed are shown below:

a) Scanning Electron Microscope (SEM)

Figure 11 shows SEM images of the carbon carriers. A secondary electron detector was chosen in terms of the superior visualisation of the topography – compared to the backscattered electron detector – and thus it is easier to compare the surfaces of the individual samples. As can be seen, the two petroleum coke samples have a compact surface without pores and the particles themselves are rather globular. In contrast, the surface of the biochar is very open-pored and, according to the source materials, the pores are elongated in the natural growth direction of the wood.

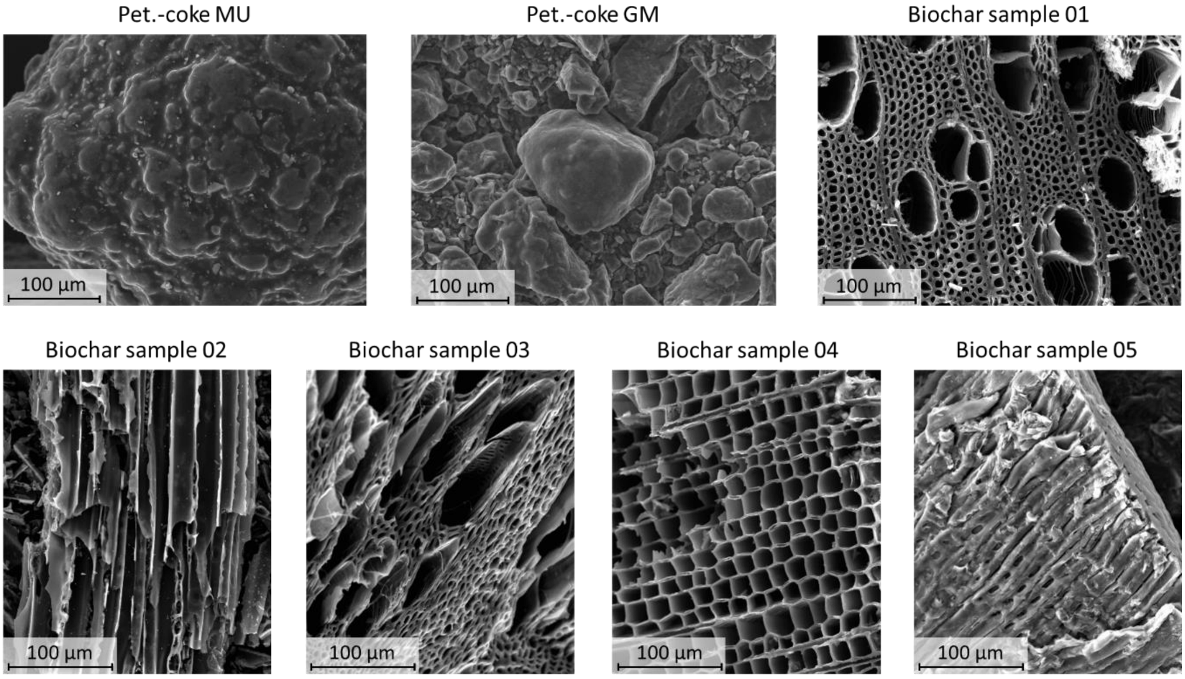

Figure 11: SEM-SE Images of the carbon carrier samples investigated

b) B.E.T.-Analysis (Specific Surface Analysis)

As the SEM images have already demonstrated, the surface areas differ between the two investigated types of carbon carriers. The measurements with a B.E.T.-analyser have confirmed a clearly higher surface area of the biochar (between 350 and 420 m²/g, see Figure 12) compared to petrol coke (< 2.5 m²/g, not shown in Figure 12). The B.E.T. analysis was performed according to ISO 9277:2014-01 with CO_2 as analysis adsorptive.

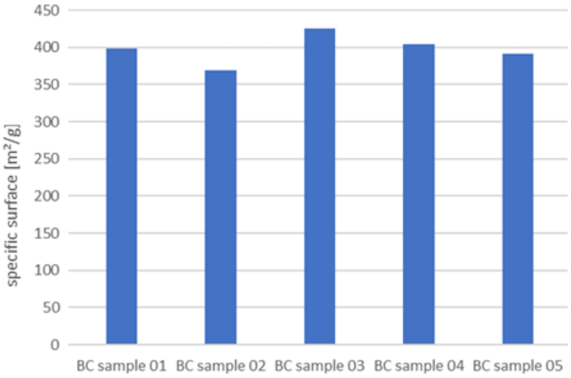

Figure 12: Specific surface of biochar samples tested (BC: biochar)

Apart from the general characterisation of biochar samples, their usability in different metallurgical processes were tested in laboratory scale. The processes evaluated included solid gas reactors like the Waelz process and liquid processes like lead recovery from slags in a smelting bath furnace or a submerged arc furnace (ferro alloy production).

The resutls showed that biochar can be seen as very promising carbon carrier for metallurgical reduction processes avoiding CO_2-emissions from fossil carriers.

However, it was important to study the different process types, evaluating which requirements are important, how different types of biochar meet these requirements and if an optimization of the biochar quality is possible.
Especially, for processes in solid stage with a certain heat-up phase the reactivity is important as losses until the material reaches the reduction zone lead to higher amounts required and increased off-gas temperatures. In case of application directly into a molten phase, the reactivity is of minor importance but the low density and possible disturbing elements in the ash have to be studied.
Within the project many small-scale trials have been performed, giving some first impressions how biochars behave when applying them for different metallurgical concepts.
Nevertheless, these trials did not deliver enough relevant and reproducable information, so that trials in bigger (technical) scale using input streems of 30 to 60 kg per batch were required.
Summarizing the results, biochar can be recommended especially for the reduction of molten phases, as for these processes a higher reactivity of the biochar in comparison to coke is not a significant problem, as the reaction in the molten phase starts immediately.
However, the lower density of biochar compared to fossil carbon carriers must be considered. Due to this, an injection into the melt is therefore better than top feeding (biochar may not penetrate the melt and may be consumed before reduction starts). In some processes, briquettes with metal dust can be made to increase the density.
For processes in solid stage the implementation of biochar is critical due to its high reactivity. Nevertheless, a substitution of fossil carbon carriers to a certain extent could be realized without generating too many negative consequences.
There are positive additional effects of biochar like the low sulfur content. Especially in processes involving Cu, Pb, Ni or Zn the formation of sulphides can also embed noble metals. Less sulfur in biochar therefore means less sulphides formed and with this less efforts are needed regarding post-treatment processes.

Processes with heat-up zones like shaft furnaces or Waelz kilns would need additional biochar treatment like agglomeration and additive utilisation, as the high reactivity leads to a significant consumption of the biochar before it reaches the reaction zone in the furnace/kiln.

3.8 WP8: Techno-economic and ecological evaluation

3.8.1 Techno-economic and ecological evaluation

Based on the experiences, information and data gained from the technology development work packages, the test runs at the testing plant at POLY and the measurements/analyses performed, a techno-economic analysis has been performed for the continuous pyrolysis process developed within this project. The constraints for the techno-economic analysis have been defined in close cooperation with the project partners and an intensive exchange of information took place.
Questionnaires for the different system components have been prepared by BIOS and forwarded to the respective partners. The filled-in questionnaires have been returned by the project partners and open questions have been discussed.

Based on these data the technical and economic evaluation has been performed. The novel technology has been compared with a present state-of-the-art continuous biochar production technology based on a screw reactor. Based on this comparison, the advantages of the new technology against the current state-of-the-art have been evaluated.
In the following, the results of the techno-economic evaluation as well as the comparison with state-of-the-art technologies are briefly summarised.

The evaluation is based on the plant concept coupled with a gas engine for electricity generation. As a reference, a continuous biochar production technology based on a screw reactor was chosen, as this is currently the technology with the most plants in operation. The economic calculations were performed for a plant with an annual biochar production capacity of 2,000 t/a.

The novel BC4I technology shows relevant advantages against the reference technology:

- No moving parts in the fuel bed:
  → No entrainment of dust particles
  → No dust filter for hot pyrolysis gas necessary
- Use of the almost dust-free pyrolysis gas in a gas engine for additional electricity production:
  → High total efficiency
  → Additional revenues
- Production of different biochar qualities is possible due to flexible residence time in the pyrolysis reactor.

In a first step, the general framework conditions (see Table 5), basic data and the calculation method for the economic evaluation were defined. The payback time for the new Biochar-for-Industry technology was determined based on a full cost calculation in accordance with the VDI 2067 guideline and compared with those of the reference technology.
According to the full cost calculation based on the guideline VDI 2067, the different types of costs are divided into four cost groups:

- Capital bound costs
- Maintenance costs
- Operating costs
- Consumption costs

Table 5: Basic data for the economic evaluation

Explanations: The fuel costs, specific electricity costs and the heating price represent current prices based on information from industrial partners; for details regarding the biochar price, see explanation in the text

Price index	[%/a]	3.0%
Interest rate	[%/a]	5.0%
Insurance	[% of invest/a]	1.0%
Utilisation period	[a]	15
Fuel costs	[€/MWh]	25
Specific electricity costs	[€/MWh]	150
Heating price	[€/MWh]	50
Biochar price	[€/t]	800

Capital bound costs consist of the annual capital costs. The annuity (annual capital costs) is calculated under consideration of the investment costs, interest rate, inflation and the lifetime.

The maintenance costs are calculated based on the input data from the project partners. For the building and the fuel storage the maintenance costs are based on VDI 2067.

All costs in connection with the operation of the plant, e.g. fuel costs and electricity costs, are included in the group of consumption costs.

Effort by the plant operator (plant operation, fuel handling) and costs for insurance and bookkeeping are considered in the operation-based costs.

The full cost calculations of the state-of-the-art system were performed with the same calculation method.

The prices are given excluding VAT. An interest rate of 5% was chosen which represents an average value of usually achievable real interest rates. Furthermore, a general price index of 3% p.a. is considered.

The fuel costs, specific electricity costs and the heating price represent current prices based on information from industrial partners.

In the evaluation the use of the biochar in metallurgical processes is considered. To be competitive with fossil coal or coke the biochar price should be in the same price range as for fossil coal or coke incl. costs for CO2-certificates/taxation. The following costs for fossil fuels can be expected according to information from industrial partners:

- Current prices for fossil coal or coke: about 300 – 500 €/t
- Current costs for CO_2-certificates: about 100 €/t (emission factor for coke: 2.9 t CO_2/t)
- Costs for fossil coal/coke incl. costs for CO_2-certificates: 600 – 800 €/t

For the evaluation biomass feedstocks with an average moisture content of 40% (w.b.) are considered. For the pyrolysis process the biomass must be dried to a moisture content of about 10% (w.b.).

The energy demand for the biomass drying process (about 1.1 kWh/kg water vaporized) can be covered by the heat produced for all systems investigated.

Table 6 provides an overview of the systems investigated.

Table 6: Systems investigated in the economic evaluation

Explanations: SOA … state-of-the-art technology: Heat demand for biomass drying: 1.1 kWh/kg water vaporized (average value according to dryer manufacturers); Water evaporation when drying from M40 to M10: 0.56 kg water per kg biomass (d.b.)

		New technology	SOA
Application		**BC4I technology**	**Continuous screw reactor**
Full load operation hours	[h/a]	7,500	7,500
Fuel power input (related to NCV, M40)	[kW]	4,433	4,288
Fuel input (M40)	[kg/h w.b.]	1,596	1,544
Biochar yield	**[kg/h d.b.]**	**267**	**267**
Nominal heating capacity	[kW]	1,204	1,422
Heat demand for biomass drying (M40	[kW]	878	849
Net heating capacity	**[kW]**	**326**	**573**
Gross electric capacity	[kW]	443	-
Electricity consumption	[kW]	44	35
Net electric capacity	**[kW]**	**399**	**-**
Annual fuel demand	[MWh/a]	33,250	32,157
Annual biochar production	[t/a d.b.]	2,000	2,000
Annual net heat production	[MWh/a]	2,447	4,300
Annual net electricity production	[MWh/a]	2,993	-

For the application of pyrolysis gas in a gas engine a lifetime of 50,000 operating hours can be expected (corresponds to 7 years of operation). For the catalyst a lifetime of 40,000 operating hours can be expected (corresponds to 6 years of operation). For the other components a lifetime of 15 years is expected.

The costs for catalyst replacement are considered within the capital bound costs (re-investment costs). For the precious metals a compensation factor (due to recycling of the precious metals) of 60% is considered. This leads to a cost reduction of about 20% when the catalyst is exchanged.

The maintenance costs for the pyrolysis plant are expected to be about 5% of the investment costs and about 4% of the investment costs for the gas engine.

The pyrolysis plant shall work fully automatically, thus only a minor personnel expense for operating the plant is considered.

For the certification of the biochar (EBC-certification) initial costs of 3,000 € are considered.

The results of the calculation of the total costs and total income per year as well as the payback time for the system investigated are shown in Table 7.

Due to the additional revenues from the electricity production, the payback time of the BC4I technology is with 10.3 years only half as high than for the state-of-the-art system (20 years).

Table 7: Total costs, total income and expected payback time for the systems investigated

		New technology	SOA
Application		**BC4I technology**	**Continuous screw reactor**
Total costs per year	**[€/a]**	**1,738,992**	**1,621,980**
Total income per year	**[€/a]**	**2,171,268**	**1,814,980**
Payback time	[a]	10.3	20.0

Following, a sensitivity analysis for certain key parameters has been performed. For instance, the impact of a reduction of the investment costs by 30% (which corresponds to an achievable funding rate) results in a reduction of the payback time for the BC4I technology from 10.3 to 8 years.
A reduction of the biomass costs by 20% results in a reduction of the payback time for the BC4I technology from 10.6 to about 7.0 years.
The sensitivity analysis of the biochar price showed that a biochar price of about 800 €/t (base case) is necessary to achieve an economically acceptable payback time for the BC4I technology.
The impact of the electricity revenues on the payback time is rather low as an increase of the electricity revenues by 20% results in a reduction of the payback time for the BC4I technology from 10.6 to about 9.3 years.
In addition to the economic evaluation, an environmental assessment has been performed. With the new BC4I technology a high GHG emissions reduction potential is given compared to the use of fossil coal or coke and conventional heat and electricity production from fossil sources (e.g. natural gas).
The following GHG emission factors according to the Austrian environmental department have been considered for the evaluation:

- Fossil coke: 2.90 t(GHG)/t
- Natural gas: 0.25 t(GHG)/MWh → considered for heat production
- Electricity: 0.23 t(GHG)/MWh

With the BC4I technology a GHG emissions reduction potential of more than 7,000 t/a compared to the use of fossil coal and conventional heat and electricity production results for an annual production of 2,000 t of biochar
With the new BC4I technology high quality biochar for several applications can be produced. Due to the use of excess heat and an integrated gas engine high overall efficiencies are possible. Thus, considerably higher revenues from energy generation from the pyrolysis gas can be gained.
Due to the additional revenues from electricity production, the payback time of the BC4I technology is with 10.3 years only half as high than for the state-of-the-art system (20 years).
Under the framework conditions considered a biochar price of about 800 €/t is necessary to achieve an economically acceptable result.
Furthermore, with the new BC4I technology a high GHG emissions reduction potential is given compared to the use of fossil coal or coke and conventional heat and electricity production from fossil sources.

Based on the results of WP7 and Task 8.1 and in close cooperation with the industrial advisory board, possible application concepts for the overall technology and for the biochar produced have been elaborated. The results show that the new BC4I technology can be technically implemented in existing metallurgical processes but due to the currently rather low prices of fossil C carriers and natural gas, the economic payback period is too high. However, the increasing demand of green metallurgical products (e.g. “green steel”) may also lead to higher product prices, if the carbon footprint of the product can be reduced accordingly. Depending on the development of the market for green products, higher green material prices may compensate for the higher costs of biochar soon.

4 Results and conclusions

4.1 Technology development and testing

Pro's

- Despite the unfavorable conditions in the pyrolysis reactor (false air inlet, entry of flue gas from the heating jacket) and a lack of a reliable level control biochar with good quality (C- contents in the range of 85 to 90%) could be produced. **So, a proof-of-concept of the counter-current pyrolysis reactor has been achieved**.
- The dust analysis showed low amounts of ash in the particles → **low entrainment of particles despite the unfavorable operating conditions** → advantage of the counter current reactor.
- Measurements of the tar concentration showed that **tar concentrations of less than 100 mg/Nm³ on average can be achieved**. Very good tar degradation in the tar conversion zone was therefore achieved, thus **confirming the function of the tar conversion zone.**
- Despite unfavorable conditions (temperature and mass flow of the PG at burner inlet too high due to false air intake), **the PG burner could be operated at almost zero CO and moderate NOx emissions**.

Con's:

- The current **concept of the pyrolysis reactor/thermal conversion zone with heating jacket did not work** and caused the entry of significant amounts of flue gas from the heating jacket to the reactor, leading to unstable conditions in the pyrolysis bed and the thermal conversion zone.
- The **fuel feeding system was not tight**, leading to the entry of false air in the reactor.
- Both flue gas and false air in the reactor lead to unstable conditions, namely the formation of soot and elevated mass flows that reduced the retention time of the pyrolysis gas in the following gas conversion zone.
- The weak points described need to be tackled in a follow-up R&D project foreseen.

4.2 Characterization and evaluation of biochars for the application in metallurgical processes

Based on the findings gained from the project, the main criteria for biochar can be defined as follows:

- Grain size:
  - Depending on the process, various grain sizes are acceptable. Especially, when briquetting is required, the grain size should be below 3 mm. Also, if additional treatment for reducing the specific surface is needed, smaller grain sizes of the starting material are beneficial.
- Density:
  - The particle density of biochar can be influenced to some extent by selecting appropriate biomass materials (biomass with higher density also leads to biochar with higher density). In liquid-stage processes a mixing with input materials with higher densities, such as flue

dusts or metallic particles is recommended, as long as this does not have a negative impact on the process.

- Reactivity:
    - In any case, the reactivity should be as low as possible. No matter what kind of biochar was analysed, reactivities are still much higher than that of fossil based carbon carriers. Higher pyrolysis temperatures and longer retention times are recommended to get rid of volatile fractions. In some cases the reduction of the specific surface area by coating, or additive utilsation to reduce the reactivity is required but causes additional costs.
- Price:
    - Biochar is more expensive than fossil carbon carriers, following the price difference needs to be overcome by CO_2 certificates or higher achievable prices for green products. At present, typical biochar prices are in the range between 800 and 1,000 €/t.
- Availability:
    - The best qualities (see above requirements) have been reached when utilising hard wood in the pyrolysis process. If not provided by windfall or other kind of waste wood sources, there is of course a competition with other sectors. In case of nonferrous metallurgical concepts required amounts are comperably low. When it comes to iron and steel industry, due to the huge amounts produced, availability is a crucial factor and can quickly limit the application of biochar.
- Applicability:
    - Biochar can be recommended especially for the reduction of molten phases, as for these processes a higher reactivity of the biochar in comparison to coke is not a significant problem, as the reaction in the molten phase starts immediately.
    - For processes in solid stage the implementation of biochar is critical due to its high reactivity. Nevertheless, a substitution of fossil carbon carriers to a certain extent could be realized without generating too many negative consequences.
    - Processes with heat-up zones like shaft furnaces or Waelz kilns would need additional biochar treatment like agglomeration and additive utilisation, as the high reactivity leads to a significant consumption of the biochar before it reaches the reaction zone in the furnace/kiln.
    - There are positive additional effects of biochar like the low sulfur content. Especially in processes involving Cu, Pb, Ni or Zn the formation of sulphides can also embed noble metals. Less sulfur in biochar therefore means less sulphides formed and with this less efforts are needed regarding post-treatment processes.

5 Outlook and recommendations

5.1 Adapted concept for the novel pyrolysis technology

Test runs at the prototype testing plant with accompanying analyses of the biochar and pyrolysis gas produced have provided a partial proof of concept for the new technology but have also revealed

relevant weaknesses and necessary technological changes, which shall be resolved through targeted R&D work in a follow-up project.
At the end of this project, the technology shall reach a TRL of 5 and shall be ready for demonstration.

5.2 Biochar application in the metallurgical industry

Based on the findings regarding potential applications of biochar in metallurgical processes, a follow-up R&D-project is currently under way. The project is a collective research project with the Austrian Economic Chamber for Mining and Steel as the project leader and MUL and BIOS as scientific partners. In addition, three industrial partners, (Stahl- und Walzwerk Marienhütte GmbH (MaH), Montanwerke Brixlegg AG (MWB) und Tiroler Rohre GmbH (TRM)) actively participate in the project. The project aims at the substitution of fossil C carriers in the secondary copper industry (MWB), cast iron industry (TRM) and secondary steel industry (MaH).
The project started in December 2023 with a duration of 3 years.

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7 Appendix

None

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