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Co-Gasification of Solid Recovered Fuel and Biochar for Synthesis Gas Production

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Abstract

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In this bachelor's thesis, co-gasification of solid recovered fuel and biochar for synthesis gas production was performed and the quality of the produced synthesis gas was investigated. The bachelor's thesis was commissioned by the VTT Technical Research Centre of Finland. The bench scale test runs were executed on the BFB100 pilot platform at the VTT Bioruukki pilot center.

The project aimed to successfully produce synthesis gas using the bubbling fluidized bed gasifier pilot platform, and especially to investigate the effect of the used co-fuel, biochar, on the quality of the synthesis gas when solid recovered fuel was used as the main fuel. The bachelor's thesis aimed to gather information on the basics of gasification, its applications, different technologies related to gasification and the possibilities for synthesis gas utilization. The benefits and potential of waste and biomass as feedstocks for gasification were also examined, as well as the emerging technologies and main key process developers of waste gasification were explored. The focus was then on the implementation of these co-gasification test runs, and mass balance calculations and various analyses were used to obtain the results of the co-gasification test runs and the produced synthesis gas.

The use of waste and biomass as feedstock for gasification has become increasingly popular due to its sustainability. VTT wants to be a part of the future transition towards more sustainable gasification. In addition to the use of solid recovered fuel, the aim was to find the positive effects of using biochar as a co-fuel in terms of more sustainable gasification and the quality of the produced synthesis gas.

Keywords: Co-gasification, biochar, solid recovered fuel, synthesis gas

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Insinöörityössä toteutettiin kiinteän kierrätyspolttoaineen ja biohiilen rinnakkaiskaasutusta synteetikaasun valmistamiseksi, sekä tutkittiin tuotetun synteetikaasun laatua. Insinöörityön toimeksiantajana toimi Teknologian tutkimuskeskus VTT Oy. Penkkimittakaavan koeajot suoritettiin BFB100-koelaitteella VTT Bioruukki Pilotointikeskuksessa.

Tavoitteena oli saada tuotettua onnistuneesti synteetikaasua leijupetikaasutin -koelaitteen avulla, sekä etenkin selvittää käytetyn rinnakkaispolttoaineen, biohiilen, vaikutusta synteetikaasun laatuun, kun pääpolttoaineena käytettiin kiinteää kierrätyspolttoainetta. Insinöörityön tarkoituksena oli koota tietoa kaasutuksen perusteista, sen käyttökohteista, erilaisista kaasutukseen liittyvistä teknologioista ja synteetikaasun hyödyntämismahdollisuuksista. Tutkittiin myös jätteiden ja biomassan hyötyjä ja potentiaalia kaasutuksen polttoaineena, sekä selvitettiin jätteiden kaasutukseen liittyviä kehitteillä olevia teknologioita ja merkittävimpiä kaasutusteknologian kehittäjiä. Tämän jälkeen keskityttiin kyseisten rinnakkaiskaasutuskoearojen toteutukseen, sekä massataselaskennan ja erilaisten analyysien avulla saatiin kerättyä tuloksia suoritetuista rinnakkaiskaasutusten koeajoista, sekä tuotetusta synteetikaasusta.

Jätteiden ja biomassan käyttö kaasutuksen raaka-aineena on tullut yhä suosittumaksi sen kestävyysvuoksi. VTT haluaa olla mukana tulevaisuuden siirtymässä kohti kestävämpää kaasutusta. Kiinteän kierrätyspolttoaineen käytön lisäksi, tavoitteena oli löytää biohiilen käytöstä rinnakkaispolttoaineena positiivisia vaikutuksia kestävämpään kaasutukseen ja tuotetun synteetikaasun laatuun.

Avainsanat: Rinnakkaiskaasutus, biohiili, kiinteä kierrätyspolttoaine, synteetikaasu

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List of Abbreviations

- AGR: Acid gas removal. A unit that is used after a water-gas shift reaction to produce carbon dioxide-free hydrogen from gasification.
- BFB: Bubbling fluidized bed. A fluidized bed reactor.
- CCGT: Combined cycle gas turbine -plant. Natural gas for electricity generation. A combination between a gas turbine and a steam turbine.
- CFB: Circulating fluidized bed. A fluidized bed reactor.
- CHP: Combined heat and power. Generating electricity and heat simultaneously at the same process.
- DC: Direct current. Electric charge unidirectional flow.
- DME: Dimethyl ether. An organic chemical compound.
- FID: Flame ionization detector. An instrument, a detector, is used in gas chromatography for measuring gas stream analytes.
- GC: Gas chromatograph. A chromatography device for the analysis and separation of compounds. It is used in analytical chemistry.
- IEA: International Energy Agency.
- IGCC: Integrated gasification combined cycle -plant. The process generates electricity and potentially captures/storage carbon to maximize efficiency and emit few pollutants.
- IPA: Isopropyl alcohol.

ISTD:	Internal standard. A chemical substance, which determines the concentration of other analytes in chromatography.
LNG:	Liquefied natural gas. Natural gas is used as a transport fuel or for non-pressurized storage.
LPG:	Liquefied petroleum gas.
MSW:	Municipal solid waste.
MW:	Megawatt. Watt is the unit of power. 1 megawatt = 1 000 000 watts.
PAH:	Polycyclic aromatic hydrocarbon. Compounds that are heavier than benzene. They have multiple aromatic rings.
PJ:	Petajoule. The joule is the unit of energy. 1 petajoule = 1.0E+15 joules.
PSA:	Pressure swing adsorption. A unit that is used after an AGR unit to produce purified hydrogen.
SNG:	Substitute/synthetic natural gas. A fuel gas (methane).
SRF:	Solid recovered fuel. Produced from mainly commercial waste (paper, textiles, plastic, card, wood).
TCD:	Thermal conductivity detector. An instrument in gas chromatography, a detector, to measure gas stream analytes.
TWh:	Terawatt-hour. A watt-hour represents the amount of power produced per hour. 1 terawatt = 1.0E+12 watts.
VTT:	VTT Technical Research Centre of Finland.

1 Introduction

This thesis was commissioned by the VTT Technical Research Centre of Finland (VTT). VTT is one of the leading research institutes in Europe. With their technology and science, they are leading developers of sustainable growth. Therefore, VTT's main target is to convert major global challenges for society and companies, as well as promote the exploitation of technology and commercialization in sustainable and innovative ways. [1.]

Writing a thesis is a part of the energy- and environmental engineering degree program. The degree program is completed at Metropolia University of Applied Sciences.

The subject of this thesis is the co-gasification of solid recovered fuel (SRF) and biochar for synthesis gas production. The thesis consists of the theoretical part which includes information about gasification's basics and applications, gasification for synthesis gas production, different technologies, and utilization of synthesis gas. Furthermore, the benefits and market potential for sustainable gasification, and information about waste gasification developments for synthesis gas production, will be clarified, as well as ongoing industrial projects and major providers. In addition to this, there is an experimental part where waste and biochar co-gasification tests are performed. Used experimental facilities, analytics, the bench scale test runs, and results are described. Finally, the conclusions are summarized.

The objective of the thesis was to compare the results with existing data on waste gasification. The use of biochar in co-gasification is not very well-known and the results of the thesis provide new information that can be used to develop the gasification of waste or biomass to produce synthesis gas. In addition, the objective was to perform successful mass balance calculations and comprehensive reporting of results in the experimental part. The users of the data are

researchers in this area, gasification technology suppliers, and potential users of the technology.

2 Gasification

Gasification itself is quite an old technology that has been used already in the late 18th century. Feedstock for gasification was only wood and coal in the early days. Emissions and applications of gasification have all changed significantly with technological progress. In addition, awareness of emissions together with technology has developed gasification in a more sustainable, renewable, and diverse way. Nowadays, a feedstock that is desired to be used is generally biomass or waste. [2.]

2.1 Basics

Gasification is a technological process where energy is produced by feeding carbon containing solid material to a gasifier and is combined with a controlled amount of oxygen and/or steam. This process occurs at a very high temperature (generally about 700–1400°C) and varying pressure levels. This produces carbon monoxide and hydrogen-containing synthesis gas as a result of chemical reactions. [2.]

The gasification process can be roughly divided into four different steps to convert synthesis gas. These steps are drying, pyrolysis, partial oxidation and reduction/gasification. However, the occurrence of these steps depends significantly on the gasification technology and the used gasifier. In addition, the names of the steps may vary slightly, but the basic principle of the concept is the same for all of them. The steps can also overlap in one reactor or the definition of the steps can be a way clearer in a staged process. [2.] Therefore, in some gasification techniques the definition and even the recognition of the steps is challenging. When considering this particular process, the steps are not unambiguous because the drying and pyrolysis steps cannot be specifically distinguished in the bubbling fluidized bed (BFB) gasifier even if, from a chemical

perspective, they occur homogeneously and simultaneously to feed materials as the controlled partial oxidation and gasification take place in the reactor. Furthermore, the biochar that is used as the co-feedstock in co-gasification is in principle already a product of the pyrolysis reaction. In addition to that, partial oxidation can also happen in a reformer, as in this case. The next paragraphs will study each step separately in more detail.

In the drying process, moisture can be obtained from the feedstock and that can be detected as water vapor [3]. This happens usually at about 300°C. When the humidity level is higher, the energy demand increases, and therefore the enthalpy of the produced gas is lower. [4.]

Pyrolysis is a thermochemical process in which this carbonaceous feedstock is dispersed by heat. The ideal temperature in a pyrolysis reaction is about 400–500°C. [4.] In addition to the high temperature, pyrolysis occurs in absence of oxygen. In these circumstances, the feedstock undergoes both chemical and physical thermal degradation into different molecules. Thus, with the help of pyrolysis, the feedstock's character changes. Therefore, different materials, even waste, get more value as feedstock for the gasification process because low-cost waste fractions can be recovered with good efficiency to produce the desired end product. In addition, pyrolysis always produces coal, or biochar from biomass, and non-condensable gases or liquids such as hydrogen (H₂), methane (CH₄), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen (N₂) and undefined hydrocarbons (C_nH_m). Desired yields and formulation of products can be determined with the used temperature in pyrolysis. [5.]

In partial oxidation the carbon (and also biochar used in co-gasification) reacts with oxygen, which is fed into the reactor in a controlled manner. Furthermore, this leads to combustion occurring. The following chemical reactions to describe the combustion (1) and gasification (2) with oxygen in the oxidation stage are





when carbon dioxide and carbon monoxide are formed. These two reactions (1, 2) are called exothermic reactions. [6, page 15.] That means they produce heat and energy is transferred to the surroundings [7].

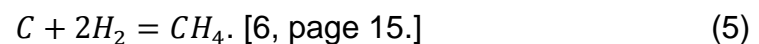
In the gasification stage (reduction zone) the obtained combustion products and water vapor, which can be fed into the reactor in a controlled manner and may also have been generated by previous steps (drying and pyrolysis), react with carbon at a very high temperature. This is demonstrated by the following chemical reversible water gas reaction (3), which reflects the gasification with steam:



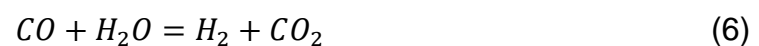
Another chemical reaction that occurs in the reduction zone is called the Boudouard reaction (4), which reflects the gasification with carbon dioxide.

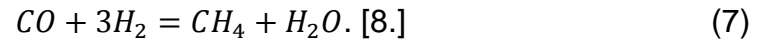


Therefore, carbon monoxide and hydrogen are formed. These are endothermic reactions. [6, page 15.] That means they absorb heat and energy is taken from the surroundings [7]. In addition, the gasification with hydrogen, which is called the methanisation reaction (5), takes place in the reduction zone, and methane (CH₄) is formed. The chemical reaction is described as



The water-gas shift reaction (6) and methanation (7) are reversible gas phase chemical reactions that also take place in the gasifier in a smaller role. However, the syngas can be processed further with these reactions depending on the desired product of the syngas. These chemical reactions are described below:





2.2 Applications

Product gas is produced by the gasification of carbonaceous solid materials. Gasification can be done in many different ways and with different gasifiers that will be listed later. The produced gas from the gasification process has multiple applications. It can be used in combined heat and power (CHP) production, high-temperature heat, and co-firing; thus, it can produce electricity or heat. The synthesis gas can also be used to obtain many different liquid fuels or chemicals by further processing. These products are either liquid fuels: Fischer-Tropsch (FT) fuels, mixed alcohols, and methanol/dimethyl ether (DME) or gaseous fuels: methane (Substitute natural gas: SNG), hydrogen, and ammonia. Uses have also been developed for the biochar produced. [2.] These possible uses of synthesis gas are illustrated in Figure 1. These applications and synthesis gas utilization will be discussed in more detail in section 3.4.

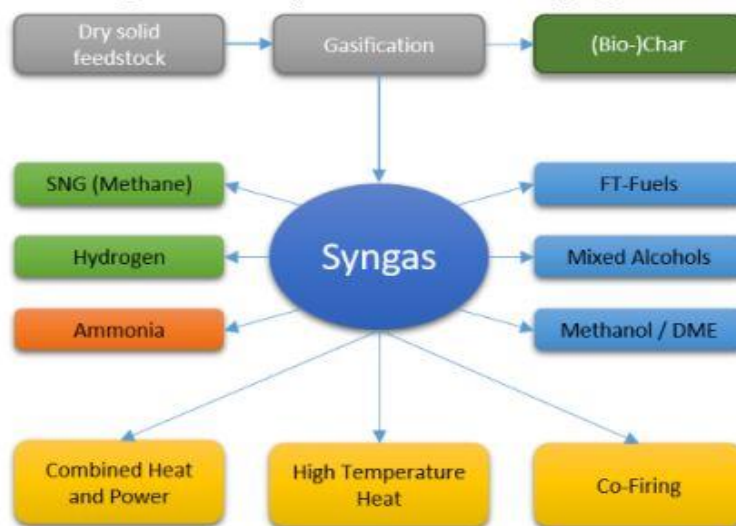


Figure 1. Synthesis gas applications [2].

3 Technologies

Gasification technologies include the different types of gasification reactors (different gasifiers), as well as the technologies to obtain desired synthesis gas from gasification. The technology also includes the synthesis gas purification and utilization.

3.1 Different Gasifiers

The gasifiers can be classified according to the different reactor types. Their design, behavior, and function differ from each other and can be selected according to the requirements, capacity, and feedstock used for gasification. Gasifiers can also be classified by the gasification agent (for example oxygen, steam, air-blown), by heat transfer (direct or indirect gasifiers), or by pressure (atmospheric or pressurized gasifier) [9, page 22]. However, the typical classification according to the used reactor type is as follows:

- fixed bed
- fluidized bed
- entrained flow
- plasma reactors.

These can be further divided into sub-concepts. [2.]

3.1.1 Fixed Bed Gasifiers

Fixed bed gasifiers, also known as moving bed gasifiers, are divided in more detail into updraft, downdraft, cross-draft, and floating-fixed-bed gasifiers [2; 9, page 22–29]. The first three of them are illustrated in Figure 2. The feedstock is fed at the top and goes through the drying and pyrolysis zone. The position of the reduction and combustion zone slightly varies depending on the air input point in the gasifier. In the updraft gasifier the syngas comes out from the top of the gasifier, in the downdraft gasifier from the bottom of the gasifier, and in the cross-draft gasifier from the side of the gasifier. On the other hand, the air is

entered respectively in the updraft gasifier from the bottom of the gasifier, in the downdraft gasifier from both sides of the gasifier and cross-draft gasifier from the other side of the gasifier. [9, pages 24–25.] It needs to be noted that the downdraft gasifiers have been classified as throat type and open-core type versions of the downdraft gasifiers. In the throat type versions, the ash content is low, and the size is uniform in the fuels that are used, for example, biomass. In the open-core type versions, the fuel can have more variation in size, ash content, and moisture. [10.] Unlike above, the floating-fixed-bed's core is a floating reduction reactor. It resembles a fluidized bed, but gasification happens inside a solid tube reactor and new char particles are constantly formed in the pyrolysis unit. The char particles stack new layers below the previous coats in the reactor. A result of this, the bulk moves upwards to a new position. There is a balance between forces of the downward and upward directions. [11.]

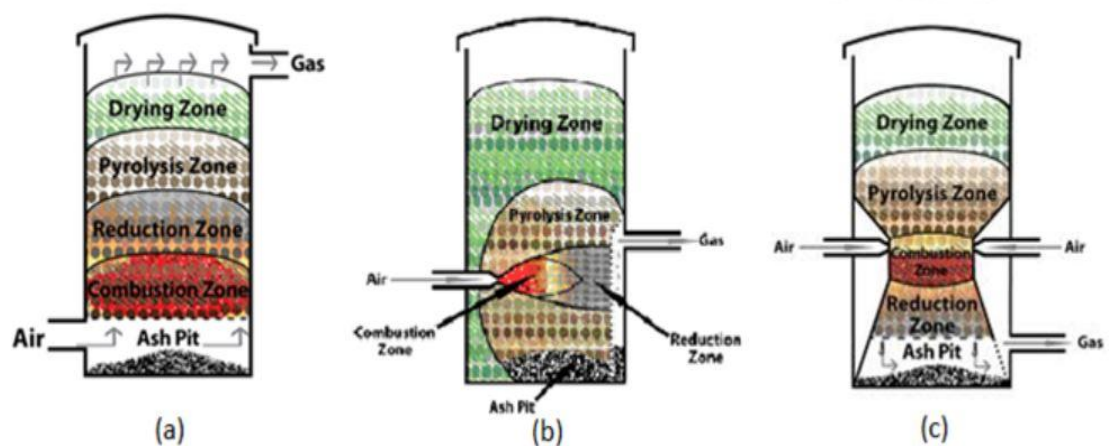


Figure 2. Updraft (a), cross-draft (b), and downdraft (c) gasifier [4].

3.1.2 Fluidized Bed Gasifiers

Fluidized bed gasifiers are bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). In the fluidized bed gasifiers, the different steps of the process cannot be properly distinguished because the temperature is almost uniform in the whole bed and thereby causing the intensive mixture to the zones. Due to the use of biomass as feedstock, fluidized bed reactors are nowadays

outperforming fixed bed reactors. The fluidized bed reactors are indeed better to tolerate different feedstock because of their flexibility of characteristics of the feedstock, for example such as ash content, moisture, and low bulk density. The fluidized bed designation is based on the behavior of solids as a fluid when they react with a gas (air, steam, or oxygen). Figure 3 illustrates the structure and operation of these gasifiers. There is usually sand at the bottom of the reactor. When the equal point between the pressure drop and the gravity of the sand particles by using air is reached in the bed, the particles become suspended and fluidization starts. The sand is preheated, and the gasification temperature is usually between 700–900°C. Feedstock is fed into the reactor with a controlled manner of gasification agent and the feedstock disperses into a combustible gas. The feedstock is fed from the side of the reactor near the bottom and the fluidization medium from the bottom of the reactor. In the bubbling fluidized bed gasifier, there is a separate interface between the upper free zone and the lower reaction zone, where the bubbling fluidized bed is determined. The fluidization velocity is about 2–3 m/s. [9, pages 29–31.] The formation of rising bubbles primarily causes the displacement of the particles [12]. On the other hand, there is no similar interface in the circulating fluidized bed. Rather, the fluidization and the existing density gradient are from the bottom to the top of the gasifier. This can be explained by the used higher velocity, which is about 5–10 m/s. Furthermore, in the circulating fluidized bed contrary to the bubbling fluidized bed, the entrained substances and char substances are circulated back on the reactor after the reactor gas outlet at the top by using a cyclone and a back leg. [9, page 29–31.]

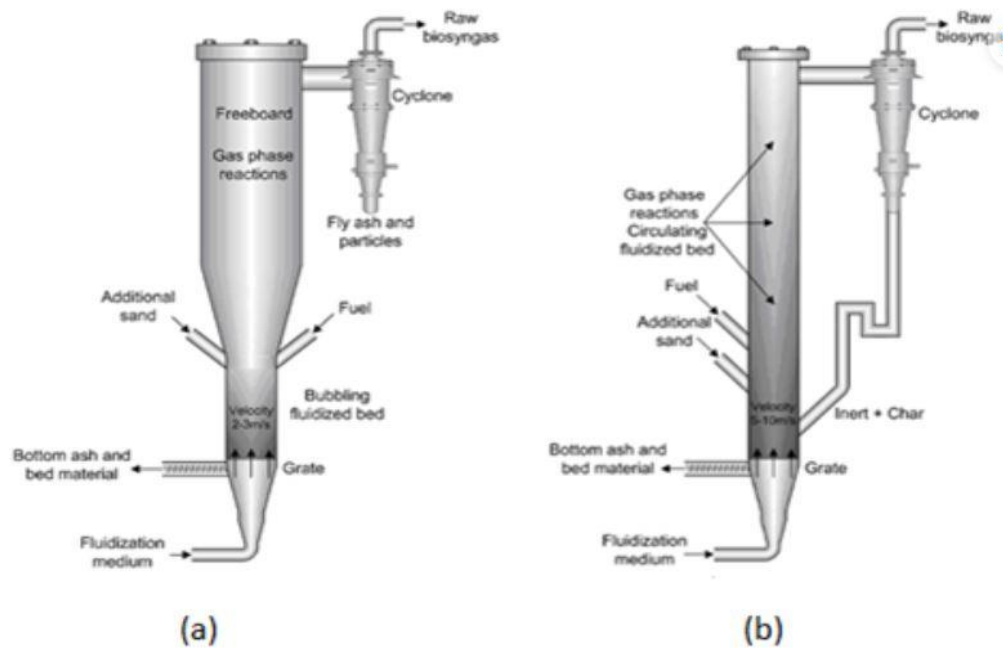


Figure 3. Bubbling fluidized bed (a) and circulating fluidized bed (b) gasifier [4].

In addition, there are dual fluidized bed gasifiers, which consist of bed-to-bed units. The action of the dual fluidized bed is called recirculating. [13.] There are different variations of the dual fluidized bed reactors depending on the used gasification agents and technology. However, the basic principle is the same in all of them, i.e. different substances (bed material, char, heat, compounds) circulate from one reactor to another, and the obtained end product is product gas (synthesis gas) and flue gas. Therefore, the idea of dual fluidized bed gasification is to combine two parallel reactors, one bed is used for combustion and the other for gasification reactions. Steam is used as a floating agent in the gasifier and air is used in the oxidizer. However, there is also, for example, variation called chemical looping combustion. It uses steam in the gasification agent for the gasification and oxidation bed, and air in the gasification agent for the bed, where metal oxidation happens. Its end products are exceptionally flue gas (carbon dioxide and water vapor) and depleted air. [14.]

3.1.3 Entrained Flow Gasifiers

Entrained flow gasifiers commonly use coal as a feedstock but nowadays biomass is increasingly being used in these gasifiers too [9, page 32]. The operation of the entrained flow gasifier is based on the turbulent flow that has been generated inside the reactor. That has been formed by feeding the feedstock (coal/biomass) and used gasification agent (the oxidant: air or oxygen, and/or steam) co-currently in the gasifier, as well as in the presence of high temperature (1300–1600°C [9, page 32]) and pressure (25–60 bar [9, page 32]). In a dense cloud flowing through the gasifier, the coal particles are surrounded and drawn in by the steam and oxidant. If the slag is formed, it comes out of the bottom of the reactor. However, there are different types of entrained flow gasifiers, such as downward-feed reactors (GE Energy/Texaco gasifier) and upflow reactors (CB&I E-Gas gasifiers) and therefore, their structure is different. [15.]

3.1.4 Plasma Reactors

Plasma reactors use plasma torches to produce plasma, which is a way of breaking down a feedstock into gas. Plasma is a form of energy, which is highly concentrated. The air stream passing through an electric arc generates plasma. There is 5000 °C at the core in the ionized gas flow. The feedstock is fed into the reactor from the side above the input of the oxygen/air and plasma torches which are near the bottom. The produced gas is obtained from the top of the reactor. Slag and possible recovered metals come out of the bottom of the reactor. [16.]

3.2 Hot Gas Filtration

Hot gas filtration has an important role in gasification because of the increased ambition to reduce emissions and produce cleaner synthesis gas. The function of the hot gas filter is to remove fly ash (dust) from the produced gas. The hot gas filter also protects against fouling and erosion of downstream units, such as reformers (catalysts) or heat exchangers and thus increases the

responsiveness and energy efficiency of the appliance. Filters also can remove heavy metals, alkali, and chloride. However, a gas cooling unit is needed to condense some of the alkali and heavy metals before the filter removes them. [17, 18.]

3.3 Tar Removal

The produced gas after the hot gas filtration still contains tars. More efforts have been made to remove tars to produce a cleaner synthesis gas. There have been various implementations of tar removal, like physical and physico-chemical ways, such as the use of organic solvent in scrubbing, but instead, thermo-chemical methods have currently been found to be the most effective way to remove tars nowadays from the synthesis gas. These include thermal- and catalytic cracking, as well as catalytic reforming. But particularly catalytic reforming might be the most efficient and popular option for synthesis gas applications. The catalytic reformer removes and converts tar compounds (heavy hydrocarbons) to main gas components (CO, CH₄, H₂, CO₂, etc.), as well as light hydrocarbon gases (methane, benzene, C₂ hydrocarbons). It also brings the main components of gas towards equilibrium to obtain the resulting cleaner synthesis gas. The catalytic reforming can also handle the non-condensable hydrocarbons and convert sulfur organic compounds into hydrogen sulfide. Catalyst reformers use metal-based, like alkali, alkaline metals, and nickel, or mineral-based, such as zirconia, zeolite, and dolomite, as a catalyst. In addition, biochar is used today to reduce the amount of tar in the synthesis gas and can also be used as a catalyst in the process. [17, 19, 20.]

3.4 Synthesis Gas Utilization

This section will examine at the technologies involved in synthesis gas utilization. The applications of gasification were mentioned in section 2.2. Now their use and production are discussed in more detail.

3.4.1 Combined Heat and Power

In a heat or power plant, the gasification unit is an integral part of the plant because of the direct use of the gas. The synthesis gas is moved after cleaning into one or several gas engines. They generate electricity and, in combination, also heat. These can be different scale applications, for example, it is used in small unit size combustion engines (output up to 800 kWth), as well as in the larger unit IGCC plants (integrated gasification combined cycle) and gas turbines (5–6 MWe an average total capacity). [2, 21.] Certain types of gasifiers are better suited for different scale applications, for example, small to medium-size applications use fixed bed gasifiers and medium to larger-size applications use pressurized fluidized bed gasifiers and circulating fluidized bed gasifiers [22, page 80].

3.4.2 Co-firing

Gasification has an important role in high temperature heat production. Co-firing of the produced gas is used as fuel for boilers to produce heat/steam. The purpose of this is to replace fossil fuels with biomass or waste instead of district heating or industrial processes. [2, 23.] Most of these installations are in Sweden, Germany, Finland, and the Netherlands [2].

3.4.3 Fuel Synthesis

The synthesis gas can also be used to produce different fuels, liquid or gaseous. These were already mentioned in section 2.2. Let's now look at their composition, manufacture, and exploitation options in more detail.

Synthetic natural gas (SNG) can be produced when hydrogen and carbon monoxide of the synthesis gas components react chemically with each other to form a methanation reaction (Equation 7). Therefore, synthetic natural gas contains mostly methane. The gas can be injected into the natural gas network. It can be used as fuel for industrial processes, households, or power generation in

combined cycle gas turbines (CCGT) and also, as a transport fuel in the form of liquid (LNG). The suitability of synthetic natural gas for long-term storage is good. [2.]

Hydrogen can be produced by a water-gas shift reaction (Equation 6) where the synthesis gas' carbon monoxide and water (steam) molecules react together forming hydrogen and carbon dioxide [2]. The aim is to obtain green, purified hydrogen free from carbon dioxide. This can be achieved by using an AGR - unit, which removes the acid gas. The carbon dioxide goes through drying and compression; in addition, any possible sulfur is removed. After that, the hydrogen rich stream goes to pressure swing absorption unit (PSA) for purification. [24.] In the future, renewable hydrogen is expected to play a significant role in replacing the use of fossil fuels as a feedstock in high-temperature heat in industry, as well as for transport and the production of power and central heating for buildings [2].

Ammonia is usually made via hydrogen from steam reforming (Equation 7) to which nitrogen is added by using an air separation unit. This forms ammonia (NH₃). [2.] Ammonia can be used for many different purposes. For example, as a fertilizer, in the textile industry for synthetic fibers (rayon and nylon) production, and as a dye or cleaner for different textiles (cotton, silk, and wool). In addition, it can be used as a coolant/refrigerant, as a neutralizer in petroleum refining, as a cleaning agent, as well as in explosives production and metallurgical processes. [25.]

Liquid biofuels or Fischer-Tropsch liquids include biodiesel, biokerosene, and biopetrol. The process by which these fuels are produced from synthesis gas is called Fischer-Tropsch synthesis. [2.] It is based on the following reaction:

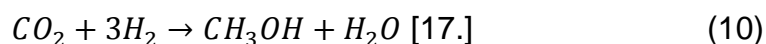


, where CH₂ means variable chain length of paraffinic hydrocarbons. Thus, a mixture of linear hydrocarbons is formed in the hydro processing of carbon monoxide. The conditions required for this are the use of catalyst (nickel, iron,

and cobalt), temperature at 180–250 °C and pressure at atmospheric. The product from the reactor effluent is called syncrude, which is processed to recently mentioned fuels. [17.] These fuels can be used in the motors of various equipment, and they would reduce emissions [2].

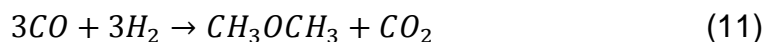
Mixed alcohols, which are C1–C4 alcohols, can also be produced. Those are a mixture of methanol, ethanol, propanol (includes isopropanol/isopropyl alcohol) and butanol (includes isobutanol). [2.] They can be exploited in transport due to their ability to increase octane number; hence, they can be used as drop-in bio-fuels to replace the use of gasoline, or octane-boosting petroleum-based fuels, and thus help reduce pollution. They can also be used to generate electricity by converting chemicals into fuel cells. [26.] High quality fuels can be converted from mixed alcohols by dehydration or oligomerization [2].

Methanol synthesis is nowadays based on the use of copper-zinc oxide-aluminum oxide (Cu-ZnO-Al₂O₃) catalyst or chromium oxide (Cr₂O₃) catalyst. By using these catalysts, methanol can be produced with a selectivity of more than 99,9 %. More by-products, like hydrocarbons, alcohols, ketones, esters and ethers, are also generated. This methanol synthesis can be represented by the following chemical reactions (Equations 9 and 10) in addition to the presence water-gas-shift reaction, the equation of which was described earlier (Equation 6).

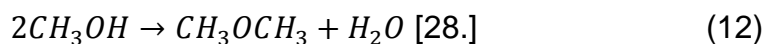


Methanol is used in the chemical industry as a derivative of various chemicals. These include the production of formaldehyde, olefins, silicone, and acetic acid. Applications of methanol have evolved to the point where it is also used in fuel production. [27.]

Dimethyl ether (DME) can be produced from a synthesis gas according to the following reaction:



However nowadays, it can also be directly produced from methanol. This is achieved by dehydrating methanol:



DME has great potential for use in diesel and Otto engines. It will help to get fuel efficiency higher and emission lower using it in diesel engines. In the Otto engines, it can be used together with liquefied petroleum gas (LPG). [2.]

The synthesis gas can also be fermented by using micro-organisms. This microbiological process can be used for biofuel production from synthesis gas. Carbon monoxide and hydrogen in the synthesis gas act as microbial metabolism substrates. With these various anaerobic carboxydrotrophic microorganisms, which main species are mesophilic- and thermophilic archaea and bacteria, ethanol, butanol, acetate, butyrate, formate, methane, and even hydrogen are produced. [29.]

4 Waste and Biomass Gasification

4.1 Benefits

Waste and biomass gasification are sustainable and renewable ways of gasification. Using them as feedstock will in many ways help us move towards cleaner energy production and a more sustainable future. In particular, it is a key part of the EU's objective to reduce carbon dioxide emissions from energy consumption. [2.]

Nowadays biomass and waste are still more commonly used and developed more widely to generate renewable heat and electricity (as feedstock for CHP and co-firing). However, developments in recent years and in future are evolving into a new generation of gasification (fuel synthesis), where the focus is to produce more biofuels, hydrogen, and biomethane from biomass and waste.

Even compared to other processes that generate energy from waste (waste-to-energy), these new generation gasification units' efficiencies are higher, environmental impact in terms of emissions are lower and their ability to produce various products from different feedstock is wider. Even negative emissions in total could be achieved by combining those units with carbon dioxide capturing, storage, and disposal, as well as developing the status of biochar in gasification. [2.]

The use of biomass and waste as feedstock also allows possible co-operation between different operators. For instance, waste wood, agricultural residues, or solid recovered fuel, which are by-products of resource managers, can be useful in industrial sectors as gasification fuels to replace the use of fossil fuels. [2.]

It also has great benefits when implementing the circular economy while the waste or biomass is used as a feedstock. In principle, the aim is to use biomass or waste that cannot be recovered in any other way. For example, residual biomass from forestry and agriculture and waste, like solid recovered fuel, furniture waste, and complex- and non-recyclable plastics. [2.] Solid recovered fuel means waste consisting of textiles, paper, plastic, card, and wood (commercial waste). Solid recovered fuel has also undergone processing, which has improved its value and quality. [30.] Due to this, using the SRF as feedstock in gasification is one of the best energy-efficient techniques [2]. Using these as feedstock also reduces the amount of waste and biomass going to the landfill, where they can release greenhouse gases, like carbon dioxide and potent methane, into the air [31].

Gasification is a more favorable option for biomass and waste recovery anyway, as biomass and waste decompose thermochemically. Due to this, biomass and waste are purified before further processing, leading to a reduction in pollutants and greenhouse gases, which contrasts with the pollutant and greenhouse gas levels in biomass or especially waste incineration or conventional combustion. [2.]

Gasification units can also produce biochar through a pyrolysis reaction (section 2.1). The organic matter in the biomass/waste breaks down under anoxic conditions, which produces a solid fraction, carbon-rich material, biochar. [2.] Thus, the benefits of biochar are that it acts as a carbon sink; in other words, it captures the carbon. A part of the carbon of biomass/waste gets trapped in the solid form, i.e. biochar. [31.] Efforts have been made to find different uses for biochar. Biochar has started to be exploited, especially in agriculture. Agricultural applications include the use of biochar as a feed additive, for sludge stabilization, as a stable bedding and as a nutrient carrier directly in soils or in biogas plants. Biochar has been used for some time for these purposes, but new applications for biochar are its use as a building material. These include asphalt and concrete, but also the use for the substitution of fossil fuels in plastics and in high-technology sector have been developed. [2.] It should also be noted that biochar is being developed for use as a co-fuel in the gasification process, which is exactly what this project aims to accomplish. This is expected to have a positive impact on the quality of the synthesis gas produced during the gasification process and on the quantity and value of the fuel used.

4.2 Market Potential

The gasification market value for all resources was estimated at 479bn US dollars in 2019, but it is set to reach by 2028 a value of 901bn US dollars. Biomass and waste currently account for only a few percent of the total. However, as has been noted, their role will grow in gasification and their shares are expected to increase in the future. [2.]

Although in the hierarchy of waste management prevention, re-use and recycling are priorities in waste management, gasification could follow these steps. Feedstock potential is significant for biomass and waste, and waste disposal could be turned from more polluting methods and landfilling to gasification. Namely, municipal solid waste (MSW) is generated over 2.1 billion tons every year at the global level, and approximately only 16 % of that is recycled. Similarly, up to 46 % of it is disposed of in so-called unsustainable ways. However,

the annual amount of municipal solid waste is expected to reach 3.75 billion tons by 2050. Thus, there will be plenty of waste in the world and therefore the feedstock potential for gasification is excellent; moreover, gasification would be a sustainable and necessary option for recovering waste. The predicted feedstock segment of the municipal waste gasification market in 2024 is worth 800 million US dollars. The amount of biomass waste will also grow in the following years and has also a high feedstock potential. Not only is the feedstock's abundance in nature and sustainability, but it is also supported by policy and regulations. Woody biomass for bioenergy production was used 451 million solid cubic meters just in Europe. Woody biomass includes primary and secondary sources. The primary sources are harvested from forests and the larger secondary sources consist of wood processing industry by-products. They are generated in sufficient quantities to be used as feedstock for gasification. [2.]

Waste and biomass producers, forest industry producers and owners can turn from disposing of waste to using it as a feedstock for gasification, and thus generate revenue streams from them. The waste and biomass gasification market is boosted by the continued growth in energy demand and the phase of transition to cleaner energy production. These include cleaner production of electricity, heat, gas and transport. [2.]

According to IEA renewables 2022 forecasts, the renewables share was 28 % of the global electricity generation, but it is expected to rise to around 38 % by 2027. Renewables are also expected to reach over 12 400 TWh generation. [32.] In the heat production sector, the renewables covered about 11,4 % and over 49 600 PJ of the total heat consumption, but it is expected to rise to 14 % and over 54 100 PJ by 2027 [33]. These numbers create huge potential for the use of renewables to produce electricity and heat in the gasification market.

In addition to these, IEA has prepared a forecast for transport biofuels. According to the main-case forecast, the total demand for biofuels increases by 35 000 million liters per year from 2022 to 2027. Of these biofuels, renewable diesel and jet fuel consumption will grow in advanced economies, and biodiesel and

ethanol in emerging economies. Waste and residues play an important role, especially in these products of advanced economies. They do cover almost 70 % of jet fuel and renewable diesel production. The main objective is of course to reduce greenhouse gases and oil use/imports in both types of economies. [34.]

Renewable natural gas, methane, is expected to challenge the use of traditional natural gas in the future. From a gasification perspective, it is obtained from the synthetic natural gas process as mentioned earlier in section 3.4.3. In Europe alone, the technical potential of synthetic natural gas from gasification is estimated at 120 billion cubic meters. This would be up to half of the total potential for renewable natural gas. By 2030, it is therefore projected that the share of renewable natural gas will reach around 8 % in Europe, which approximately means 35 billion cubic meters of renewable natural gas. At the global level, the renewable natural gas demand is also growing quickly, and by 2030, production from all technologies, gasification included, could reach over 100 billion cubic meters. [2.]

In addition, the biochar's applications have been expanded, as previously mentioned, and its beneficial use has become more common. Therefore, the biochar market potential has started to grow exponentially, and the growth rate was 70 % in 2020. It is also worth mentioning that according to the European Biochar Industry Consortium a 3-year constant annual growth rate is 42 % and a 5-year constant annual growth rate is 38 %. [2.]

5 Waste Gasification Developments for Synthesis Gas Production

The use of waste as feedstock for gasification has become more common due to its sustainability, as well as the other benefits and the potential it holds. New gasification technologies are therefore constantly being developed for different types of waste. Examples of emerging waste gasification technologies for synthesis gas production are gathered from the IEA's publication. There are plenty

of developers and providers of waste gasification, and projects are constantly being introduced.

5.1 Emerging Gasification Technologies for Waste

Heliostorm Gasification Technology

The first technology is located in the United States. The used gasification method is ionic gasification, and the technology is called heliostorm gasification technology by Cogent Energy Systems. Here, the shredded waste, such as municipal solid waste, medical waste or agricultural residues is fed into a hopper, through which it passes to a sealed conveyor. Oxygen is supplied to the end of the conveyor and the waste enters to plasma gasifier, where the waste reacts with the plasma field with a temperature of even up to 3000–10 000 °C. They have been granted a patent for this plasma reactor because it is DC-DC hybrid plasma system with several electrode arrays arranged in modular units in longitudinal opposition. Nitrogen acts as a gasification agent and inorganic material is removed from the gasifier. The produced gas still undergoes scrubbing and energy recovery process, where the recuperated heat and the final synthesis gas are obtained. This can be used in electricity (off-grid) generation and liquid fuels or even hydrogen production. [35.]

Moving Injection Horizontal Gasification

The moving injection horizontal gasification technology by Wildfire Energy in Australia is gasification with moving injection in the fixed-bed gasifier. The moving injection duct with a nozzle set, where the gasification agent (air) is supplied, is in contact with the feedstock at several points in the horizontal fixed-bed gasifier. Feedstock that is used is municipal solid waste, green waste, forestry, and agriculture waste. Ash is removed from the gasifier when it is offline and an automated mechanism at the bottom of the reactor cools down the unit for reloading. The feedstock is refilled on top of the layer of char that has been formed at the bottom of the reactor. The heat of the produced gas is recovered

and fed into the feedstock drying reactor. Then, the gas also undergoes the cleaning process. The clean synthesis gas can be fed into a gas engine to generate power, but the focus has been on the development of hydrogen production. [35.]

Multifuel Conversion Technology

The multifuel conversion technology is entrained flow gasification that use sewage sludge and its ash, plastic waste, or in the long-term other biomass waste as feedstock. Its main applications are considered to be the recovery of phosphorus, but also the production of synthesis gas which is used for power generation and hydrocarbon processing. In this technology, the feedstock material is dried and chopped before it enters the gasifier. This entrained flow gasifier has an immersion quench and liquid ash removal. Gasification occurs at about 1500 °C atmospheric pressure and in a refractory lined reactor. Oxygen and steam are used as gasification agents. A water scrubber and an immersion quench are used to purify the synthesis gas for combusting the main raw gas stream in the boiler at the adjacent power plant. In addition, a ceramic candle filter and separator for phosphorus are parts of the unit. This technology was developed by RWE Power AG in Germany. [35.]

Plasma Gasification and Plasma Refining System

For municipal waste that has not been processed is being developed a technology called plasma gasification and plasma refining system. The technology is from Canada by Plasco Conversion Technologies Inc. The aim is to generate power through a combined cycle with a gas engine. This is accomplished through a three-step process, and the method that is used is plasma gasification of tar. First, the MSW is shredded, and it is separated into two different size fractions via electromagnetic iron separation. In addition, aluminum is removed by using eddy current separators. The volatile gases from degassing and pyrolysis are passed into a refining chamber, and the char capture vessel collects the remaining solid material where char gasification occurs to produce a

synthesis gas. Gasification agents, preheated oxygen or air, are turbulently mixed with the volatiles. After this, they are exposed to the plasma clouds, which is supposed to break down the tars. After the cracking reactions, the synthesis gas undergoes the cleaning and cooling process, as well as the heat recovery. A wet electrostatic precipitator, an activated char vessel, and a venturi and sulfur scrubbers are parts of the cleaning process. [35.]

The RadGas Technology

In the United Kingdom, a technology called the RadGas technology is being developed by Advanced Biofuels Solutions Ltd. They are producing bio-methane, vitrified ash, and carbon dioxide from refuse-derived fuel. They achieve this by using a fluidized-bed gasifier with oxygen and steam as the gasification agents, as well as using a plasma converter unit as the catalytic chamber. Refuse-derived fuel is fed into the gasifier after the drying. The plasma converter removes sulfur, heavy metals, and condensable hydrocarbons from the produced synthesis gas at high temperatures. In addition, the formed ash is vitrified and removed. After this, the synthesis gas is sent to the cooling and cleaning unit. Cooling is done by process steam and cleaning by particulate filter, and acid and alkali contaminant scrubber. Finally, the clean synthesis gas is led to a methanation unit, which upgrades it catalytically into biomethane and carbon dioxide. [35.]

Inclined Indirect Flaming Pyrolysis Reaction Rotary Gasification

In the United States developer SUNY Cobleskill/Caribou Biofuels has developed a technology called inclined indirect flaming pyrolysis reaction rotary gasification. Here, the feedstock that is used is municipal solid waste, non-hazardous site waste, or residues from forestry. The main applications are power generation or biochar and biofuel production. The process starts when untreated waste is fed into a feeding and compression unit, which mechanically removes moisture from the waste. The waste is pushed into this inclined rotary gasifier, where it reaches the bottom of the reactor by rotating downwards in the reactor,

and halfway through it dries. The rotary motion spreads the char particles and therefore facilitates the conversion of the waste in the gasifier. The incline and rotation speed of the gasifier can be adjusted to find the optimal outcome. The gas exits from the top of the rotating drum. Ash is also formed, and it is removed from the gasifier. The synthesis gas cooling and cleaning is based on spraying the synthesis gas into a quencher, condensing organic aerosols, and using this as a liquid in an impingement scrubber. The synthesis gas is then polished and fed into a diesel engine by mixing it with combustion air or it is combusted with diesel oil in a diesel engine for power generation applications. [35.]

TreaTech Hydrothermal Gasification System

Lastly, in Switzerland a technology called TreaTech hydrothermal gasification system has been developed by TreaTech SARL (working in collaboration with The Paul Scherrer Institute). The technology is suitable for the use of sewage sludge as a feedstock, and producing biomethane (SNG) and mineral salts, such as phosphorus, from it. The wet sewage sludge is transferred first to the developer's patented salt separator which is operating at 400 °C and 300 bar pressure. The mineral salts are removed and sent to further processing to obtain nutrients. Next, sulfur is removed before the sludge enters the gasifier to produce gas with support of a ruthenium-based catalyst. The gas purification produces process water in addition to the final product, gas. [35.]

5.2 Providers and Projects

In addition to the developers and projects mentioned above, there are still many other important participants and projects that are ongoing or under development in the field of waste and biomass gasification around the world. Projects and providers are still mainly located in Europe and North America. But also, in Asia, especially in Japan and China sustainable gasification is becoming more popular. Below is a list of some main providers with the currently operational project(s) to promote sustainable gasification in the main influencing countries:

- Austria: Syncraft, Urbas, Glock Oekoenergie, Hargassner, and Froeling.
- Germany: Burkhardt, Spanner RE, Energos, EQTEC, Envirotherm, and BioLiq.
- Finland: Valmet, Andritz, and VTT.
- The United Kingdom: Chinook, Refgas system, Biomass Power, Energos, EQTEC, Outotec, Nexterra, and SEC Technology.
- France: LLT, PRME, and Gaya.
- The Netherlands: LLT.
- Belgium: Xylowatt.
- Spain: EQTEC.
- The United States: WTEC, PRME, Outotec, Fulcrum, TRI, and Nexterra.
- Canada: Outotec, Nexterra, and Enerkem.
- China: Andritz, Valmet, and Anhui Conch Kawasaki Engineering Co.
- Japan: Ebara UBE Process.

Hence, some of the major individual companies related to sustainable gasification are for example, Enerkem, TRI, Fulcrum and Nexterra. They have impressive amounts of funding and several various projects (also planned) at global level. In addition, Enerkem, TRI and Fulcrum are considered to be the first major commercial developers of waste gasification for synthesis gas production.

Enerkem has an operational plant and project called Alberta Biofuels in Edmonton, Canada. It is even the first collaboration on such a large scale, with a such large city and producer turning waste to biofuels, such as gasification of RDF to methanol and ethanol. [35, 36.] Enerkem has also projects in Varennes (Canada), Tarragona (Spain), and Rotterdam (the Netherlands) that are planned and awaiting approval. In addition to these, they are planning implementation in the Asia Pacific. [36.]

Fulcrum and TRI have both been involved in a project of Sierra biofuels plant [37, 38]. The plant produces Fischer-Tropsch syncrude and it is located in Nevada, United States. TRI has also a process demonstration unit in North Carolina, United States. The objective is to produce biochemicals and biofuels from

biomass and MSW. TRI also supplied commercial black liquor gasification system to a facility in Ontario, Canada, which was the first in the world. In addition, TRI demonstrated the upgrading of the Fischer-Tropsch liquids to fuels used in jets and military. [37.] Fulcrum, on the other hand, has also plants under development; the Centerpoint biofuels plant in Indiana and the Trinity fuels plant in Gulf Coast, in the United States. Moreover, the Fulcrum Northpoint plant is being developed in Cheshire, England. [38.]

Nexterra has had various projects in the United States, Canada, and the United Kingdom. Some of them have been decommissioned, but others are still in operation. In the United States, they have had three active projects: US Veterans Affairs Medical Center (Battle Creek, Michigan), University of South Carolina (Columbia, South Carolina), and Oak Ridge National Laboratory (Oak Ridge, Tennessee). However, the first one is the only system currently in operation, and provides heat and power from biomass gasification to the medical center. On the other hand, there are a total of five operational gasification systems in Canada. The projects: University of British Columbia (Vancouver, British Columbia), University of Northern British Columbia (Prince George, British Columbia), Dockside Green (Victoria, British Columbia), Kruger Products Paper Mill (New Westminster, British Columbia), and Tolko Industries Plywood Mill (Kamloops, British Columbia), are all exemplary gasification systems producing heat or electricity, using mainly wood-based waste and reducing the use of natural gas in particular as an energy source in the regions concerned. One project is located in Tyseley, Birmingham, United Kingdom. The powerplant is estimated to produce 10 MW of electricity by gasification of different wood waste (about 67 000 tons per year). [39.]

Let's take a closer look at sustainable gasification in Finland. Valmet is a technology provider for the project in Lahti and the project is in collaboration with Lahti Energia Oy. The gasification plant "Lahti Energy Kymijärvi II" in Lahti uses SRF in CHP production. The capacity of the plant is 160 MW or 250 000 tons a year. In Finland, Valmet has two other projects, one in Vaasa and one in Äänekoski. In Vaasa, the project has been implemented in co-operation with

Vaskiluodon Voima Oy. The gasification plant uses forest residues for indirect co-firing and its capacity is 140 MW. The other project in Äänekoski is implemented in co-operation with Metsä Group Bioproduct Mill. This gasification plant uses forest residues (bark and wood) in lime kiln gasifiers and the plant's capacity is 50 MW. [40.] Technology provider Andritz also works in Finland in the project of lime kiln gasifiers. The project is implemented in collaboration with Metsä Fibre Oy, and the CFB gasification plant is located in Joutseno. It uses forest residues as feedstock. [41.] VTT is a technology provider in Finland for the Comsyn project. Its purpose is to produce Fischer-Tropsch liquids from forest residues. In addition to these operational projects in Finland, the project City Refinery Vuosaari is planned. It involves co-operation between technology providers Helen, VTT, and Lassila & Tikanoja. The project aims to produce CHP and biofuels from biomass residues and difficult recyclable materials. The plant is planned to be established in this decade. [35, 42.]

6 Solid Recovered Fuel and Biochar Co-gasification Tests

The solid recovered fuel and biochar co-gasification test was carried out by VTT, and the test runs were performed in their facilities. Next, let's look in more detail at the experimental facility and analytics used in these co-gasification test runs. This is followed by a description of the implementation of the bench scale test runs themselves, and the obtained results, such as the properties of the produced gas and especially the impact of using biochar as co-fuel in solid recovered fuel gasification. The assembly of the bubbling fluidized bed test rig BFB100 is illustrated in Figure 4.

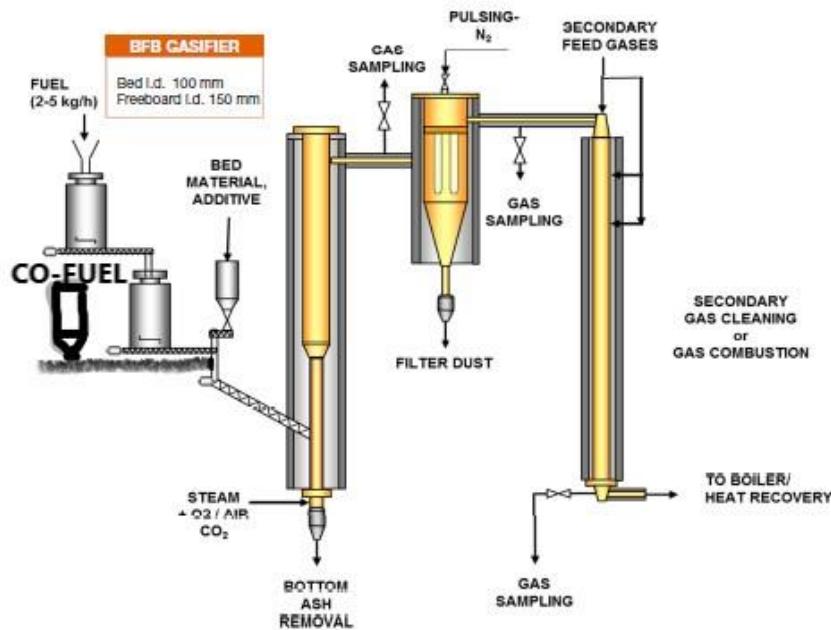


Figure 4. The bubbling fluidized bed test rig BFB100.

6.1 Description of Experimental Facility

VTT's BFB100 test unit was used as the gasification unit for the solid recovered fuel and biochar co-gasification test runs. The whole gasification unit is shown in Figure 5. In the figure, the different main parts of the gasification unit are marked with numbers and explained. The unit also includes fuel tanks, which are not shown in Figure 5 but are pictured in the next section. All these main parts are also discussed in more detail in the following sections. The gasification unit is also equipped with electric furnaces, which are used to preheat the unit and compensate for heat losses during the run.

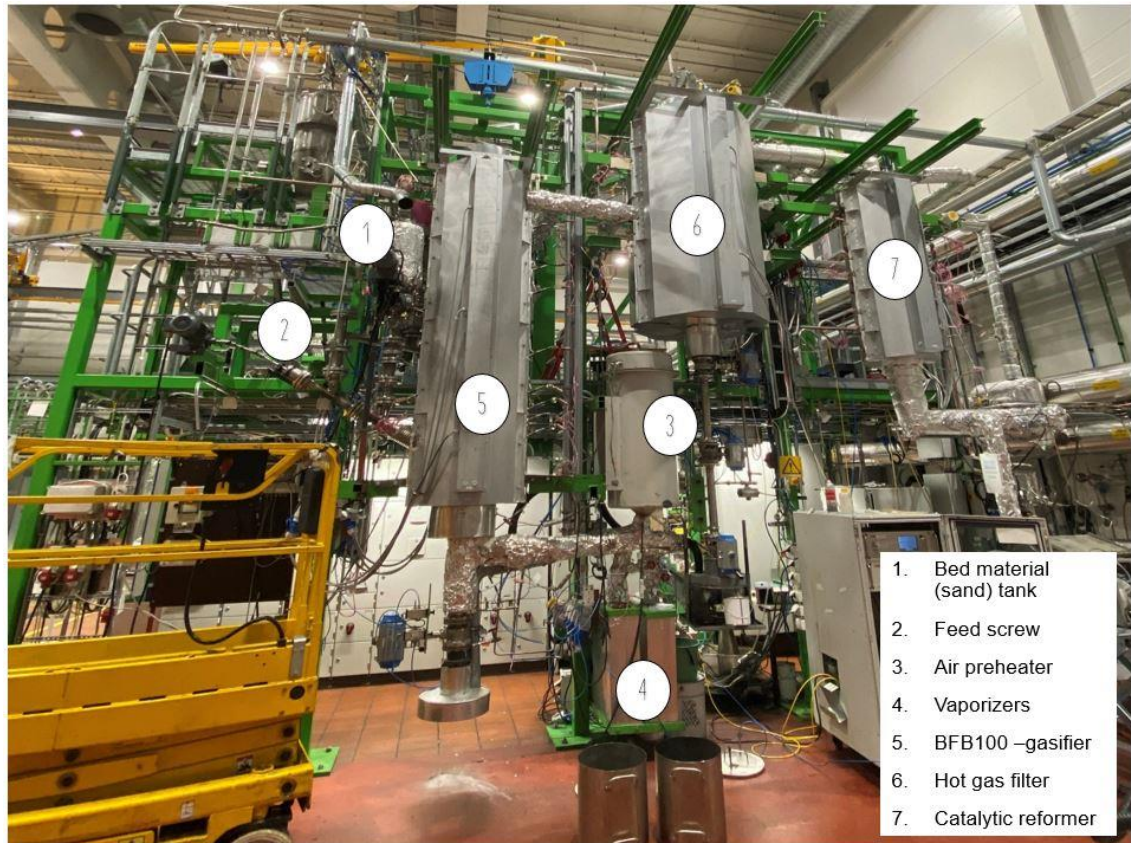


Figure 5. The BFB100 gasification unit from the front view, and the main parts are marked and explained.

6.1.1 Fuel Tanks

The fuel tanks are located behind the gasification unit at the top. Fuel tanks in this project include two consecutive tanks for the solid recovered fuel feed, and one tank for the biochar feed. Figure 6 illustrates the two solid recovered fuel tanks. The solid recovered fuel is filled into the upper tank, from where it is transported via a screw to the lower tank. From there, the solid recovered fuel is transported by the dosing screw to the feed screw that conveys it into the reactor. The fuel tank filled with about 8 kg of solid recovered fuel at a time.



Figure 6. The solid recovered fuel tanks. The filling tank is the upper tank, and the feed tank is the lower tank.

The biochar tank is located next to the solid recovered fuel tank. The biochar tank can hold about 1.9 kg of biochar at a time. Biochar is also transported by the dosing screw to the feed screw. The biochar tank is shown in Figure 7.



Figure 7. The biochar tank.

6.1.2 Bed Material (Sand) Tank

The bed material tank is illustrated in Figure 5 as number 1. The bed material used in these test runs was sand with a particle size of 0.28–0.50 mm. The sand is filled into the tank through an openable glass lid on top of the tank. The initial batch of sand used in these test runs was 4840 g. The bed material make-up feed was set to 1.3 Hz during the runs, which is just over 300 g/h.

6.1.3 Fuel Feeding Screws

The fuel dosing screws are used to set the desired fuel feed rates. From the dosing screws, the fuels enter the feed screw. The feed screw is number 2 in

Figure 5. It has a motor at one end that turns the screw. The feed screw rotation speed is usually set at around 30 Hz while running. The feed screw feeds the fuels (solid recovered fuel, biochar, and sand) to the reactor.

6.1.4 Air Preheater and Vaporizers

The air preheater and vaporizers are components related to the gasification agents fed into the reactor. The air preheater is shown as number 3 and the vaporizers as number 4 in Figure 5. The air preheater heats the used oxygen and/or nitrogen before entering them into the process. Its aim is to increase the thermal efficiency of the process and also to prevent water from condensing. The vaporizers, on the other hand, evaporate water into water vapor, which is also fed into the reactor. There are two vaporizers because the two water mass flow controllers ensure a wider feed range. The temperature of gasification agents (water vapor and oxygen) is about 300 °C when they enter the reactor.

6.1.5 BFB100 -Gasifier

The BFB100 -gasifier is number 5 in Figure 5. The gasifier consists of the grate, reactor tube (bed and freeboard), and the surrounding electric ovens. This entity is called the BFB100 -gasifier. It should be noted that when the text refers to a reactor, it refers to the reactor tube of this gasifier, where gasification occurs. Oxygen is consumed immediately above the grate at the bottom of the reactor tube. The sand bed material forms a bubbling bed on top of the grate, in which the fuel is fed. The reactor tube expands upwards; thus, it consists of the lower bed- and the upper freeboard sections. The bed's inner diameter is 100 mm and the freeboard's inner diameter is 150 mm. The total length of the gasifier is approximately 2.8 meters. The typical fluidizing velocity applied in this bubbling fluidized-bed gasifier is between 30–60 cm/s. Below the grate is still the removal valve for the bottom ash. Fuels and sand from the feed screw enter the reactor from the side of the gasifier near the bottom (about at 800 mm above the gas distributor plate). The gasification agents (oxygen and steam) are in turn fed to the bottom of the reactor through the grate. The produced gas comes out of the

top end of the gasifier and goes in the filter. The operation of the bubbling fluidized bed is described in more detail in section 3.1.2.

6.1.6 Hot Gas Filter

The hot gas filter is shown in Figure 5 as number 6. There are two metallic filter elements (candles) inside the filter. They are made of iron-chromium-aluminum alloy which is resistant to mechanical stress and high temperatures. Their outer diameter is 60 mm and their length is 1.1 m. The filter removes particulates and most of alkali and heavy metals and chlorine from the produced gas. The fly ash that accumulates on top of the filter candles is periodically removed by pulsing with nitrogen (2 bar). The detached particulates are removed at the bottom of the filter. The filter is set to pulse once an hour during the run.

6.1.7 Catalytic Reformer

The reformer is the last part in Figure 5, number 7. The reformer's inner diameter is 102 mm, and its bed height is about 0,55 m. There is a commercial nickel catalyst in the reformer. In addition, the reformer has an inlet for the feed gases (nitrogen, oxygen, carbon dioxide) at the top of the reformer. In these specific runs, oxygen and nitrogen were used as feed gases in the reformer. The quantities of these feed gases are mainly adjusted according to temperature in the reformer (example values in section 6.3.2). The catalytic reformer converts light hydrocarbon gas and tars into synthesis gas (reforming), and it also brings the main components of the gas (hydrogen, carbon monoxide, carbon dioxide and water) toward the equilibrium, as illustrated by the water gas shift reaction (Equation 6) [20].

6.2 Description of Analytics

This process includes many different analytical measuring units. Their function is to provide information on the operation of the process and, more specifically, on the properties and concentrations of the produced gas content. These are

two online gas analyzers, two micro gas chromatography (micro GC) units, tar sampling and related analytics.

6.2.1 Online Gas Analysis

The online gas analysis consists of two gas analyzer units, one after the filter and one after the reformer. As shown in Figure 8, ABB's gas analyzer is used for online analysis in this project. It measures the following compounds: carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), oxygen (O₂) and hydrogen (H₂). These values are expressed in the analyzer as a volume percent (vol%). The online analyzers draw the results as graphs on the computer during gasification and they are only practical for that purpose. Analyzers need to be checked and calibrated before each run.

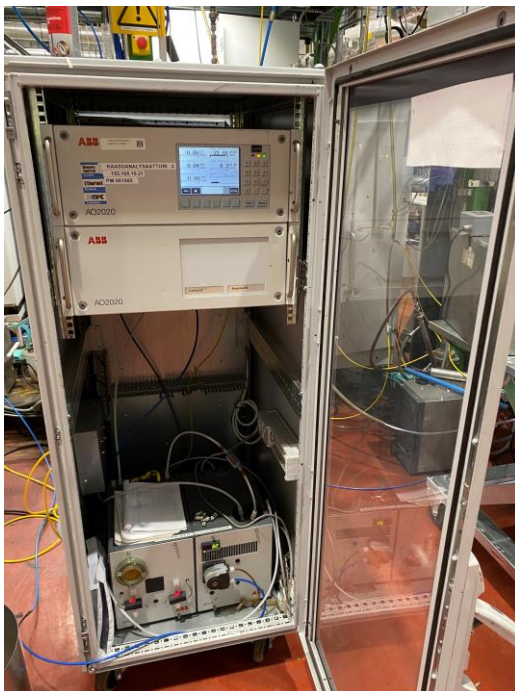


Figure 8. ABB's gas analyzer. Used for online gas analysis in this project.

6.2.2 Tar Sampling and analysis

Tar sampling method is based on the European tar protocol, “Measurement of organic contaminants (tar) in biomass producer gases” by CEN/BT/TF 143 working group (including VTT), the technical specification CEN/TS 15439:2006 [43]. Tars were measured after the filter and after the reformer. Tar sampling is based on the absorption of tar and water from the gas into the solvent (IPA) of the impinger bottles. The impinger bottles must first be filled in the following way:

- the first bottle: 70 ml of IPA + glass beads
- the second bottle: 70 ml of IPA
- the third bottle: 70 ml of IPA
- the fourth bottle: 70 ml of IPA
- the fifth bottle: 70ml of IPA + glass beads
- the sixth bottle: glass beads [44].

The first four bottles are placed in a water bath that is maintained at around 20 °C and the last two bottles in a 50/50% mixture of water and glycol that is cooled down to -15 °C. The impinger bottles are connected in series and the first bottle is connected to the gas source after the filter or reformer. This can be observed in Figure 9.

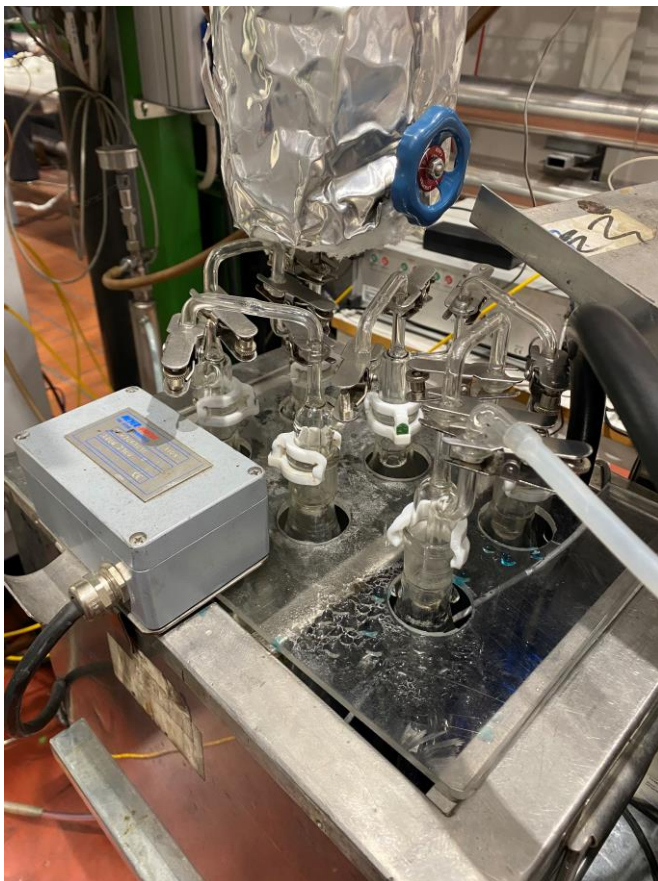


Figure 9. The glass bottles are connected in the sequence in the container.

The last bottle is still connected to the pump and the gas flow meter from which the volume of gas that is pumped through the bottles can be read. Pressure and temperature gauges have also been added to the installation to monitor and record values during the pumping. The whole sampling unit is shown in Figure 10.



Figure 10. The tar sampling set-up.

The gas sample volume was usually around 30 liters after the filter and 100 liters after the reformer, and they were taken twice per set point in this project. After the sampling, the assemblies of the impinger bottles are removed, and they are lifted out of the water/glycol bath. After this, the samples from impinger bottles at the measurement point are poured into the same bottle and glass beads are separated. The volume of the sample is read and written down. Then an internal standard substance (ISTD) is prepared by diluting 1.0145 g dodecane with IPA. A gas chromatograph is calibrated by ISTD. 5 ml of ISTD is mixed with 20 ml of the sample and transferred to gas chromatograph sample vials. The gas chromatographs measure the samples. [45.] There are two gas chromatographs, the other determines polycyclic aromatic hydrocarbon (PAH) compounds, and the other one determines water concentration. The PAH chromatograph is equipped with a FID and the water chromatograph with a TCD. The gas chromatographs are pictured in Figures 11 and 12.



Figure 11. The gas chromatograph (Agilent 6890N) with FID to analyze polycyclic aromatic hydrocarbons (PAH) compounds.



Figure 12. The gas chromatograph (Agilent 7890A) with TCD detector analyze water concentration.

6.2.3 Micro GC

Micro gas chromatography (GC) also analyzes gas samples after the filter and reformer. The micro GC unit is pictured in Figure 13. The gas flows through the unit, and helium is used as a carrier gas. The micro GC units are equipped with a TCD. Three signals were used, each with its own column. Analyses are transferred directly to the adjacent computer. Micro GC serves as the basis for calculating the balance sheet.

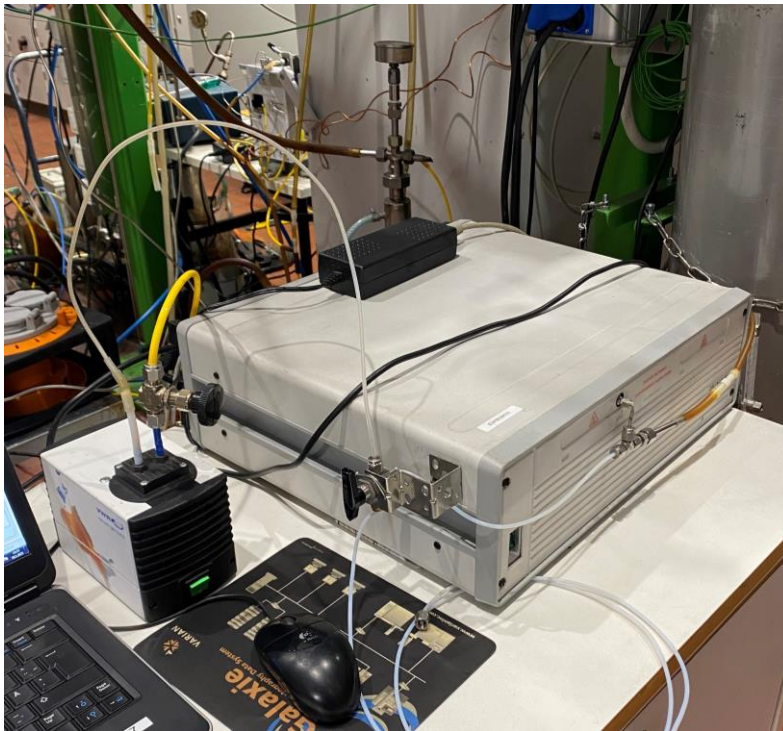


Figure 13. The micro GC unit (after the reformer).

Figure 14 shows the compounds that the micro GC unit recognizes in these test runs. The micro GC analyzes the amounts (%), peak area ($\mu\text{V}\cdot\text{s}$), and amount per area of the compounds in the gas. Retention time (RT, min) is used to identify each compound. Retention time is the time that the compound has been in the column after the injection. That depends on the chemical composition of the compound. [46.]

Signal	Retention Time [min]	Type	Area [µV*s]	Amt/Area	Amount [%]	Name
1	0,768	PB	7414,54225	2,66656e-005	0,19771	CO2
1	0,877	PV	3,8807e+004	6,19626e-005	2,40461	C2H4
1	0,979	VB	2,2317e+004	5,92274e-005	1,32181	C2H6
1	1,283	-	-	-	-	C2H2
3	0,835	BB	8895,54820	2,34346e-004	2,08464	C3H6
3	1,589	BB	397,93562	1,94446e-004	0,07738	C3H4
3	2,716	BB	1494,24122	1,71079e-004	0,25563	t-2-C4H8
3	2,851	-	-	-	-	C5H12
3	2,969	BB	1561,79192	2,80566e-004	0,43819	1,3-butadiene
4	0,612	BP	3753,11602	1,18730e-004	0,44561	Hydrogen
4	0,751	-	-	-	-	Oxygen
4	0,906	VV	4,2905e+004	2,01719e-003	86,54849	Nitrogen
4	1,199	VV	1612,80965	8,92573e-004	1,43955	CH4
4	1,513	VB	124,25168	2,15959e-003	0,26833	CO

Total amount = 95,48194

Figure 14. Micro GC's sample menu on the computer screen.

6.3 Bench Scale Test Runs

The biochar and solid recovered fuel co-gasification bench scale test runs were performed at the VTT Bioruukki pilot center. The fuels used in these co-gasification test runs are in pellet form (see Figures 15 and 16). The objective was to produce a synthesis gas with these fuels using the BFB100 gasification unit and get results on the impact of biochar as a co-fuel.



Figure 15. Solid recovered fuel pellets.



Figure 16. Biochar pellets. BCFB 22/04 -test run's hot filter dust that is pelletized in Germany by an EIFER partner. About 10 % corn starch as a binder.

The compositions of these fuels are shown in Figure 17. It describes the lower heating value and moisture content of fuels as well as the proximate and ultimate analysis of the dry matter by weight percent (wt-%).

Feedstock	SRF pellets	Biochar pellets
Lower heating value (LHV), MJ/kg (dry basis)	20,0	24,3
Moisture, wt-%	6,0	2,6
Proximate analysis, wt-% (dry matter)		
Volatile matter	69,1	13,4
Fixed carbon	12,7	62,8
Ash	18,2	23,8
Ultimate analysis, wt-% (dry matter)		
Ash	18,2	0,0
C	48	69,1
H	6,4	1,0
N	1,1	0,3
O (as difference)	25,45	5,8
S	0,85	0,05

Figure 17. Composition table for SRF and biochar pellets.

There were three runs in total. The first two runs were on January 11th and 12th, 2023. After the first two runs, there was still a need to implement one more run next week on January 19th, 2023.

6.3.1 Preparations

Before the test runs, some preparations must be done for the gasification unit. Firstly, the unit must be leak tested. This is done by closing all gas outlets and increasing the pressure in the unit. The pressure drop rate indicates the size of the leak. In case of leakage, the leakage point is detected by using a soap spray bottle and a carbon monoxide detector.

Then it is important to remember to calibrate the analyzers and gasification agent feeders. At the same time, an unobstructed gas supply to the analyzers through hoses is ensured.

After these, the sand tank is emptied of old sand residues if necessary and then pre-filled with new sand starting bed, which in total was 4840 g of 0.28–0.50 mm sand. Also, the biochar and solid recovered fuel (about 8 kg) are tanked in their respective tanks ready for use. Pre-heating of the test rig starts on the preceding day. Electric ovens and pre-heaters are used to gradually raise the temperature in the reactor to around 600 °C under nitrogen flow. The test rig is then left overnight under nitrogen atmosphere.

6.3.2 Test Runs

The test runs are started in the morning by raising the reactor temperatures closer to the target operation temperatures with the use of electric ovens and heaters. The initial bed material batch is fed into the reactor. The furnace in which the produced gas is combusted is turned on at this point as well as the online gas analyzers and micro GC units.

The primary nitrogen feed is turned off when the desired temperature is reached in the reactor and fluidization is switched to steam and oxygen. Once stabilized, the fuel feeding can be started, and make-up bed material feed is set to 1.3 Hz. Also now, the purge nitrogen is set at 0.5 g/s, and reformer's nitrogen about at 0.212 g/s, and oxygen to the reformer about at 0.1–0.2 g/s (the settings of the reformer values vary according to its temperature). The feed screw is set about at 30 Hz while running. The pressure differential increase of the bed, gas analyses, and temperatures must be monitored and, if necessary, the heating of the reactor furnaces and trace heating need to be adjusted to achieve the target values. The set point can start once steady-state conditions have been reached in the process.

When the set point has started, nitrogen is set to pulse every hour into the filter. That means the nitrogen is pulsed about at 2 bars through the filter pushing the dust from the metal candles to the bottom of the filter. This is removed from the bottom of the filter and dust is collected in a can. In addition to this, the bottom ash is periodically removed from the bottom of the reactor and placed in a

container. These samples from the reactor (bottom ash) and filter (dust) are weighed and collected for analysis.

In the first test run (on January 11th), the set point was called BFB 23/02A. The fuel supply ratio target was set as follows: solid recovered fuel 90 m-% and biochar 10 m-%. The fuel feed screws were set at solid recovered fuel feed 20.6 Hz (= calibrated feed rate 4209 g/h) and biochar 3.5 Hz (= calibrated feed rate 473 g/h). However, in this first run, it was noticed that there were problems with the biochar feed. The biochar feed tank was found to be so narrow that the pellets could sometimes form a blockage with each other, preventing the pellets from passing through to the feed screw. This could only be avoided by rattling or poking the tank, which was not the ideal situation. However, from the control room it was possible to recognize the stoppage of biochar feed by noticing a decrease in the hydrogen content in the online gas analysis, as well as by detecting the dispersion between the three temperatures nearest to the bottom of the reactor bed.

In the second test run (on January 12th), the set point was called BFB 23/02B and the attention was drawn to the above-mentioned problems of the first running day's biochar supply. The target of the supply ratio was set as follows: solid recover fuel 95 m-% and biochar 5 m-%. The feed screws were set at 21.9 Hz (= calibrated feed rate 4470 g/h) of solid recovered fuel and 1.8 Hz (= calibrated feed rate 234 g/h) of biochar. On these both days of test runs, the gasification agents were adjusted about at 0.461 g/s of oxygen (45 m-%) and 0.552 g/s of water vapor (55 m-%).

The third test run was held on the next week (on January 19th). At that time, the objective was to run two set points on the same day, lasting about 3 hours per set point, which was different from the last two runs, when there was one set point taken per day (6 hours). In the first set point, the only fuel used was solid recovered fuel. This first set point was named BFB 23/03A. The feed screw of the solid recovered fuel was set at 25.1 Hz (= calibrated feed rate 5111 g/h). After the first set point, the biochar was added again as a co-fuel together with

solid recovered fuel. This was the start of the second set point, and it was named BFB 23/03B. The split of the set points was used to further highlight the differences in produced gas by using biochar as co-fuel with solid recovered fuel. The supply ratio target was then 90 m-% of solid recovered fuel and 10 m-% of biochar. The solid recovered fuel feed screw was set at 22.3 Hz (= calibrated feed rate 4550 g/h) and the biochar feed screw at 3.7 Hz (= calibrated feed rate 501 g/h). Gasification agents were adjusted about at 0.38 g/s of oxygen (41,4 m-%) and 0.544 g/s of water vapor (58,6 m-%) in this third test run. In addition, the gasification temperature at these two set points was kept at 850 °C instead of 890–900 °C as in the two previous runs mentioned above.

At the end of test runs, the feeding of the bed material (sand), solid recovered fuel, and biochar are stopped. Oxygen feed to the reactor and reformer is stopped, and water vapor is put on bypass. The gasification agents are switched to nitrogen (1.0 g/s). All oxygen valves are closed. The rest of the bed material is taken out to be cooled in nitrogen, and it is weighed when it has cooled down. The micro GC units and furnace are turned off. The speed of the feed screw is reduced from 30 Hz to 5 Hz. Also, the nitrogen is set to pulse every 3–4 hours into the filter. The water vapor supply is switched off when water comes from the bypass. Finally, the gasification unit is cooled down in nitrogen overnight.

6.3.3 Maintenance

Maintenance is always performed on the gasification unit after running. An exception may be made for consecutive running days and if it is the same run as the previous one, for example in these test runs, the maintenance was made until after the second day of running (January 12th). The second maintenance was carried out after the last run (January 19th). The basic maintenance of the BFB100 gasification unit includes the following operations:

- The grate of the reactor is extracted through the bottom of the reactor and samples from the top of the grate are collected and weighed.

- The reactor tube is inspected for any residues.
- The fuel supply valve is opened by hand and the remaining fuel (solid recovered fuel pellets) is run down into a separate bucket and weighed.
- The sand tank is run down empty through the reactor into a separate bucket and weighed.
- The possible co-fuel (biochar pellets) tank is run down empty through to the reactor into a separate bucket and weighed.
- The feed screw is removed, and it is cleaned mechanically using a steel brush.
- The feed screw tube, reactor tube, and filter tube are cleaned by using a long steel tube brush.
- Samples of these just mentioned above are collected and weighed.
- The sampling hoses for analyzers are cleaned with solvent if necessary.
- The whole gasification unit is oxidized.

6.4 Results

Gas composition results indicate the effect on the gas produced in the gasification test runs when biochar is used as a co-fuel with solid recovered fuel. Set points from earlier test runs (BFB 22/38B1 and BFB 22/38B2) have been included in the results for reference. It should also be noted that the last two set points were taken in lower gasifier (bed) temperatures (about 850 °C), and they are comparable to each other, meanwhile the other set points, where the gasification occurred about at 890 °C, are comparable to each other. Benzene and tar concentrations (in dry gas, g/m³n) after filter in all set points are illustrated by bar charts in Figure 18.

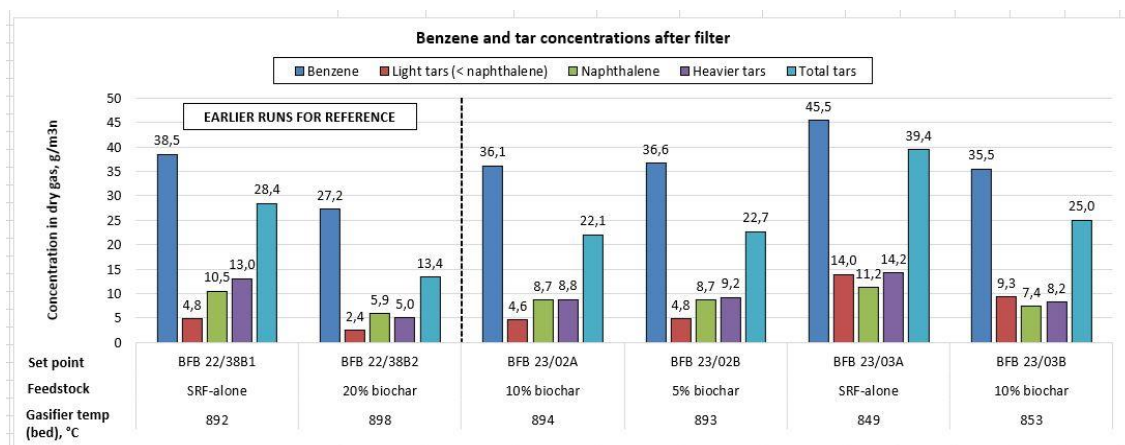


Figure 18. Benzene and tar concentrations after the filter of all set points.

As can be seen, biochar has a downward effect on the concentrations of benzene and tars. Especially on the last test run day, the difference is noticeable when two different set points (BFB 23/03A and BFB 23/03B) were taken at the 850 °C temperature with SRF alone and then with biochar. Figure 19 further illustrates the same effect with percentage changes when comparing the set points with biochar to set points with SRF-alone.

Change in tar concentration in comparison to SRF-alone gasification						
Set point	BFB 22/3881	BFB 22/3882	BFB 23/02A	BFB 23/02B	BFB 23/03A	BFB 23/03B
Share of biochar in feedstock mixture	SRF-alone	20% biochar	10% biochar	5% biochar	SRF-alone	10% biochar
Gasification temp, °C	892	898	894	893	849	853
Benzene	-	-29,3	-6,1	-4,8	-	-22,0
Light tars (<naphthalene)	-	-49,7	-5,0	-0,6	-	-33,3
Naphthalene	-	-43,9	-17,5	-17,2	-	-33,6
Heavier tars	-	-61,5	-32,5	-29,5	-	-42,2
Total tars	-	-53,0	-22,3	-20,0	-	-36,6

Figure 19. Percentage changes in benzene and tar concentrations in comparison to SRF-alone gasification.

The concentrations are examined after the filter because it is important to monitor the gasification process itself and the effect of biochar in gasification. The concentrations of benzene and tars of course decreased significantly after the reformer, but surely it is good to minimize the load of the reformer. In addition to this, the results of the reformer are not fully comparable, as the reformer has been operated under varying conditions.

In addition, using biochar as co-fuel also increases the proportion of hydrogen (H₂) and carbon monoxide (CO) in the gas. On the other hand, the amounts of other dry gas compounds are reduced, and the value of the synthesis gas increases. This can be seen in the dry gas analysis after the filter in Figure 20. It describes the analysis of the last two set points (BFB 23/03A and BFB 23/03B), where set point “A” was without biochar and set point “B” was with biochar.

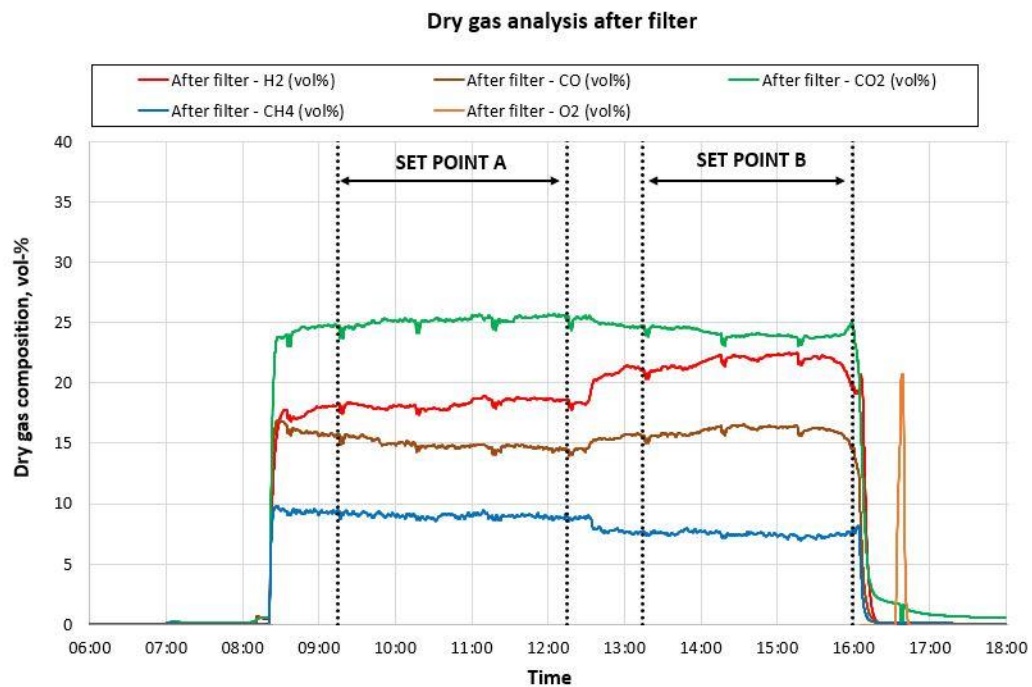


Figure 20. Dry gas analysis after the filter of set points BFB23/03A (set point A) and BFB 23/03B (set point B).

Dry gas composition after the filter is illustrated in Figure 21. It shows the overall picture of all compounds in produced gas (dry basis) after the filter in all set points. Quantities are expressed as volume percentages.

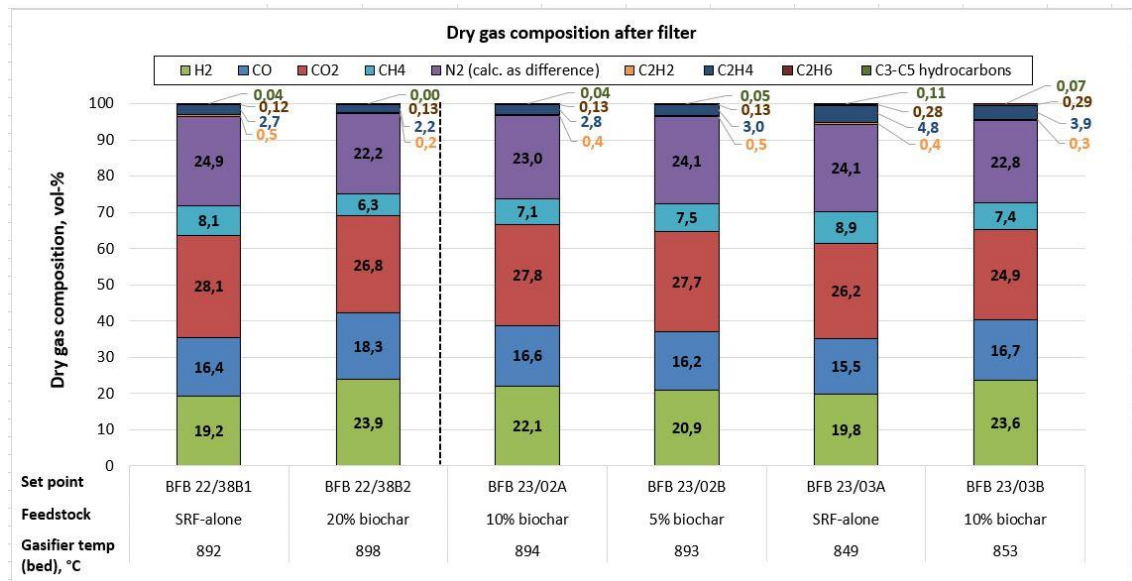


Figure 21. Dry gas composition after the filter in volume percentages.

It should also be noted that the operation of the filter and reformer remained stable during the test runs. Figure 22 illustrates the operation of the filter at the same set points (BFB23/03A and BFB23/03B). As hot filter dust accumulates on the filter candles, the pressure drop measured across the filter (filter pd 670) starts to rise. However, whenever pulse nitrogen is applied to the filter, the dust is almost completely removed, and this is observed as a drop in the pressure difference. The pressure difference always drops to the same level before the dust starts to build up again. It is also noted that dust accumulates significantly more at set point B when biochar is involved. Even in this situation, the pressure drop always returns to the initial level after pulsing, and the filter remains stable throughout the run.

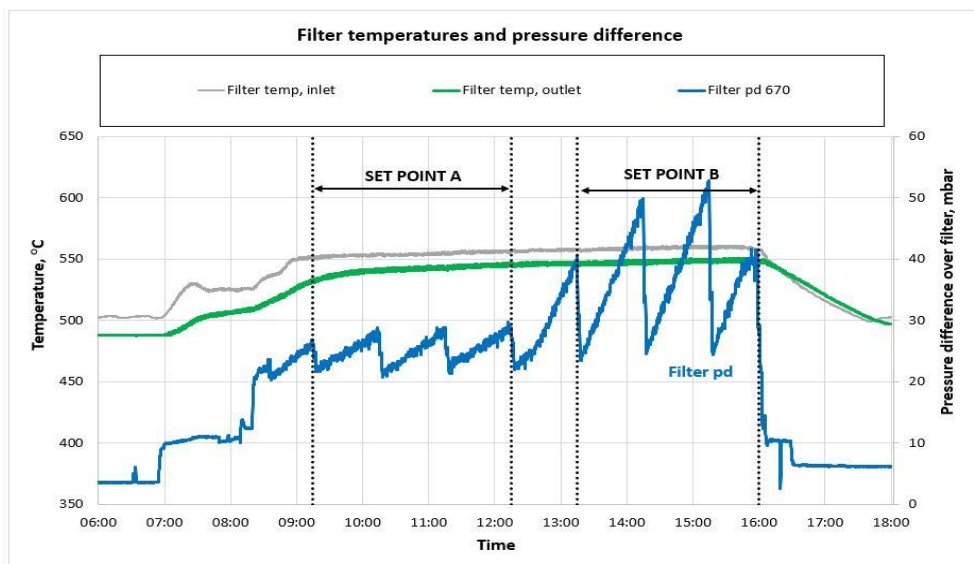


Figure 22. Filter temperatures and pressure difference in set points BFB23/03A (set point A) and BFB 23/03B (set point B).

The same can be concluded from the reformer's analysis in Figure 23. The pressure difference measured over the catalysts does not increase significantly, and the level remains relatively constant throughout the run. Thus, no carbon accumulates in the reformer. It can therefore be concluded that the produced gas could be filtered and reformed well.

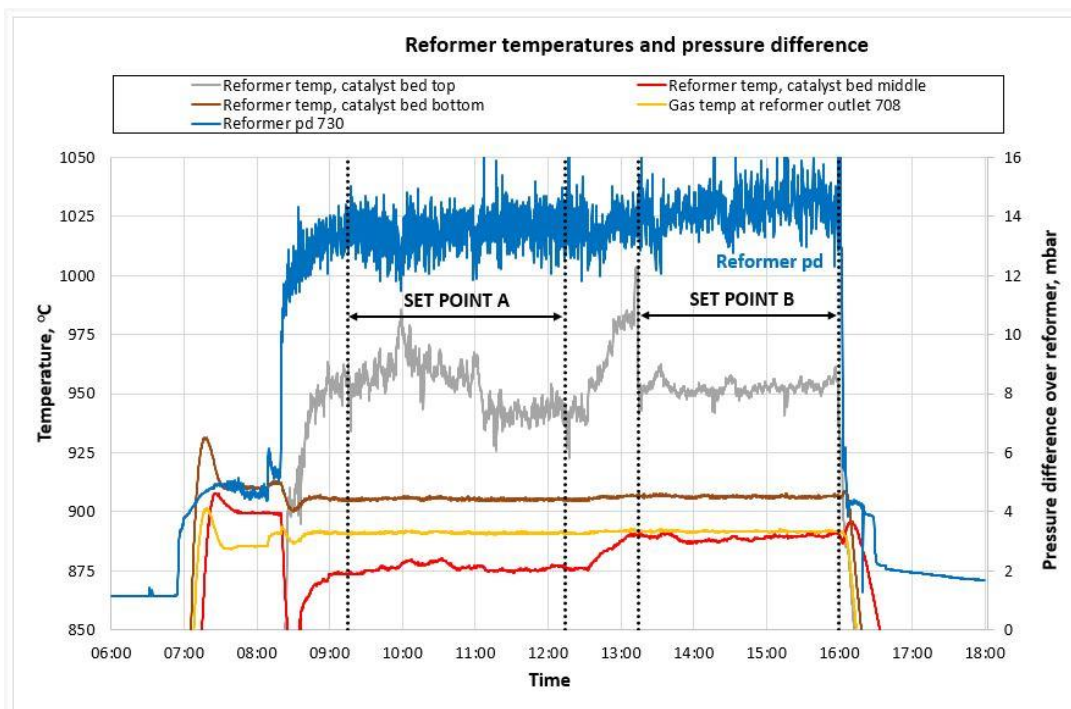


Figure 23. Reformer temperatures and pressure difference in set points BFB23/03A (set point A) and BFB23/03B (set point B).

A summary of the overall compositions of the feedstock mixtures used in the test runs is shown in Figure 24. Individual composition data for SRF and biochar were presented earlier in section 6.3 (Figure 17).

Test campaign	BFB 23/02A	BFB 23/02B	BFB 23/03A	BFB 23/03B
Date	11.1.2023	12.1.2023	19.1.2023	19.1.2023
Time (set point)	12:30-15:48	10:00 - 14:00	09:15 - 12:15	13:15-16:00
Gasification mode	oxygen+steam	oxygen+steam	oxygen+steam	oxygen+steam
Feedstock				
Feedstock mixture, wt/wt	90 % SRF / 10 % char	95 % SRF / 5 % char	100% SRF	90 % SRF / 10 % char
Lower heating value (LHV), MJ/kg (dry basis)	20,44	20,22	20,00	20,46
Moisture, wt-%	5,7	5,8	6,0	5,7
Proximate analysis, wt-% (dry matter)				
Volatile matter	62,9	65,7	68,5	62,7
Fixed carbon	18,3	15,8	13,3	18,5
Ash	18,8	18,5	18,2	18,8
Ultimate analysis, wt-% (dry matter)				
Ash	18,8	18,5	18,2	18,8
C	50,1	49,1	48,0	50,2
H	5,9	6,1	6,4	5,8
N	1,0	1,1	1,1	1,0
O (as difference)	23,5	24,5	25,5	23,4
S	0,77	0,81	0,85	0,77
Cl	not analysed	not analysed	not analysed	not analysed
Bed material	Sand 100%	Sand 100%	Sand 100%	Sand 100%

Figure 24. Composition table of the feedstock mixtures used in the test runs.

Figure 25 summarizes the values obtained for the gasifier, filter, and reformer. The results described above for gas composition and quality after the filter are also summarized in the figure.

Test campaign	BFB 23/02A	BFB 23/02B	BFB 23/03A	BFB 23/03B
Date	11.1.2023	12.1.2023	19.1.2023	19.1.2023
Time (set point)	12:30-15:48	10:00 - 14:00	09:15 - 12:15	13:15-16:00
Gasification mode	oxygen+steam	oxygen+steam	oxygen+steam	oxygen+steam
Gasifier				
Fuel feed rate, g/s	1,330	1,338	1,460	1,448
Bed material feed rate, g/s	0,0530	0,0422	0,0422	0,0201
Oxygen feed rate, g/s	0,462	0,460	0,380	0,380
Steam feed rate, g/s	0,570	0,552	0,544	0,544
Purge nitrogen feed rate, g/s	0,501	0,501	0,501	0,501
Bottom ash removal, g/s	0,149	0,138	0,147	0,119
Steam-to-fuel feed ratio, kg/kg-daf	0,56	0,54	0,48	0,49
Steam-to-fuel feed ratio, kg/kg dry	0,45	0,44	0,40	0,40
O ₂ feed, % of stoich.combustion	23,3	23,4	17,9	17,6
Bed/freeboard temperature, °C	894 / 888	893 / 883	849 / 841	853 / 843
Pressure in freeboard, bar(a)	1,05	1,05	1,05	1,07
Fluidising velocity, m/s	0,51	0,50	0,45	0,44
Gas velocity in freeboard, m/s	0,55	0,55	0,52	0,52
Carbon conversion to gas and tar, %	94,2	95,3	96,3	90,5
Filter				
Filter temperature, °C (inlet/outlet)	561 / 550	550 / 537	554 / 541	559 / 548
Face velocity on the filter, cm/s	1,90	1,66	1,87	1,66
Filter dust, g/s	0,187	0,181	0,188	0,228
Gas composition after filter				
Dry gas flow rate, m ³ /h (purge N ₂ included)	5,8	5,7	5,6	6,1
Wet gas flow rate, m ³ /h (purge N ₂ included)	8,9	9,0	8,9	8,9
Dry gas composition: purge N₂ included, vol-%				
CO	16,6	16,2	15,5	16,7
CO ₂	27,8	27,7	26,2	24,9
H ₂	22,1	20,9	19,8	23,6
N ₂	23,0	24,1	24,1	22,8
CH ₄	7,1	7,5	8,9	7,4
C ₂ H ₂	0,4	0,5	0,4	0,3
C ₂ H ₄	2,8	3,0	4,8	3,9
C ₂ H ₆	0,1	0,1	0,3	0,3
C ₃ -C ₅ hydrocarbons	0,0	0,0	0,1	0,1
SUM:	100,0	100,0	100,0	100,0
H ₂ O content in wet gas, vol-%	33,3	34,6	35,3	30,0
Benzene concentration, g/m ³ n (in dry gas)	36,1	36,6	45,5	35,5
Tar concentration, g/m ³ n (in dry gas)	22,1	22,7	39,4	25,0
Reformer				
Oxygen feed rate, g/s	0,148	0,141	0,200	0,231
Nitrogen feed rate, g/s	0,214	0,214	0,202	0,231
Reformer outlet temperature, °C	883	883	891	892

Figure 25. Values obtained from the gasifier, filter, and reformer, and the results of the produced gas (after the filter) in the test runs.

7 Conclusions

Gasification is becoming more sustainable and versatile day by day. The use of waste and biomass is increasing as a feedstock for gasification and will help achieve a more sustainable future. In addition to the benefits and market potential waste and biomass have, the emerging technologies are constantly being developed and providers and developers are creating more projects all the time. The role of fuel synthesis in the utilization of synthesis gas is also growing and new applications are constantly being sought.

The solid recovered fuel and biochar co-gasification test runs were completed. The gasification unit worked properly during the test runs and synthesis gas was produced. The analyses worked and the results were obtained on the quality of the synthesis gas and the performance of the gasification unit. The effects of biochar were also observed, which was considered one of the main objectives.

However, for the use of biochar as a co-fuel to achieve truly significant results in tar reduction, the feed-in rate should be close to 20 %. Of course, the less biochar you have to use the better, but then the tar levels increase. On the other hand, the use of biochar can also be a good way to improve the stability of filtration and reforming, by cutting down the tar concentration in the gas and thus inhibiting tar-induced blinding of filters or coke/soot formation in the reformer. Biochar co-feeding can also improve the filter performance in cases where the particulate concentration in the gas is low, which might cause clogging of the filter especially when combined with a high tar load and high filter temperatures. Biochar co-feeding can be used to increase the particulate concentration in the gas, which forms a protective dust layer on top of the filter against clogging. The use of biochar as a co-fuel is a relatively new innovation; therefore, there are not yet comparable results on its use in practice. However, it can be stated that the use of biochar as a co-fuel, especially with solid recovered fuel, has proven to work and is a good new tool for the future.

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