Achieving carbon-negative bioenergy systems from plant materials

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Introduction

There is a need to develop next-generation bioenergy systems that exhibit net carbon capture. Biomass removes carbon dioxide from the atmosphere during growth and, if converted to biofuel, has the potential to be 'carbon negative', especially if combined with carbon capture and storage. Accurately accounting for below-ground soil carbon, owing to root exudation and decay in the plant's rhizosphere, is also important for achieving net carbon capture. To achieve ambitious targets for global reductions in greenhouse gas emissions, biomass crops should generate high yield from minimal input energy while minimising environmental impacts that could make crop production less sustainable. This collection reviews advances in producing next-generation biofuels from non-food plant materials. Part 1 discusses key technologies to achieve this goal such as biomass gasification, fast pyrolysis and torrefaction. Chapters 1–3 address advances in technology, applications and commercial development. Part 2 assess advances in the production of biofuels from non-food crops: jatropha, oilseeds (such as canola and rapeseed), *Miscanthus*, switchgrass, willow and seaweed.

Part 1 Technologies

The first chapter in the book reviews developments in thermal gasification. This very flexible technique allows many different biomass feedstocks to be converted into a wide variety of products such as heat, electricity, chemicals and transport fuels as well as high value ash and biochar co-products. The chapter reviews current research to optimize process performance, fuel and product flexibility, including types of gasifier and gasification operating variables. It assesses developments in biomass gasification for heat and power generation as well as biofuel production. The chapter concludes by assessing developments in flexible biorefineries with integrated systems capable of polygeneration of different core and co-products.

Chapter 2 discusses the use of fast pyrolysis for biofuel production. Pyrolysis is a thermal depolymerization and fragmentation process carried out at moderate temperatures in the absence of oxygen and with a wide range of reaction residence times. It can convert a wide range of solid materials, ranging from woody biomass and algae to waste plastics, into complex mixtures of low molecular weight organic molecules. The chapter begins by examining the chemical reaction kinetics of fast pyrolysis as well as fast pyrolysis process technologies, including the transition from hydroprocessing to catalytic upgrading. It then describes pyrolysis co-products and their uses. The chapter

also reviews the use of both technoeconomic assessment (TEA) and life-cycle assessment (LCA) to assess process efficiency and sustainability. Finally, the chapter looks at the developments in commercialization of biomass fast pyrolysis.

The final chapter in Part 1, Chapter 3, discusses how biofuels can be produced using torrefaction. Significant investments have been made around the world to accommodate the use of dried and pelleted biomass materials in power plants. Substituting biomass for coal in coal-based boiler systems without degrading boiler capacity requires pretreatment to make its properties similar to the coal that it is displacing. The pretreatment technologies currently under active development include: torrefaction, steam explosion, and hydrothermal carbonization (wet torrefaction). This chapter reviews the factors associated with biomass pretreatment and the use of the advanced biomass-based fuels in power plants. It also provides a case study which describes the use of torrefied wood pellets at the Portland General Electric Boardman Facility in Oregon in the US.

Part 2   Materials

Part 2 of the book begins with a review of how biodiesel can be produced from renewable sources. There is increasing interest in the production of biodiesel from non-edible oil sources such as waste or recycled oil and animal fats. Transesterification is the most used method to convert triglycerides (TG) from different types of lipids. After reviewing the range of available feedstocks, Chapter 4 uses thermodynamic analysis to investigate the main three transesterification reaction systems: triolein and supercritical methanol (T&SCM), triolein and supercritical ethanol (T&SCE), and triolein and supercritical isopropanol (T&SCI). Using a case study, it identifies ways of optimizing supercritical transesterification technology for biodiesel production, as well as ways of improving the quality of the biodiesel manufactured from the process.

The subject of Chapter 5 is the production of biodiesel from oilseeds, in particular *Jatropha curcas*. The importance of edible oils for food applications makes non-edible oils a key feedstock for biodiesel production, including the seeds of *J. curcas*. The chapter begins by reviewing the characteristics of *Jatropha curcas* L. and how it can be used as a biodiesel feedstock through the use of transesterification. It then discusses the factors affecting the efficiency of enzymatic transesterification using immobilised lipase and provides a section on the life cycle assessment (LCA) of *Jatropha curcas* for biodiesel production. The chapter concludes by providing an economic analysis of biodiesel production using this feedstock.

Chapter 6 also reviews the production of biodiesel from oilseeds but instead focuses on canola and rapeseed. Currently, rapeseed oil is the dominant

feedstock for biodiesel production in Europe, while canola oil is also extensively used for biodiesel production in the Pacific Northwest of North America. The chapter describes current technologies and constraints of biodiesel production and examines life cycle assessment of canola/rapeseed biodiesel production. Finally, the chapter looks ahead to future trends of research in this area and provides guidance on further reading.

Chapter 7 discusses the sustainable use of *Miscanthus* for biofuel. The chapter focuses on research demonstrating that Miscanthus embodies a range of attributes (e.g. C4 photosynthesis combined with cold tolerance, high energy output/input ratios, efficient nutrient recycling and high yield from minimal agronomic input) that make it an ideal sustainable biomass crop for biofuels. Sections on both nutrient use efficiency and water use/water use efficiency are included. The chapter also discusses carbon flux and life cycle assessments for different end uses to improve the efficiency and sustainability of the process.

The next chapter addresses the sustainable use of switchgrass for biofuel. Switchgrass, a productive, perennial warm-season grass, native to much of North America, has significant potential as a sustainable biofuel crop. Chapter 8 begins by discussing switchgrass and environmental sustainability metrics. It then reviews the challenges that switchgrass faces in becoming a primary feedstock resource and provides a section on the production and agronomics of switchgrass in the context of sustainability. The chapter also reviews the economic, policy and social issues associated with the development of a sustainable biofuel industry. The chapter also includes a case study on burning switchgrass as a biofuel to illustrate biofuel production in practice.

Chapter 9 reviews the sustainable production of willow for biofuel use. Intensively managed plantations of willow (Salix spp.) are gaining interest worldwide, mainly due to their efficient and sustainable land use along with an increasing demand for biofuel resources. Willows have traditionally been used as biofuel in the form of wood chips for direct combustion in heat and power plants, but there is an increasing interest in using willow biomass as raw material for other biofuel supply chains. The chapter provides an overview of the challenges and key issues in the sustainable production and use of willow as feedstock for biofuel production in northern-temperate regions, including the issues of feedstock quality for biofuel use, feedstock productivity, cropping security, biodiversity, nutrient uptake and use, carbon accumulation and sequestration, and environmental impact. Finally, the chapter looks ahead to future research trends in this area and provides useful sources for further reading.

The final chapter of the book addresses the sustainable use of seaweed for biofuel. Chapter 10 describes the biological advantages and disadvantages of

seaweed in terms of its use as an energy crop and examines global production trends The chapter reviews methods of seaweed cultivation, together with harvesting and supply chain logistics. It provides a systematic review of conversion routes to producing biofuels and other value-added products from seaweed. Finally, the chapter includes detailed case studies of potential industrial-scale processes for three different conversion routes and looks ahead to future research trends in this area.

Part 1

Technologies

Chapter 1

Biomass gasification for bioenergy

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1 Introduction

Gasification is a partial thermal oxidation of carbon-rich materials yielding a non-condensable gas product (CO_2, CO, H_2, H_2O and other gaseous hydrocarbons) and smaller quantities of by-products such as char, ash and condensable fractions including water, tars and oils. Biomass gasification platforms are most commonly designed for conversion of wood in the form of wood pellets, wood chips or waste wood. However, it is possible to extend the potential range of organic material fractions converted in thermal gasification to cover various organic secondary resources. This includes agricultural, municipal and industrial by-products and residues such as cereal straw, fibre residues, sludge and organic waste fractions.

Biomass-based energy systems have a unique potential for genuine carbon-negative energy production. There are two main routes that may be pursued individually or in a complementary combination: (i) combination with carbon capture and storage (CCS) and (ii) processes with co-production of carbon-rich char/ash fractions as well as other by-products to replace current, fossil-based products in the market. CCS has a huge potential, but the technology

has to mature and the economic feasibility needs to improve for it to penetrate market barriers (Álamo et al., 2018). The technical potential for carbon sequestration via bioenergy processes with carbon-rich residuals is smaller than via CCS, but it is cheaper, robust and readily applicable. The potential to produce carbon-negative energy in this way, arise from a combination of high net energy efficiency and a potential for carbon sequestration via the ash/char fraction as illustrated in Fig. 1. Emissions from peripheral unit processes and upstream inputs influence the net potential of this approach. The level of direct carbon negativity will be given by the amount of long-term sequestered carbon minus all emissions related to biomass fuel procurement and pre-treatment, production and use of utilities (water, chemicals, fuels) as well as the production and maintenance of the plant and peripheral systems (Thomsen et al., 2011).

Additional contribution from downstream CCS added to this system will have a substantial potential to increase the level of carbon negativity. Even CCS processes with low coverage and/or efficiency may provide a sizable net contribution when combined with efficient low-carbon biomass-based energy
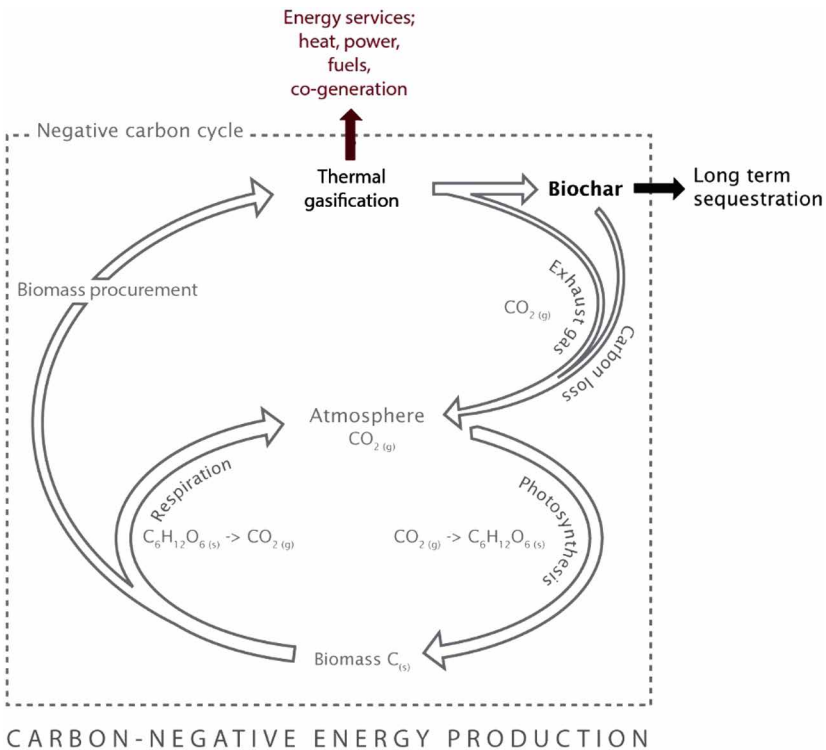
Figure 1 Schematics of the ideal carbon-negative biomass-based CHP system. Source: adapted with permission from Thomsen et al. (2011).

systems. Systems with high net energy efficiency will have the highest abatement potential. In thermal systems, these are most often cases with utilization of the inevitable heat production, that is biomass-based heat systems or biomass-based co-generation systems. Thermal gasification of biomass is unique in this regard, since the platform excels in overall efficiency and flexibility.

Gasification is no new invention. First steps in the development of gasification started in the late 1600s. Hundred years later, in 1792, coal producer gas was reported to be used for lighting and later on for cooking and heating. Almost simultaneously, the water-gas-shift reaction was described and within a few decades, the first commercially used gasifier was built. Since the early 1900s, application of producer gas rapidly spread into power production, combined heat and power (CHP) production and operation of vehicle motors as well as into gasification of wood and other biomasses (Behera and Varma, 2019).

Despite the advantages that biomass gasification offers, it has not yet been able to consolidate its role and become a fully mature technology. Thus, a majority of biomass gasification projects remain at the pilot or demonstration scale. This is due to inherent challenges of biomass as a fuel and insufficient resources allocation to address operational issues related to the following (Asadullah, 2014a; Heyne et al., 2013; Sansaniwal et al., 2017; Zhang et al., 2013a):

- Supply chain management (transportation and storage due to low-energy density);
- Handling, pre-treatment and fuel feeding;
- Optimizing the energy efficiency to high moisture content feedstock;
- Addressing variations in biomass fuel properties;
- Unrealistic fuel flexibility expectations;
- Unrealistic product property expectations;
- Upscaling of specific gasifier reactors;
- Problems with gas cleaning, conditioning and impurities such as sulphur compounds (e.g. H_2S, COS), hydrogen chloride, alkali and ammonia;
- Tar-related issues, for example condensation at lower temperatures which can lead to fouling and plugging of the plant pipelines, filters, catalyst units or engines; and
- Ash-related problems such as sintering, agglomeration, deposition, erosion and corrosion.

There is a firm belief in academia and industry that all mentioned technical problems can be overcome and that most of the solutions already exist. However, the foremost barrier for biomass gasification is associated with the

economic risk in a rapidly changing energy market. Thus, policy measures ensuring long-term economic viability of the projects should be implemented.

The aim of this chapter was to provide an insight into the versatility and benefits of biomass gasification processes and its products in relation to production of carbon-negative bioenergy from plant-based materials. General key issues related to designing a gasification plant are reviewed and discussed, and several new concepts and solutions in the form of process integration schemes, polygeneration strategies and biochar uses are described.

2 Fundamentals of biomass gasification

Biomass gasification involves a sequence of several stages occurring at different temperatures: drying (100–200°C), pyrolysis (200–700°C), partial combustion (>800°C) and reduction or gasification (700–900°C). These stages, depending on the specific gasifier design, often overlap.

- Drying: Evaporation of the moisture contained in the feedstock. The amount of heat required in this stage is proportional to the feedstock moisture content. The drying often takes place as a preliminary step in the pyrolysis stage and the required heat for both sets of processes is usually supplied from the oxidation stage.
- Pyrolysis: Thermal decomposition of biomass in the absence of oxygen/air. The cracking of chemical bonds takes place, resulting in the formation of molecules with a lower molecular weight. Thus, different fractions are obtained: solid char, liquid/condensed tars and a gaseous fraction. The condensable fraction of the pyrolysis gas will usually mix with the evaporated water from the drying stage as well as released cell bound water. Product weight and energy ratios will depend on the nature of the biomass, the reactor design and operating conditions of the process. Pyrolysis is a net endothermic stage and the heat required comes from the oxidation stage of the process.
- Oxidation: Usually, gasification involves a stage with partial oxidation to provide heat for the drying, pyrolysis and char gasification. During the partial oxidation, a part of the organic material in the fuel is oxidized and heat is released from the net exothermic reactions in the process. A partial oxidation is conducted by supplying, for example, air or pre-heated air to the gas/tar or to the char in a sub-stoichiometric ratio.
- Reduction or gasification: During the reduction/gasification step, the carbon matrix of the pyrolysis char is decomposed by reaction with gasification agents CO_2 and/or H_2O at elevated temperatures under a reducing atmosphere leading to formation of combustible gases. The gas from pyrolysis and char gasification can be mixed subsequently or

prior to the char gasification stage. The reduction step is endothermic, and the temperature at which it takes place has a fundamental role in determining the composition of the final gas and its characteristics (LHV, tar presence).

The quality of the gas produced in biomass gasification varies according to the gasifying agent used, the feedstock, bed material, operational conditions (temperature, pressure, air-to-fuel ratio) and gasification technology.

2.1 Biomass resources

Biomass is a broad concept that includes 'the biodegradable fraction of products, waste and residues of biological origin from agriculture (including vegetal and animal substances), forestry and related industries, including fisheries and the aquaculture as well as the biodegradable fraction of industrial and municipal wastes' (2009/28/EC European Directive). Even though gasification platforms are often designed for conversion of conventional biomass types, primarily wood, the global increase in demand for bioenergy has facilitated growing efforts to extend the potential range of organic material fractions converted in thermal processes. As a result, there is a growing focus on thermal utilization of various secondary organic resources including: (Thomsen et al., 2016):

- Agricultural by-products and residues: For example, crop residues (stalk, leaf, cob etc.), manure fibres, muck and bedding and fibres from biogas slurry;
- Municipal by-products and residues: For example, source segregated organic waste, used textiles, grass and cuttings from road and park maintenance, beach cleaning waste and sewage sludge; and
- Industrial by-products and residues: For example, residues from breweries, food packaging, food retail, food preparation or residues from production of non-food products based on the partial conversion of animal and vegetable raw materials.

Optimized treatment of secondary resources has great potentials from an economic, environmental and resource political point of view (Thomsen et al., 2016). However, the diversity of biomass resources makes it essential to characterize them thoroughly, as their physical-chemical properties will have a direct impact on the design of the gasification plant as well as on the technical and economic feasibility of the process. This characterization should be carried out before choosing the gasification technology to avoid subsequent problems. The biomass properties that have the highest impact on gasification technology are:

- *Biomass particle size* (Molino et al., 2018; Sansaniwal et al., 2017; Sikarwar et al., 2016): Reducing the biomass particle size increases the pre-treatment cost of the feedstock, but it increases the surface area and decreases the diffusion resistance. This results in improved heat and mass transfer, increased reaction rates, fuel conversion, carbon conversion efficiency and decreased char and tar yields. Conventional gasifiers can take particle sizes in the range of 0.15–51mm. Particles of 0.15 mm are required for entrained flow gasifiers while fixed-bed reactors, with longer residence times, can tolerate particles up to 51 mm. Usually, bubbling fluidized-bed (BFB) reactors can take particles of up to 6 mm.
- *Moisture content* (Molino et al., 2016, 2018; Ruiz et al., 2013; Sansaniwal et al., 2017; Sikarwar et al., 2016): High moisture contents increase the energy required for water evaporation and steam gasification reactions that, in turn, may lower the gasifier operating temperature especially in the first stages. Reducing the moisture content may in some cases increase the energy efficiency, especially if low-temperature heat cannot be utilized. In addition, a dryer fuel will increase syngas quality, syngas HHV and decrease the conversion emissions. Fluctuations in biomass moisture content lead to variations in bed temperature, and this causes changes in the composition of the syngas generated.

  The required moisture content of the biomass depends on the gasifier design; updraft fixed-bed gasifiers can operate with moisture contents up to 60% (w/w), while downdraft fixed gasifiers can take maximum moisture contents of 25% (w/w). However, values around 10–20% (w/w) are generally recommended for conventional gasification technologies and will keep bed temperatures moderately stable.
- *Ash content* (Molino et al., 2018; Sansaniwal et al., 2017; Sikarwar et al., 2016): The ash content in biomass plays a significant role in thermal biomass utilization, especially if it contains alkali metals such as potassium or halides such as chlorine. Slagging, fouling and corrosion are important – and potentially critical, issues that may be caused by the inorganic species present in the biomass. It is not possible to give any general biomass criteria related to ash content as the potential problems relate to a combination of process design, process temperature profile, ash quantity and ash composition. However, generally, biomass with ash content lower than 2% (w/w) can be used as feedstock material in all types of gasifiers even though there may still be issues related to corrosion and long-term deposit build-up.
- *Bulk density:* Bulk density will have a strong influence on the transportation costs, handling and feeding of the biomass in the gasification plant. Biomass with a low bulk density might cause severe feeding problems to the gasification units because of getting stuck in the feeding line. These

problems can be overcome by densifying the bulky biomass; however, this will result in higher energy consumption and cost.

Organic resources that are initially found to be unsuited for thermal gasification may still have a fuel potential through fuel design or thermal pre-treatment. Torrefaction is a well-known process used to pre-treat biomass resources for various purposes and may render organic material more coal like. Many other problematic issues may be overcome by fuel design, for example through proper mixing. Recent studies on these issues have indicated many potential benefits related to moisture content, ash melting-related issues and ash/char by-product quality (Skoglund et al., 2016; Thomsen et al., 2016, 2017a,b,c).

2.2 Types of gasifiers

The design of a biomass gasifier depends ideally on the fuel characteristics (size, shape, moisture content, ash content) and the marketability of the end products. The principal design concepts, even though there are others available, can be classified in fixed beds, fluidized beds and entrained flow reactors (Table 1).

Fixed-bed reactors are often considered the best choice for small-scale plants of up to 10 MW. Within fixed-bed reactors, it is possible to distinguish updraft and downdraft configurations. In updraft gasifiers, the biomass is supplied from the top and the gasifying agent from the bottom (counter-current). For these gasifiers, the sequence for biomass is drying → pyrolysis → reduction → combustion. Instead, in downdraft gasifiers, the biomass and gasifying agent are supplied from the top (co-current). Thus, the sequence is drying → pyrolysis → combustion → reduction. The main difference is that in downdraft gasifiers the decomposition products from drying and pyrolysis go through thermal cracking in the oxidation zone, thus produce less tar and a higher-quality gas than updraft gasifiers, where the pyrolysis gas goes directly into the producer gas. Fixed-bed gasifiers are simple in construction and operate at low gas velocity with high carbon conversion and long residence time.

Fluidized-bed reactors, including BFB and circulating fluidized-bed (CFB) reactors, are based on the principle of fluidization in which both the fuel and the hot bed material (inert inorganic material and/or catalyst) is made to behave as a fluid by mixing the high-density bed and fuel material with a low-density fluidization agent, for example, air, steam or other gas. The semi-suspended conditions are kept by means of the gasifying agent added at the appropriate velocity. These gasifiers provide an excellent gas-solid mixing, a uniform temperature and solid/gas concentration in the entire bed. It is not possible to distinguish the different zones in single-reactor fluidized-bed systems (drying,

Table 1 Comparison of different types of gasifiers (Basu, 2018; E4tech, 2009; Molino et al., 2016, 2018; Ruiz et al., 2013)

Gasifier	Downdraft	Updraft	Bubbling fluidized bed	Circulating fluidized bed	Entrained flow bed
Technology	Simple, reliable and proven. Simple reactor with relatively low investment cost		Plants with higher investment and maintenance costs. Good ability to scale-up		Complex. High investment and maintenance costs
Fuel specifications	<51 mm	<51 mm	<6 mm	<6 mm	<0.15 mm
Tar (g/Nm³)	0.015–3.0	30–150	3.7–61.9	4–20	0.01–4
Ash and particles in syngas	Low	High	High	High	Low
Gasification temperature	900–1050°C	950–1150°C	800–1000°C	800–1000°C	1300–1500°C
Syngas exit temperature	700°C	150–400°C	800–1000°C		>1260°C
Capacity	<5 MWe	<10 MWe	1–20 MWe	2–100 MWe	5–100 MWe
Carbon conversion efficiency	High	High	High. Loss of carbon in ash	High	High
Process flexibility	Very limited. Any change in the process variables needs a new design		Flexible to loads less than design		Very limited. Size and energy content of the fuel must be in a narrow range
Hot gas efficiency	85–90%	90–95%	89%	89%	80%

pyrolysis, reduction and combustion) due to the intense gas-solid mixing. Fluidized-bed gasifiers usually operate at relatively low temperatures (700–900°C) to prevent ash sintering and agglomeration and are the preferred option for large-scale plants due to superior scalability characteristics compared to fixed-bed systems.

Entrained flow reactors operate at high temperatures (1400°C) and high pressure (20–70 bar) by injecting powdered fuel into a high-speed stream of the gasifying medium and into the reactor. Thus, the gas stream entrains the fuel particles and directs the flow direction and speed through the reactor system.

2.3 Gasification operating variables

The operating parameters such as temperature, pressure, gasifying agent and equivalence ratio (ER) will have a very important role in determining the gasification performance, syngas yield and gas composition.

2.3.1 Temperature

Temperature is a crucial parameter in biomass gasification which, to a large extent, controls the gas composition, reaction rate, tar concentration, ash-related problems and so forth. Low temperatures generally result in higher tar content and low CO and H_2 content in the product gas. High-temperature gasification, on the other hand, leads to a desired high yield of CO and H_2 while reducing the tar content. However, high gasification temperatures present two major potential drawbacks: ash-melting problems, especially for high ash-containing biomass, and rigorous reactor specifications.

2.3.2 Pressure

Biomass gasification can be operated at atmospheric pressure or at higher pressures usually depending on the downstream application of the product gas. If the product gas is used in turbines or in Fischer–Tropsch synthesis, then pressurized gasification can be convenient even though it is more technologically complex. A reduction in the tar yield and in light hydrocarbons can be achieved by operation at higher pressures (Asadullah, 2014a; Molino et al., 2018).

2.3.3 Gasifying agent

Air, steam, pure oxygen, carbon dioxide or mixtures of them can be used as gasifying agents. The selection will depend on the gas quality requirements for

the downstream applications and the economics of the overall process. Air is the cheapest and most cost-effective gasifying agent and has been extensively applied for heat and power generation purposes. It results in a highly nitrogen diluted and low-quality gas with low H_2 content (8–14 vol. %) and a heating value in the range of 4–7 MJ/Nm^3 (Matas Güell et al., 2012). Pure oxygen is the most expensive gasifying agent because it requires an air-separation unit, but it leads to a syngas with a heating value up to 28 MJ/m^3, higher concentrations of CO, H_2 and low concentration of tars (Asadullah, 2014a; Molino et al., 2018). The cost of steam is somewhere between air and oxygen and leads to a product gas with a heating value around 10–18 MJ/Nm^3 and with a higher concentration of H_2 as a result of the water-gas-shift reaction, but it reduces the thermal efficiency of the gasification. Steam-only gasification requires an external energy supply due to the endothermic reactions involved in the process. CO_2 gasification results in a product gas rich in CO because of the reaction of CO_2 and carbon; however, this reaction is slow and external heat supply is required.

2.3.4 Equivalence ratio (ER)

The ER can be defined as the ratio between air-to-fuel ratio of the gasification process and the air-to-fuel ratio for complete stoichiometric combustion. ER is a relevant parameter because it defines the degree of combustion and, thus, the temperature and distribution of gas, tar and char in the gasifier. ER optimal values are in the range of 0.2–0.3 for fixed-bed and fluidized-bed gasifiers, while entrained flow gasifiers usually require a 20% higher ER (Molino et al., 2018). ER lower than 0.2 results in an incomplete gasification, while ER higher than 0.4 approach the combustion. Decreasing the ER results in higher concentrations of H_2 and CO and higher calorific value of the product gas. Increasing the ER has the opposite effect and increases the CO_2 concentration but it reduces the tar yield. Thus, it is necessary to optimize the process depending on the downstream applications.

2.4 Synthesis gas requirements for further applications

The gas produced from biomass gasification is rarely used directly in downstream applications. Usually the gas needs to be cooled and cleaned to ensure smooth and efficient operation. The gasifier design, feedstock type, gasifying agent and other operating parameters will influence the gas composition and the quantity and type of impurities. The gas quality is a key driver in the technical and economic feasibility of different application schemes. In Table 2, a range of generalized quality measures accepted by engine, gas turbine and fuel-cell applications are provided.

Table 2 Acceptable range of impurities for different applications (Hasler and Nussbaumer, 1999; Sansaniwal et al., 2017; Singh et al., 2014)

	IC engine	Gas turbine	Fuel cell
Particles (mg/Nm^3)	<50	<30	–
Particulate matter (μm)	<100	<5	<1
Tar (mg/Nm^3)	<10	<5	<1
Alkali metals (mg/Nm)	–	<0.24	–

In fuel synthesis from gasification producer gas, the gas quality requirements may be even higher than for direct production of electricity and heat. The catalysts used in Fischer–Tropsch synthesis are sensitive to even very small amounts of impurities. In commercial operation, catalysts are replaced or regenerated after a certain operational period. Thus, the definition of the gas cleaning is therefore based on economic considerations: investment in gas cleaning versus accepting decreasing production due to poisoning of the catalyst. Requirements for feed gas quality of different downstream applications can be found elsewhere (Boerrigter et al., 2004; Molino et al., 2018; Tijmensen et al., 2002).

2.5 Gas cleaning processes

As previously mentioned, cleaning and conditioning of the product gas may be required to remove contaminants and potential catalyst poisons as well as to achieve the qualitative composition required by, for example, biofuel production processes. There are several papers available in the literature that have recently addressed and analysed the different possible cleaning processes (Abdoulmoumine et al., 2015; Asadullah, 2014b; Woolcock and Brown, 2013). In this section, a brief summary of commonly applied physical, thermal and catalytic gas cleaning technologies is presented.

2.5.1 Physical gas cleaning

Physical gas cleaning is one of the simplest cleaning methods and includes filtration and wet scrubbing to remove tar and particulate matter from the gas through gas/solid or gas/liquid interactions. Filtration can be conducted at high or low temperatures. High-temperature filtration requires temperature tolerable materials such as ceramics, fibre glass, composites or sand. Low-temperature filtration processes can use charcoal, cotton fibres as filtration media. Filtration techniques often face the problem of clogging and deposition of gas particles causing a pressure drop across the filtration. Back-flushing the filtration media with, for example, nitrogen may revitalize the performance of the filter.

Wet scrubbing is usually done at low or ambient temperature using water, oil or another solvent but faces the problem of producing high amounts of contaminated liquid that needs to be treated.

2.5.2 Thermal gas cleaning

Thermal decomposition consists of degrading (cracking) heavy aromatic tar compounds into smaller, lighter and non-condensable gas species such as methane, hydrogen and carbon dioxide at temperatures around 1000°C. The most problematic aspects of high-temperature cracking relate to the required temperature resistance of the setup that needs a complex and highly controllable heating system and intensive cooling system for the gas afterwards as well as possible ash-melting-related problems (Asadullah, 2014a).

2.5.3 Catalytic gas cleaning

It is possible that physical and thermal gas cleaning steps are not enough to fulfil stringent requirements of some downstream applications. Thus, the utilization of effective catalysts is often considered a method to decrease the concentration of tar and ammonia in the product gas. Catalytic decomposition usually occurs at much lower temperatures (600–800°C) than thermal cracking (>1000°C). Catalysts for tar removal have been tested and used directly in the gasifier reactor as well as in secondary catalytic reactors. Sometimes, additional oxidant (O_2 or H_2O) is injected into the secondary catalytic bed. Tars can be cracked or hydrocracked into light hydrocarbons or converted into CO and H_2 through steam and dry reforming reactions. The spectrum of studied catalytic materials covers acidic solids for cracking, basic solids for 'reforming' reactions and metal oxides with both acidic and metal sites for cracking and hydrocracking reactions (Torres et al., 2007). Desirable properties of a good catalyst for any of these reactions are (Sutton et al., 2001): (i) capability to efficiently convert tars into useful gas products in an environment containing high concentrations of H_2, CO, CO_2 and H_2O at temperatures of 600–800°C at ambient pressure (or even higher temperatures for pressurized reactors); (ii) resistance to deactivation and poisoning by species in the gas, such as sulphur-containing compounds; and (iii) resistance to attrition. It is also desirable to carry out the tar conversion process in such a way as to keep the deposition of carbonaceous materials on the catalyst surface under control.

In biomass gasification, most of the nitrogen ends up as ammonia (NH_3) and N_2 with lower concentrations of hydrogen cyanide (HCN), isocyanic acid (HNCO) and nitrogen oxides (NOx). Nitrogen-containing species are undesirable because they can poison catalysts or serve as precursors for NOx in downstream burners, gas engines or gas turbines. Most of the literature on

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