Chapter 8
Intermediate Biofuels to Support a Flexible Application of Biomass

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Abstract As the previous book chapters concluded, the future bioenergy provision concepts for power, heat and transport fuels are characterised by more complex demands. A future energy market is characterised by the need for a sustainable flexible energy carrier with homogeneous properties for application in the fields of CHP, heat and fuel. To some extent these energy carriers are already available today (see Chaps. 4, 5, 6 and 7). However, in many cases untreated biomass cannot fulfil the requirements of existing and future conversion processes or demands respectively. As far as solid biofuels are concerned, the high moisture content of untreated biofuels coupled with a low energy density and high biological activity require the development of often costly storage, transport and conversion techniques. Various research activities are still ongoing to improve the utilisation of biofuels in existing and future technologies, available infrastructure and therefore also in logistic and storage issues. A similar development can be observed regarding the biogenic substitutes for natural gas (biomethane, bio-SNG). Such upgraded "new" – or rather "advanced" – solid and gaseous biofuels are high energy value products for gasification and combustion in industrial conversion plants as well as for domestic applications with excellent advantages in flexible energy provision. The amount of advanced solid biofuels in the markets of heating and power or combined heat and power systems will increase, as will the share of the biogenic substitutes for natural gas with further development and process optimisation.

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This chapter reviews the current developments in selected biomass pretreatment processes and their intermediate biofuel products that have the potential to increase flexible bioenergy production in the short and mid-term. On the one hand, these include biomass densification without thermal treatment as well as torrefaction and hydrothermal treatment for producing intermediate solid biomass. On the other hand, technologies for biogenic substitutes for natural gas are evaluated. The focus lies on the surplus value of the technologies in terms of flexibility during energy production or use of the advanced solid biofuels or biogenic substitutes for natural gas as intermediate bioenergy carriers.

8.1 Introduction

A future energy market is characterised by the need for sustainable energy carriers that fulfil the demands of the more flexible application that is anticipated in the fields of combined heat and power (CHP), heat and fuel. These future energy carriers will feature homogeneous properties for flexible provision, fast reaction times when operating during the conversion process, usage in small, medium and large scale plants as well as the utilization of a broad biomass resource base.

In the future, a sharp distinction between the fields of CHP, heat and fuel will no longer be possible and interactions will be commonplace, (see Chap. 2). As far as biomass is concerned, two types of future or intermediate fuels are promising (see Fig. 8.1). These are the advanced solid biofuels and biogenic substitutes for natural gas.

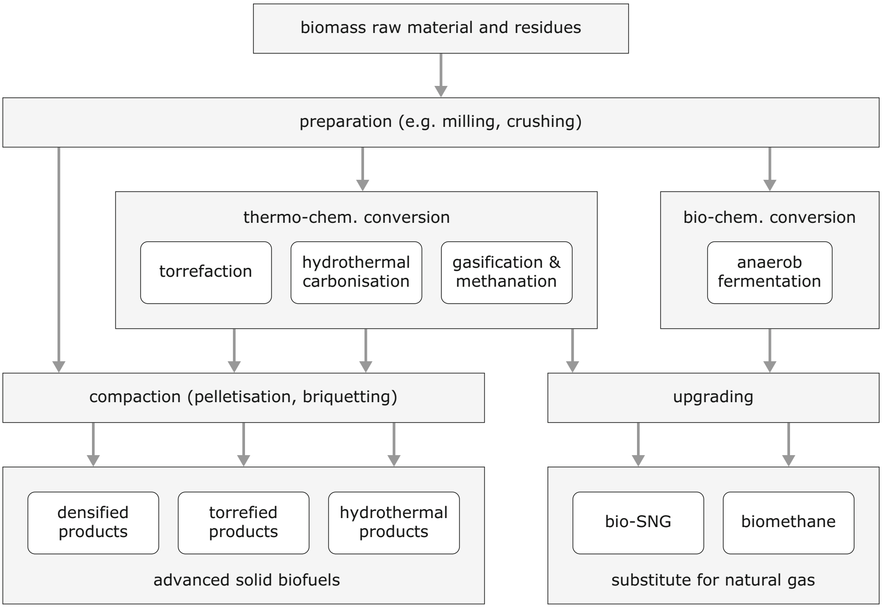


Fig. 8.1 Selected intermediate bioenergy carriers for supporting the flexible application of biomass

From the advanced solid biofuels, the densified and thermally treated ones (torrefaction and hydrothermal carbonisation) are considered and from the biogenic substitutes for natural gas, biomethane or bio-SNG are considered. Each biofuel has its own advantages in terms of flexible properties compared to conventional fuels. To some extent, these energy carries are already available today or still under development.

The potential contribution of the advanced solid biofuels and the gaseous biofuels to a future energy supply system is different:

Advanced solid biofuels have advantages over loose material (wood chips, straw chops, mixtures of landscape residues etc.) in combustion and gasification systems due to improved product qualities of the fuels, which can be summarized as follows:

- Homogeneous material (carbon content, heating value, water content, shape and form, higher mechanical durability, higher bulk density, etc.)
- Reduced water retention leading to no or only low biological degradation caused by a low moisture content, reduced self-heating risk and increased storage stability
- Low dust formation during the biofuel transportation and redistribution, reduced health and safety risks (e.g. dust explosion), improved handling of logistics
- Fuel quality committed to improving the desired conversion characteristics (e.g. avoiding emissions, slagging, corrosion problems) from blending with additives, several other raw biomass materials or thermal treatment

Biomethane extend the possibilities for the application of biomass in all established applications of natural gas, such as efficient and flexible processes for power generation, transport fuel, chemical base materials for further synthesis, easy controllable plants and innovative application technologies such as fuel cells and better storage opportunities. With the existing natural gas grid, biomethane can be transported and stored in the existing infrastructure without additional investment costs. Furthermore, a wide range of feedstocks can be converted.

Advanced solid biofuels as well as biomethane, play an important role due to their properties in supporting a modern energy system in the fields of heat, power and fuel and are therefore worth looking at more closely. Nevertheless, there are many other biogenic fuels, such as liquid fuels for transport, which are also relevant and should therefore also be considered (see Chap. 7).

8.2 Advanced Solid Biofuels

Intermediate solid biofuels can be divided into the densified biofuels such as standard pellets or briquettes and the thermally treated biomass which can also be in the form of pellets or briquettes but produced by a different substrate and/or process. Thermally-treated products are not ready for the market at present, but they aim to come onto the market as a commodity fuel in the short to mid term and contribute to a more flexible energy provision. Different thermal-treatment processes can be used to produce advanced solid biofuels i.e. torrefaction, hydrothermal carbonisation, steam explosion or fast pyrolysis, whereby the first two options are presented later on, because these are the most developed ones.

8.2.1 Densified Solid Biofuels

Pressure agglomeration processes such as briquetting and pelletizing are used to improve the mechanical and physical properties of solid biofuels. The aim is to convert particles or fibers into products with reduced volume and designated forms and properties such as reduced moisture content. These special fuel properties are especially suitable for long distance transport, efficient storage requirements as well as advantages in process control of the conversion system through the automatic feeding of a fuel with homogenous fuel properties. These properties are essential for a flexible usage.

Raw Material

Generally, all kinds of solid biomass can be densified if a feedstock-specific process adaptation can be assumed. The densification of woody materials is particularly relevant, because the energy density of woody biomass is naturally high compared to other solid raw materials [16]. Predominantly low-grade wood fractions such as wood residues and the by-products of saw mills and the wood processing industry are used, due to their low moisture content (reduced drying demand) and relatively homogeneous material properties. However, as the biomass potential is limited, there is an increasing interest in alternative green wood fractions, such as forest residues, stem wood (from catastrophic events such as storms, windthrow or bark beetle infestations) or short rotation coppice [33]. Prospectively, the use of green wood in pellet production is expected to increase [4] as is the use of herbaceous materials such as straw and hay.

Process

The densification of solid biomass involves drying down to a moisture content of 15–20 %, milling and conditioning the material in the form of regulating the water content and improving product quality e.g. adding binders to improve durability, densification and cooling [16]. To achieve the required standardised physical-mechanical properties of the end product, an optimal parameter combination is required. The production of high-quality fuel pellets or briquettes is very similar, with the difference being in the product size (pellets have a diameter less than 25 mm, briquettes are larger [9]). Moreover, the briquetting process doesn't normally require cooling or sieving. Figure 8.2 illustrates the process.

More information about the properties of standard pellets can be found in Table 8.1, where they are compared with torrefied pellets, wood chips and coal.

Fig. 8.2 Process steps for densified solid biofuels

Table 8.1 Comparison of standard and torrefied pellets with wood chips/coal (Adapted [34])

	Wood chips	Wood pellets	Torrefied wood pellets	Coal
Moisture content (wt%)	30–55	7–10	1–5	10–15
Calorific value (LHV, MJ/kg) as received	7–12	15–17	18–24	23–28
Volatile matter (wt%, dry basis)	70–84	75–84	55–80	15–30
Fixed carbon (wt%, dry basis)	16–25	16–25	22–35	50–55
Bulk density (kg/l)	0.20–0.30	0.55–0.65	0.65–0.80	0.80–0.85
Vol. energy density (GJ/m^3)	1.4–3.6	8–11	12–19	18–24
Hygroscopic properties	Hydrophilic	Hydrophilic	(Moderately) hydrophobic	Hydrophobic
Biological degradation	Fast	Fast	Slow	None
Milling requirements	Special	Special	Standard–feedstock-specific	Standard
Product consistency	Limited	High	High	High

wt% = weight percentage

Energy Balance

Depending on the quality of the feedstock, about 3–10 % of the energy content of the biomass is necessary for the production of pellets. The specific energy consumption of a wood pellet press is between 1.3 % and 2.7 % based on the energy content of the pellets [33]. In the case of wood briquette production this percentage may be lower. However, the energy balance of the process – which directly influences the cost balance – depends mainly on the raw material used.

Cost Range

The largest cost factors in pellet production are the raw material (43–73 %) itself and the potential drying need (ca. 35 %) [25]. When compared with the densification of woody material, the production costs of alternative fuel pellets (e. g. hay or straw pellets) are expected to be slightly lower due to a reduced demand for drying.

Stage of Development

Pellet mills and briquette presses are state of the art and available on the market. The international product standard (EN 14961-2/3; ISO 17225-2/3) has supported the implementation of wood pellets and briquettes as a commodity fuel on the market for almost 20 years. In 2012, the European wood pellet market became the world's largest market with a production of 10.5 million tons. Between 60 % and 70 % of the world's market volume of 22.4–24.5 million tons were consumed in the EU in 2012. The four largest pellet-producing countries in the EU are Germany (2.2 million t), Sweden (1.2 million t), Latvia (1 million t) and Austria (0.9 million t). The largest wood pellet exporters to the EU are the USA with 1.8 million t and Canada with 1.3 million t. Russia, the Ukraine and Belarus follow and the mid -term expectations for a future growth in the market are promising with an estimated demand that is triple to tenfold [10].

8.2.2 Torrefied Fuels

Torrefaction is a thermochemical pretreatment for carbonaceous feedstock, including a multitude of different biomasses [32]. Torrefied biofuels that are densified show almost the same properties as densified biofuels without thermal treatment. When compared with standard pellets however, the pellets form torrefied biomass show better properties for grinding, chemical and biological degradation during storage and they are expected to show improved combustion or gasification behaviour.

However, it is important to consider the high reactivity of ground torrefied biomass during storage, which calls for inert conditions if spontaneous combustion is to be prevented [29].

Raw Material

Different kinds of dry feedstock can be used for the torrefaction of biomass. Currently, the research focus is on woody biomass but straw and other biomass residues are gaining more popularity. The physio-chemical composition of the product will largely affect how much of the raw materials will be transformed into a gaseous phase or remain as a solid [5]. So far torrefaction has mainly only been performed on woody biomass.

Process

The torrefaction process can best be described as a mild pyrolysis under inert or almost inert (small percentage of oxygen) conditions and near atmospheric pressure within the temperature range of 200–320 °C. By increasing the torrefaction temperature, the amount of volatiles released from the biomass increases while hemicellulose, lignin and cellulose are decomposed. The torrefied product is influenced by the biomass composition, the heating rate and the residence time. The degree of torrefaction is often described by a combined mass- and energy yield while the relative reduction in volatiles can also be used [26].

In Table 8.1 key parameters of torrefied and standard pellets are compared with wood chips and coal.

Energy Balance

Torrefaction requires certain energy input which can – in the best case – be provided by an auto-thermal operation of the process. Therefore, it is important to capture and utilise as much energy as possible that is contained in the torrefaction gas and to recycle it to the torrefaction process and drying of the biomass prior to torrefaction. The energy that is transferred into the torrefaction gas, typically around 10 % (Fig. 8.3) is strongly affected by the torrefaction temperature and residence time. These two are therefore the key parameters that will affect the energy efficiency of

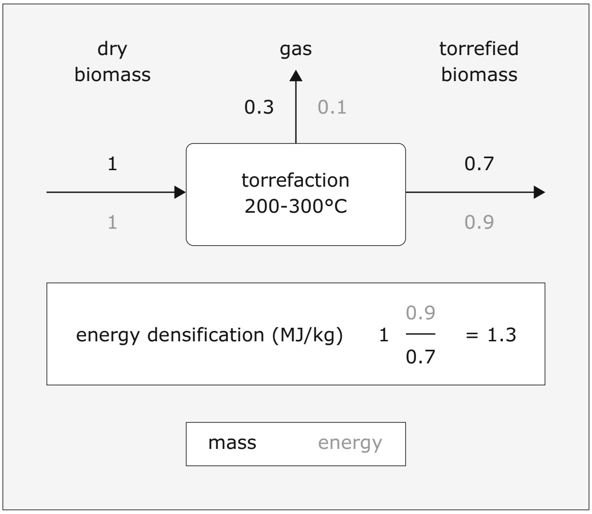


Fig. 8.3 Energy/mass balance of the biomass torrefaction process [17]

the overall process. Only when the energy content of the torrefaction gas is large enough to balance the heat demand of drying and torrefaction, can an auto-thermal operation be achieved [29].

Additionally, the densification of torrefied material is more energy-intensive than palletisation/briquetting of untreated biomass due to lower self-binding forces in the material (reduced hemicellulose and lignin). On the other hand, less energy is required to grind torrefied materials, particularly enhancing energy efficiency and enabling its utilisation in dust boilers.

Cost Range

Generally, it is expected that additional thermal treatment processes of the biomass automatically result in higher production costs than the densification of untreated material. At present the prices for torrefied (and densified) biofuels range between three to tenfold of the price of standard wood pellets, as described in Sect. 8.2.1. The cost variation highly depends on factors, such as raw material availability and quality, treatment technology, logistics and end-use requirements. Furthermore, the technology has not yet been made commercially available on the market, which also contributes to higher costs compared to standard pellets. Optimistic market observers assume that torrefaction will become commercially available within the next 1–2 years [8].

Stage of Development

Numerous activities exist pronouncing a worldwide installation of torrefaction plants with a total production capacity between 300,000–500,000 t, mainly installed in the U.S. or European market [34]. Worldwide, approximately 50 technology developers or initiatives are currently battling on the market to present the first commercially-run torrefaction plant. Different reactor designs for the production of torrefied biomass are still at the pilot or demonstration stage with preliminary demo-units in operation. The most important concepts seem to be the compact moving bed and the fluidised moving bed reactors [8]. However, at the current stage of development, there are only a handful of existing installations operating as demonstration or pilot plants and producing several kilograms to several thousand tons. Fuel standardisation was started back in 2012 [15].

8.2.3 Hydrothermal Carbonised Fuels

In the hydrothermal process, the hydrothermal carbonisation (HTC) is the process for the production of a solid fuel, so-called “biocoal” from a wet feedstock. The process is performed under high temperatures and pressures with a wide range of feedstock. The product can be used for energy provision as well as for material use (i.e. for soil improvement) [30].

Raw Material

In addition to biomasses with established applications in the combustion or the biogas processes, there is an important potential of wet and not very biodegradable biomass such as food industry wastes, municipal biowaste, digestates from biogas processes and sewage sludge. The utilisation of this potential is of major importance for extending the feedstock base of the bioenergy supply [32].

Process

The HTC is a hydrothermal process for the production of a solid fuel, the so called "biocoal". It is performed in pressurised hot water at 180–250 °C. The pressure is determined by the temperature because liquid water is necessary as a reaction agent that is why 10–40 bar are common. In some cases, an acidic catalyst is used. Currently, an operation time of 1.5–6 h is standard. Because the hydrothermal carbonisation process (HTC) takes place in liquid water, no preliminary drying is needed. Generally, the process consists of a pre-treatment where the biomass is mixed with water, the conversion is influenced by heat and pressure and a post-processing where the water content of the product is reduced, see Fig. 8.4.

In contrast to biological processes, hydrothermal processes are able to convert all organic fractions including lignin. The properties of biocoal mainly depend on the reaction conditions. With increasing residence time, the product changes its state to become more like coal. Elementary analysis values are listed in Table 8.2 Examples of fuel properties of biocoal from hydrothermal carbonisation process HTC compared with brown coal and biomass (dry matter) [7, 28].

During the conversion of biomass into biocoal the reaction mechanisms of hydrolysis, dehydration, decarboxylation, aromatization and condensation polymerisation are involved.

An efficient removal of the reaction agent water is of major importance for the economic production of an applicable product. Because of the altered structure, water can be removed much easier using mechanical processes compared to the water content of raw biomass. This is one of the major advantages of HTC, enabling an efficient fuel production.

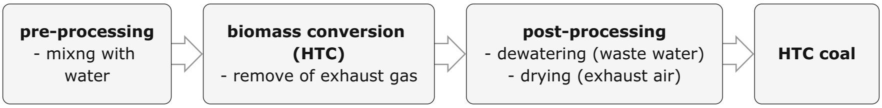
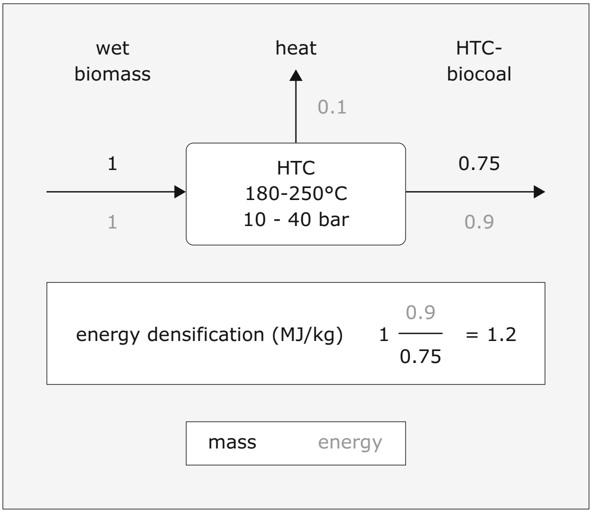


Fig. 8.4 Process steps of hydrothermal carbonisation process

Table 8.2 Examples of fuel properties of biocoal from hydrothermal carbonisation process HTC compared with brown coal and biomass (dry matter) [7, 28]

	HTC-biocoal			
	From green waste	From municipal bio-waste	From digestate (dry fermentation)	Brown coal briquette
Heating value (LHV)	16.7 MJ/kg	19.4 MJ/kg	18.1 MJ/kg	24.9 MJ/kg
Ash content	27 %	17 %	22 %	4.2 %
Sulphur content	0.13 %	0.2 %	0.3 %	0.3 %
Nitrogen content	1.1 %	1.8 %	1.6 %	0.74 %
Chlorine content	0.04 %	0.08 %	0.18 %	0.027 %

Fig. 8.5 Energy balance for HTC



Energy Balance

The types of feedstock used as well as the plant design strongly influence the energy balance. Figure 8.5 shows an example of an energy balance for the HTC process. It is normally found that the conversion reaction occurs after pre-heating the biomass and the reaction agent water without any need for or surplus of energy. Another important energy demand is the heat for product drying. Mechanical water separation is possible, if a higher dry matter content is needed, then thermal drying is necessary.

Stage of Development

Generally speaking, it can be said that the transformation from the laboratory scale to the technical scale is currently ongoing. Preliminary demonstration plants are in their initial operation phase, for example in Halle (Germany) a unit for the application of landscape management matter, bio-residues and fermentation residues has been installed [20]. Because of the state of development, substantive economic figures cannot currently be published. Compared to torrefied solid biofuels for HTC products, fuel standardisation has not yet been started.

8.3 Biomethane

With the overall goal of this book in mind, the main focus of this subchapter is the synthetic methane from the gasification of biomass (bio-SNG) as well as the biomethane from the biochemical conversion process with an upgrading of biogas to a methane-rich gas with the focus on flexibility.

Bio-based synthetic natural gas (bio-SNG) and biomethane from upgrading biogas are biogenic substitutes for natural gas with methane (CH_4) that is produced as much as 99.9 % pure. Bio-SNG is produced thermo-chemically, primarily from lignin-based substrates such as wood. Biomethane is produced biochemically by cleaning and upgrading raw biogas. The state-of-the-art, further perspectives and the advantages of a flexible usage are outlined in the following.

8.3.1 Bio-based Synthetic Natural Gas Bio-SNG

Raw Material

The SNG-process is a particularly promising alternative for dry and solid biomass with low degradability and high lignin content such as wood and straw. In contrast to the Power-to-Gas process, which utilises carbon dioxide and hydrogen, the SNG-process converts carbon monoxide and hydrogen generated in a biomass gasifier into methane.

Process

A typical SNG-plant incorporates the following process steps: biomass pretreatment, gasification, synthesis gas treatment, methane synthesis and methane separation (see Fig. 8.6). Because of the complex technology involved, SNG-plants are favoured for medium to large scale facilities with up to 500 MW bio-SNG

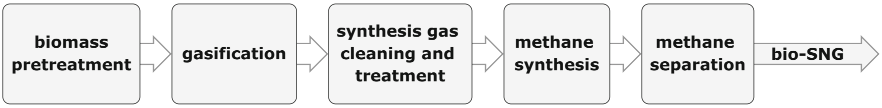


Fig. 8.6 Bio-SNG process chain

output. The two major process steps are gasification and synthesis, although the other steps are also crucial for success.

Gasification is defined as the conversion of a solid or liquid fuel, here biomass, to a gaseous fuel, mainly hydrogen and carbon monoxide, in a reaction with an added reaction agent. The gasification process consists of the typical process steps: drying, pyrolytic decomposition, oxidation, reduction and gas phase reactions. For these reactions, many different reactor concepts are available, including fixed bed, fluidised bed and flow reactor concepts [3, 21, 23, 24, 27].

The choice of gasifier has a major influence on the economic size of a facility, the required biomass pre-treatment, the synthesis gas treatment as well as the plant's flexibility.

- Fluidised bed gasifiers can convert fuel particles with an average size of several millimetres. Because of the chemical equilibrium, the total carbon content cannot be converted. If a single-stage fluidised-bed reactor is applied, then the unconverted carbon will remain in the ash. In a two-stage gasifier such as the Fast Internally Circulating Fluidised Bed Gasifier (FICFB) the remaining carbon is converted in the second chamber for heat supply whereas in the first reactor, gasification will take place. Preliminary demonstration plants are now in operation.
- In an entrained-flow gasifier the reactions take place while the particles are transported by the fluid phase. The chopping of biomass to the necessary particle size (less than 1 mm) is expensive and normally only possible with a thermal pre-treatment, such as torrefaction. Entrained flow gasifiers are mainly suitable for large-scale SNG-plants, where several hundred MW are the norm.

The following **methane synthesis** or **methanation** is the exothermic, catalytic conversion of the synthesis gas to methane (CH_4), carbon dioxide and water. Side reactions are the water-gas-shift-reaction and the Boudouard reaction. Due to the selectivity, activity and costs, commercial projects focus on Ni catalysts, whereas others are possible [22]. Common methanation reactors are adiabatic fixed bed and isothermal fluidised bed reactors. Currently, the bio-SNG production is exclusively demonstrated in combination with steam and/or oxygen-blown gasification because of the high nitrogen content in the synthesis gas when air is used as a reaction agent.

Because of the similarities between SNG and biogas (methane, carbon dioxide and water content) processes similar to biogas upgrading can be employed, see Sect. 8.3.2. Depending on usage and distribution, further steps such as compression for gas grid injection have to be applied.

Stage of Development

The production of regenerative methane from the thermo-chemical pathway is still under development with few demonstration plants so far. An implementation of this technology for SNG production is expected over the next couple of years [13].

8.3.2 *Biomethane from Upgrading of Biogas*

Raw Material

The basic raw material for biomethane from the biochemical pathway is the same as for biogas production with a combustion purpose. Usually it is sourced from energy crops, agricultural residues e.g. straw, manure and industrial or organic waste. Depending on the basic feedstock and the specific digestion properties, a raw biogas with various gas qualities is produced; see Chap. 2.

In summary, raw biogas is essentially a mixture of methane and carbon dioxide, while the proportion of methane is usually higher than that of carbon dioxide. Because of its chemical composition, raw biogas cannot replace natural gas without further treatment.

Process

To exploit its full potential, the raw biogas has to be upgraded. After upgrading the biogas to biomethane, it shows almost the same properties as natural gas and can therefore be fed into the existing natural gas grid infrastructure. There are various ways of upgrading biomethane from biogas. In essence, they all reduce the CO_2 content while enriching the CH_4 content of the raw biogas. Depending upon the upgrading technology and the raw gas quality, pre- and post-treatment are required. Figure 8.7 shows the schematic process of biogas upgrading.

Pre-treatment Depending on the composition of the raw biogas and the CH_4 enrichment technology, different pre-treatments have to be applied, mainly to reduce sulphur, water or other undesired components such as siloxane.

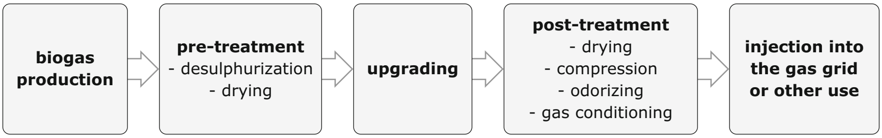


Fig. 8.7 Schematic diagram of the biogas upgrading process

CH_4-Enrichment (Biogas Upgrading) Currently there are five main technologies being used for biogas upgrading. Other technologies such as cryogenic separation, liquefaction and small-scale upgrading processes are still being developed. The upgrading capacity from the state-of-the-art technologies ranges between 250 and 2,800 m^3/h STP (Standard Temperature and Pressure) raw biogas input, see Table 8.3.

- Water scrubbing (WS): dissolve of CO_2 in water under pressure in an absorption column. A methane-rich gas leaves the top of the absorption column while the CO_2 is released in a second column by pressure release.
- Pressure swing adsorption (PSA): based on selective adsorption of CO_2 on adsorbents such as active carbon. The process operates under pressure. For the reuse of adsorbents, the CO_2 desorbs from the adsorbents by pressure release.
- Chemical absorption: dissolving of CO_2 in a solvent (amine) in an absorption column. A methane-rich gas leaves the top of the absorption column while the CO_2 is released in a second column through heating of the solvent.

Table 8.3 Overview[a] of raw biogas CH_4 enrichment technologies [1, 2, 12, 31], (costs for biogas production, upgrading and injection into the gas grid [according to the German version [13]])

Parameter	WS	PSA	Chemical absorption	Physical absorption	Membrane separation
Operating pressure in bar(a)	5–10	4–7	1–3	4–8	5–10
Regenerating temperature in °C	–	–	120–160	70–80	–
Plant size range[b, c] in m^3/h STP	350–2,800	400–2,800	500–2,000	250–2,800	400–700
Electric energy demand[b] in kWh/m^3 STP	0.17–0.23	<0.19	0.09	0.23–0.27	0.24
Thermic energy demand[b] in kWh/m^3 STP	0	0	0.6	Internal provision from lean gas	0
Max. extern usable heat[b] in kWh/m^3 STP	0.06–0.18	<0.1	0.3	0.12–0.13	0.36
Methane slip before lean gas treatment in %	<2	<2	<0.1	1–4	<5
Methane purity[a] in %	95–99	95–99	>99	95–99	95–99
Lean gas treatment necessary?	Yes	Yes	No	Yes	Yes
Specific biomethane costs in €ct/kWh Hs	6.2–8.3	6.4–8.5	7.1–8.1	6.5–8.7	8.3–8.8

[a] Values in operation can differ and can be customised
[b] Referring to raw biogas
[c] Currently available on the market

- Physical absorption: similar to water scrubbing. Instead of water, an organic solvent with a higher absorption capacity of CO_2 is used. The process operates under pressure, the solvent has to be heated for desorption.
- Membrane separation: the process operates under pressure with 1–3 membrane process steps. The separation is based on the different kinetic diameters of the molecules and the resulting permeation through the membrane. Carbon dioxide and other components (e.g. ammonia, oxygen and hydrogen) transport the membrane to the permeate side while methane mainly remains on the retentate side.

Post-treatment According to applicable law and technical instructions, biomethane must fulfil specific requirements for usage as a transport fuel, for gas grid injection or for other usages. This includes drying, compression, odorising, gas conditioning and lean gas treatments. The post treatment depends upon the upgrading technology, the usage (e.g. gas grid injection) and the local applicable law.

Cost Range

The cost range (Table 8.3) for upgrading biogas depends on various factors. These can be input parameters such as substrate and energy costs, technology factors such as energy consumption and methane slip as well as post-treatment factors such as gas conditioning requirements and the pressure stage. Such upgrading costs can range between 6.2 and 8.8 €ct/kWh Hs [12].

Stage of Development

The first biogas to biomethane upgrading plant was implemented in Germany in 2006. Since then a steady increase has been observed, see Sect. 2.5.2. Although there are now (end of 2013) more than 120 plants in operation [6], there is still need of improvement. The newest technology for upgrading is the membrane process. Manufacturers of those upgrading plants that already exist show an on-going commitment to improving the technologies on offer or have started to implement new ones such as membrane upgrading. To summarize, the upgrading from biogas to biomethane is an expanding market with increasing efficiency. In the long-run, it will be those technologies with the best energy- and cost-efficiency combined with the best operating and maintenance properties that will prevail. At this moment in time, the membrane technology looks promising. So far no uniform standards across the European Union or even worldwide for that matter have been implemented, but are still under development. With the implementation of standardized gaseous fuel properties, a further boost for market penetration is estimated [2, 6, 12].

8.4 Contributing to a Flexible Energy Supply

From the previous chapters of the book it can be concluded that a future energy market will be characterised by the need for a sustainable flexible energy carrier with homogeneous properties for application in the fields of combined heat and power generation, heat and fuel. The previous sections of this chapter introduced two kinds of intermediates: advanced solid biofuels and biogenic substitutes for natural gas. Each of them with their specific flexibility properties has the potential to contribute to a well-balanced energy market.

8.4.1 Flexibility Through Solid Fuels

Flexible bioenergy provision from solid biofuels demands (i) smaller conversion units in the heat sector, (ii) higher technical demands (ramp loads, gasification systems) in the electricity and transport sector, (iii) the capability to widen the resource base from wood to other, less homogenous solid biofuels like straw, residues from gardening etc. and (iv) improved time-dependent application due to ideal storage and easy transport factors (energy production on demand). Therefore, the development of intermediates is the counterpart of the development of new, flexible concepts.

Wood pellets, which have been on the market for nearly 20 years now, are a success story in this field. Due to their fuel properties they are suitable for automated stoves and boilers for small houses as well for medium and large scale boilers for e. g. municipal facilities or industrial applications. The availability of this technology has been one of the starting points for discussing the future options of a flexible energy supply in this chapter. The weakness of the conventional pellet technology is that so far only a limited assortment of woody biomass can be used as feedstock.

Torrefied pellets have the potential to provide the desired quality from wood pellets from a wider resource base. Additionally, with thermo-chemical pretreatment, the fuel properties change towards an even lower degree of biodegradability, become easier to grind and show a more stable reaction time for the particles in the conversion process. So far, torrefied pellets have mainly been developed for the option of using biomass in coal-fired power plants, but an examination of additional markets is already underway.[1] From today's perspective it is only possible to state the systemic advantages of those new properties. For example: future heating systems might be designed smaller because process control is easier. In the long term, new

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[1] e.g. in the European-FP7-project "SECTOR – Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction (2012–2015) or in the national project financed by the BMWI "FlexiTorr" (Flexibilisation of energy supply in small bioenergy generation plants due to the use of torrefied biomass), 2013–2013.

concepts are also imaginable that grind the fuel before combustion in other devices (i.e. dust boiler).

The development of HTC pellets is also in this direction, but with greater uncertainties because of the wider quality ranges of the material and the earlier step of technical development.

8.4.2 Flexibility Through Biomethane

The application of biomethane is another approach to a flexible bioenergy provision. This approach leads to a decoupling of the production and the use of the energy carrier, and thus allows various options for flexible bioenergy provision. This includes (i) short term, daily, weekly and seasonal flexible power provision (through long- to short-term storage and demand-based applications), (ii) providing a defined fuel for the transport sector and (iii) using the fuel in existing conversion units without technical adaptions. Hence, the main advantages of flexible energy provision from biomethane and bio-SNG can be compared with their similarity to natural gas.

Another flexibility option can be seen during production. Especially in combination with a power-to-gas-concept, see Chap. 2, where CO_2 from the upgrading process is needed to convert H_2 with solar or wind power to methane. Additionally, the product process itself can provide (with limits) more flexibility. Therefore, during the bio-SNG process, the type of gasifier and methanation unit combined with a change of load can influence the capacity. Fluidised bed and entrained flow gasifiers react quickly (in a matter of minutes) to a change in the load (0–100 %). Whereas fixed-bed gasifiers need a very long time to start and stop, a partial load can only be realised from 60 to 100 % [18, 19]. In any case it needs to be taken into account that a partial load has a much lower efficiency than a full load and in particular that plants in standby cool down rapidly without additional heating. For fluidised bed and entrained flow gasifiers it takes several minutes and in some cases hours to preheat the gasifier before the gasification reactions start. The main reason is the refractory material in the gasifier which has a high heat capacity and a limited temperature change velocity due to dilation and brittleness. The deployment time of methane synthesis is approximately 5 min, while the cold start time is in the range of hours [14]. The energy requirement for standby is about 1 % of max capacity. For implementation, more research on partial load operation of a synthesis plant is necessary.

During the biomethane process, a similar effect can be reached by a change of load. The production rate of the available default plant sizes (250 up to 2,800 m^3/h STP raw biogas upgrading capacity) can be modified. In most cases, the ability for down regulation is higher than for up regulation [2, 31]. Even the choice of substrates or operation mode of the digester can influence the productivity and thus the flexibility, see Chap. 6.

8.5 Conclusion

The **advanced solid biofuels** can contribute to a more flexible energy supply due to their favourable fuel parameters (e.g. low water content, easier to grind, high energy density or reduced volatile compounds) that not only enable an easier substitution of solid fossil fuels (with minor cost-incentive technical plant adaptations) but also a better process control of the biofuel in the conversion system and especially for thermally-treated fuels, much more flexible storage and transport options.

A successful instrument to improve the market implementation of thermally-treated solid biofuels can be seen by the success story of the worldwide production and trading system of wood pellets, which has clearly shown that there is a mutual interaction between the development of conversion technologies and fuels. The final potential of advanced solid biofuels can as such therefore not yet be described and is strongly dependent on the development of technologies.

Biomethane can contribute to a more flexible energy supply due to their similarity to natural gas as well as the flexible production and storage of the fuel. Therefore they can make a significant contribution to a flexible energy system, e.g. in the form of power-to-gas concepts or by meeting on demand energy provision in the heat, power or fuel sector. However, the demand for biogenic substitutions in these sectors is different.

The strengths and opportunities of these intermediates can be most greatly seen in logistics and usage, where there is easy and low price transportation through the already existing gas grid, new domestic and international markets and new applications such as shipping fuel [11].

Nevertheless, as is the case with all technologies, the production of intermediates not only shows strengths and opportunities but is also associated with weaknesses and threats. For example, the intermediate treatment processes are cost-intensive and often interconnected with additional demands for safety requirements in transportation and storage. The higher production costs have the potential of becoming economically feasible, by substantially reducing the cost and improving process efficiency. In addition, lower investment costs for transport, storage, conversion systems and maintenance services are to be expected as a result of the high-quality intermediate biofuels, if they can be implemented as a commodity biofuel on the market. Biogenic substitutes for natural gas are momentarily bound by transport to the gas grid, different quality standards between countries as well as high production efforts combined with high production costs. The technology is still developing however, which will ultimately lead to higher production efficiency. Furthermore, transport outside of the natural gas grid is possible under certain circumstances and will gain further importance in the future.

In the short-term, torrefied biomass will be available and biomethane is already commercially available through the biochemical process. However, the production of a biogenic substitute for natural gas from the thermochemical pathway, bio-SNG, is still under development and will be ready for the market in the long-term. It also appears that similar can be said for the implementation of the HTC process.

The resulting potential for a smart and future-based bioenergy system is versatile, promising and not yet even fully predictable. The historical development of the wood pellets market showed that especially supporting political and legal framework conditions can favour the way for a new biofuel implementation on national and international markets. Therefore, for the widespread market implementation and penetration of intermediate biofuels, they must be supported by an international fuel standardisation with a certification system along with the respective safety regulations.

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