Technologies for Flexible Bioenergy

IEA Bioenergy: Task 44

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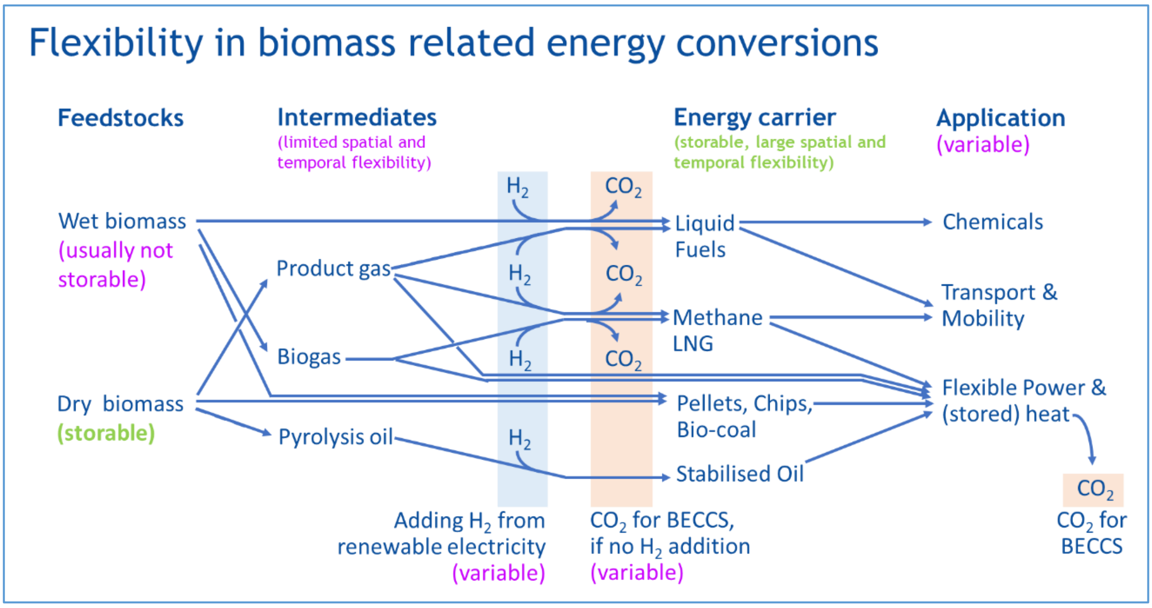

Technologies for Flexible Bioenergy

Tilman Schildhauer[1], Pieter Kroon[2], Ernst Höftberger[3], Emanuele Moioli[1], Gabriel Reichert[3], Florian Kupelwieser[3]

1 Paul Scherrer Institut, Switzerland, 2 TNO, The Netherlands, 3 BEST – Bioenergy and Sustainable Technologies GmbH Austria

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Executive summary

The increasing share of renewable energy sources such as photovoltaic systems and wind turbines, of which electricity production depends on weather conditions, leads to a need for more flexibility and controllability of other energy sources, energy carriers and energy storage devices. Flexibility can be defined from different perspectives, such as from system, process or component level perspective. Bioenergy and system integration cover multiple dimensions of flexibility, including temporal and spatial flexibility, as well as flexibility with respect to feedstock, operation, and end-products.

This report wants to highlight a number of technologies which make the inherent flexibility of sustainable bioenergy usable. A concise overview of the technical possibilities is presented, in the appendix more detailed information on individual flexible bioenergy technologies including references is given.

The flexibility of bioenergy has several dimensions:

- Short term flexibility to balance and stabilize the electricity grid by both positive and negative ancillary services
- Long term flexibility by biomass-based energy carriers that can be (seasonally) stored and transported within existing infrastructure

By far not all of the technically possible and successfully demonstrated process options are regularly applied. While burning biomass or biomass based intermediates and energy carriers for production of heat or combined heat and power is quite common, the flexibility of these units for **positive ancillary services** is only rarely exploited; mostly in countries where suited incentives such as a flexibility premium exist.

Negative ancillary service, i.e. the flexible up-take of electricity that cannot be used otherwise at time and site of its production by e.g. Power-to-Gas or Power-to-Liquid type processes, is technically solved and was successfully demonstrated only for biogas-upgrading by methanation of the CO_2 content. Flexible hydrogen addition to wood gasification gas or within hydrothermal gasification or liquefaction is still under development.

Long term flexibility, i.e. the conversion of biomass to energy carriers that can be easily transported or stored within existing infrastructure, is quite common for biogas upgrading by CO_2 separation. The conversion of wood to non-solid energy carriers such as methane, stabilized pyrolysis oil, Fischer-Tropsch Diesel or similar has been demonstrated, but most have not found a good business case yet.

As a common observation, the processes that work in most countries are starting from waste streams that have to be treated but cannot easily be valorized otherwise, e.g. sewage sludge to biogas to biomethane. The flexible use of woody feedstock is so far limited from two sides: on the one hand, simple combustion to cover heat needs is a financially more attractive alternative to more complex conversion processes, as long as there is sufficient heat demand. On the other hand, due to the value of energy wood and the more complex processes, energy carriers based on wood have a higher price difference to fossil energy carriers than those starting from biogas from waste inputs.

With the further increasing share of variable renewables like PV and wind in the energy system, the flexibility of bioenergy, i.e. positive and negative ancillary services for the electricity grid and options for storage and transport within existing infrastructure, will become more and more important, but depend on a suitable market design and for some period also support schemes to anticipate for upcoming higher flexibility needs in the energy system and to allow the stakeholders to decide for the better investments.

1 Introduction

The increasing share of renewable energy sources such as photovoltaic systems and wind turbines, of which electricity production depends on weather conditions, leads to a need for more flexibility and controllability of other energy sources, energy carriers and energy storage devices. Demand site management (e.g. ask electricity intensive industry or households to lower demand in case of shortages, and use more electricity when there is a surplus) and grid reinforcement can help to reduce but certainly not solve the problems. Besides electricity storage in batteries, redox flow batteries, pumped hydro storage power plants, and hydrogen based technologies also sustainable biomass and waste streams containing biomass can contribute to the stability and resilience of the energy system if applied in a flexible manner.

Flexibility can be defined from different perspectives, such as from system, process or component level perspective. Bioenergy and system integration cover multiple dimensions of flexibility, including temporal and spatial flexibility, as well as flexibility with respect to feedstock, operation, and end-products. IEA Bioenergy Task 44, a working group within the IEA Bioenergy Technology Collaboration Programme focusing on 'Flexible Bioenergy and System Integration', has defined flexible bioenergy as follows: "Flexible bioenergy is defined as a bioenergy system that can provide multiple services and benefits to the energy system under varying operating conditions and/or loads. […]", see https://task44.ieabioenergy.com/flexible-bioenergy/.

This report wants to highlight a number of technologies which make the inherent flexibility of sustainable bioenergy usable. While in the following chapter, a concise overview of the technical possibilities is presented, in the appendix more detailed information on individual flexible bioenergy technologies including references is given.

The flexibility of bioenergy has several dimensions:

1) ***Short term flexibility*** to balance and stabilize the electricity grid by both ***positive*** and ***negative ancillary services***
2) ***Long term flexibility*** by biomass-based ***energy carriers*** that can be (seasonally) ***stored and transported within existing infrastructure***

Positive ancillary service means that a biomass-based power plant can flexibly increase its electricity production to compensate for drops in renewable electricity by photovoltaic systems, hydropower plants or wind turbines or to complement them, if they do not cover the demand e.g. because of lack of wind or solar radiation (night time, winter at northern latitudes). Biomass flexibility can also be used to supply peak electricity when demand is high. Further, biomass can also be used to flexibly cover peaks in heat demand.

Using biomass for ***negative ancillary service*** (i.e. for the uptake of electricity if more is produced than can be consumed at the given location or transported away) is less obvious. Only few biomass conversion technologies allow the direct incorporation of electricity within electrochemical reactions, and these are still under development. Instead, the otherwise not usable electricity can be used to operate water electrolysis, which produces hydrogen. The hydrogen can be used immediately, e.g. for mobility and for replacing grey hydrogen in industrial processes, or can be stored to some extent in tanks or with a fraction of few percent in the natural gas grid. If larger amounts of hydrogen have to be stored, it is favorable to convert it to energy carriers for which a storage and distribution infrastructure exists. As many of these energy carriers such as methane (Synthetic Natural Gas), methanol, diesel fuel or gasoline are hydrocarbons, their production from the hydrogen needs a carbon source. Here biomass can play a role by delivering this carbon either as bio-based product gas from gasification or similar processes, or as biogenic CO_2. Biogenic CO_2 is an inherent by-product of all fermentations, anaerobic digestions or ethanol production, but also present in product gas from gasification or pyrolysis, or can be recovered from flue gases from biomass combustion in CHPs or paper pulp plants (CCU, Carbon Capture and Utilisation).

Long term flexibility of bioenergy refers to the option to store and transport biomass and to have several options how to use it energetically, which could be steered according to market demand (e.g. more focus on heat and power production in colder seasons). While the storability and transportability is proven for wood and some other types of relatively dry and highly dense materials (e.g. pellets from straw or grass, grain etc.), most biomass contains significant amounts of moisture and has the tendency to decay or to be converted to CO_2 or methane by microorganisms if left untreated, thereby losing the potential energy content if no further measures are taken. Examples for such non-stable biomass categories are municipal waste, sewage sludge, manure, food (processing) residues, green wastes, etc. In consequence, such feedstocks have to be converted to energy carriers which can be stored and transported within existing infrastructure. Energy carriers can be liquid, gaseous or solid; the most important feature is the often standardized quality, which simplifies transport, handling, storage and trading, and increases the options to use them for the different energy services.

As an overview, Table 1 shows which feedstocks, intermediates, energy carriers and energy services are in the focus of this report. Oil, starch or sugars crops (feedstocks for first generation biofuels) are not included in this report.

Table 1: Feedstocks, intermediates, energy carriers and energy services that are in the focus of this report.

Feedstocks	**Intermediates**	**Energy Carriers**	**Application/Sector**
	(limited spatial and temporal flexibility)	*(storable, large spatial and temporal flexibility)*	*(variable demand profiles)*
Wet biomass *(usually not storable)* Dry biomass *(storable)*	Biogas Product gas Pyrolysis oil Biogenic CO2, H2 from renewable electricity	Liquid fuels (Methanol, Diesel, Kerosene) Bio-Methane, Bio-LNG Stabilized oil Pellets, Chips	Chemicals Transport & Mobility Combined heat and power (CHP) Heat Negative emissions (BECCS), Power-to-C_xH_y

2 Stage of development

This chapter discusses how far the flexible bioenergy technologies are developed. To obtain the information presented here, Task 44 members designed a questionnaire that forms the base for the technology descriptions in the Appendix. The questionnaires were filled in by Task 44 before sending them out to the technical IEA Bioenergy Tasks 32 (Combustion), 33 (Gasification), 37 (Biogas) and 39 (Biofuels). The feedback of the technical Tasks was then used to improve the information in the Appendix.

When considering the detailed information for each technology in the appendix, ***three groups of flexible bioenergy*** technologies can be distinguished:

a) Technologies already implemented and applied, i.e. they work technically and at least in some countries can be operated under economically favorable conditions,
b) Technologies which have been demonstrated technically at sufficiently large scale, but are missing a business case so far, such that are not yet broadly applied,
c) Technologies under development, which have not yet reached demonstration.

In this report, we understand demonstration as sufficiently long operation of a plant at Technical readiness level TRL 7 or higher, i.e. pilot scale plant operated within a complete process chain using real feedstock as input.

In the following sections, these three development phases are discussed for technologies starting from both wet and dry feedstock.

2.1 TECHNOLOGIES ALREADY APPLIED

2.1.1 Wet feedstock for flexible electricity production (positive/negative ancillary services)

Wet biomass such as sewage sludge, manure, food (processing) residues, green wastes and energy crops (e.g. maize) cannot immediately be used for energy purposes, because their water content is very high. For most of these feedstocks, the energy content would not suffice to supply the heat to evaporate the water content in a combustion. Therefore, natural decay mechanisms are exploited which under oxygen-deficient conditions, referred to as anaerobic digestion, convert most of the carbon in the biomass to biogas, a mixture of mainly methane and carbon dioxide. While the methane formation is thermodynamically favoured at low temperatures (and high pressures), the carbon dioxide formation relates to the oxygen and the hydrogen content in the feedstock. The higher the oxygen content and the lower the hydrogen content in the feedstock, the higher the carbon dioxide content in the biogas. Green wastes that are rich in cellulose lead to high carbon dioxide fractions of up to 50%, while the biogas from sewage sludge can reach methane content of 63% and biogas from old fats and slaughterhouse wastes even up to 70%.

Besides methane, carbon dioxide and some impurities in the biogas (traces of oxygen, nitrogen, sulfur species; depending on the feedstock also terpenes, siloxanes and some aromatic compounds), anaerobic digestion also produces a waste water stream polluted by organic compounds and a solid “digestate” rich in carbon and inorganic compounds. While several processes under development such as hydrothermal liquefaction or hydrothermal gasification are able to fully convert also the energy in these two streams, today the waste water has to be cleaned in a waste water treatment plant, while the digestate containing most of the nutrients is used as fertilizer and soil conditioner.

As biogas is combustible, it can be used, after primary removal of humidity and sulfur species, for any combustion process for heating or in an internal combustion engine to produce heat and power. In the latter, electrical efficiencies of around 30% are reached; the necessary gas cleaning for more advanced devices such as high temperature fuel cells (SOFC) with higher electrical efficiencies is still under development.

Figure 1: EnviTec biogas plant (Source: EnviTec Biogas AG)

In thousands of plants, biogas is converted in gas engines to electricity and heat based on the instantaneous biogas production. Here, flexibility can be reached by adding an inflatable storage device that allows postponing the biogas use by several hours. This opens the pathway to stabilize the electricity grid by positive and negative ancillary services as the gas engines can be operated between 0% and 100% with a start-up time of < 5 minutes. This option is incentivized, e.g. in Germany, by a “flexibility premium”.

In some countries, biogas production for combined heat and power (CHP) production plays a considerable role. With the power in general being fed into the electricity grid, different types of application of the heat prevail. While a small share of the produced heat is consumed on site to heat the fermenter, the majority is either also used on site to heat buildings and stables or, in the case of larger heat volumes, is injected into a heating network to supply connected residential buildings with space heating. Additional limitations such as the seasonal variations in heat-demand but also opportunities such as the heat capacity of the infrastructure and buildings providing flexibility have to be considered for this established technology.

Another option, though not yet really applied, is the flexible use of biomethane in the natural gas grid (for the production of biomethane cf. to next section). In this concept, referred to as “biomass swarm”, a number of CHPs that are connected to the natural gas grid can be operated according to the needs of the electricity grid. At the same time, heat storage tanks take up the heat from the CHP and release it later as needed, e.g. for hot water and heating in a building. While the natural gas grid serves as the storage that decouples production of the biomethane from its conversion, it has to be ensured by buying biomethane certificates that the same amount of biomethane is fed to the gas grid.

Instead of anaerobic digestion wet streams might be converted, at higher temperature and pressure, to waste water and low moisture biomass. This is discussed in section 2.3.2 Hydrothermal processes.

2.1.2 Renewable natural gas/biomethane from wet feedstock (long-term flexibility)

The production of electricity from biogas leads to relatively high costs per kWh due to the costs of the biomass treatment, the moderate electrical efficiency of gas engines (<30-40%) and the lack of heat demand at the biogas production location, if no district heating grid or other (industrial) heat consumer is close-by. While many countries still have support schemes for electricity from biomass, renewable electricity from photovoltaic systems and wind turbines has become significantly cheaper. That prompts many biogas producers to choose a different market for their product, i.e. biomethane as a renewable alternative to fossil natural gas. While biogas can only be used on the spot as discussed in the previous section, the upgrading to biomethane allows to store and transport the bioenergy in the natural gas infrastructure and to use it in existing, well-developed and efficient applications.

On the one hand, biomethane can be stored for several weeks in the grid or even months if a cavern is available. This allows shifting the consumption and potential re-electrification in flexible CHPs (as mentioned above) or in combined cycle power plants (comprising a gas turbine and a steam turbine) to the winter when electricity is less available from PV systems. On the other hand, biomethane can be used in transport and mobility; be it as renewable compressed natural gas (CNG) which is state-of-the art in several countries, e.g. Switzerland and Sweden, be it as liquefied biomethane (LBG) for the use in long-distance or heavy-duty trucks which is a rising and fast way for decarbonisation of heavy transport.

Meanwhile, hundreds of biogas upgrading installations exist and can be operated at economically favourable conditions mainly due to the willingness of clients to pay a higher price for renewable natural gas. While direct financial support schemes are often absent, and the price for a CO_2 emission certificate is not yet sufficiently high to support a larger number of biomass based plants, the gas industry in several countries committed itself to replace natural gas by renewable alternatives such as biomethane.

Figure 2: Gas upgrading plant, Winterthur, Switzerland (Source: Hitachi Zosen Inova AG)

As natural gas consists mainly of methane, upgrading of biogas to biomethane means primarily separation of the CO_2 content, accompanied with desulfurization, drying and addition of odorant. Most countries have clear specification for the unrestricted injection of biomethane into the gas grid, fixing the methane content at a minimum value of 95-96%. Several technologies are available and are operated in commercial plants which differ with respect to the separation principle and therefore in the type of energy input for the gas separation. While pressurized water scrubbers, pressure swing adsorption and membrane separation units need electricity for gas pressurization, chemical scrubbers (e.g. amine based) need some electricity for pumping of the amine solution and a significant amount of heat for the regeneration of the amine solution. With the increasing need to avoid methane emissions from the upgrading plant and due to the relative absence of suitable renewable heat sources for regeneration of amine solution, there is a recent tendency towards membrane based gas upgrading processes.

The biogas upgrading would be able to go easily and fast into part load if necessary; this feature is however only rarely needed with the present operation schemes. This might change when the CO_2 in the biogas is more and more used as input for Power-to-Gas processes either directly or downstream of the separation (see also section 2.3.1), because of the not always constant supply of renewable hydrogen. Besides conversion to hydrocarbons, this biogenic CO_2 could also be used for sequestration, thus allowing for negative CO_2 emissions, if a suitable CO_2 infrastructure is available (e.g. pipelines for gaseous CO_2, or transport containers for liquefied CO_2). While Power-to-Gas has been demonstrated successfully, and use of biogenic CO_2 e.g. in food industry is applied at several places, storage of biogenic CO_2 for negative emissions is still under development.

2.1.3 Dry feedstock for flexible heat and electricity production (positive/negative ancillary services)

Combustion of dry biomass such as wood (chips or pellets) or torrefied biomass and subsequent electricity production by means of steam turbines or organic Rankine cycles (ORC) is state-of-the art up to the scale of several 10s to 100s MW. Similarly to biogas fired CHPs, the economic feasibility depends on support schemes for renewable electricity from biomass and/or on the level of carbon pricing like CO_2 tax on fossil fuels or the price level of e.g. the European trading System ETS. Moreover, for wood, also the scale of the plant as well as the price and quality of the feedstock (e.g. ash content, size distribution, humidity) have an important role on the efficiency and the costs. As the feedstock can be stored, these plants can be used for ancillary services. The start-up time of the combustion ranges from few hours to one day, but the turbines and the ORC can be ramped up and down within minutes. The combustion can be modulated between 1/3 or half to full capacity (which also offers important flexibility in case of pure heating systems), while the turbines allow 0-100% flexibility.

Figure 3: Stora Enso Langerbrugge utilizes renewable energy in paper production. Technology: Valmet CFB Boiler (circulating fluidized bed boiler) (Source: Valmet Oyj)

Besides the combustion of wood and use of the heat in steam turbines and ORCs, also the gasification of wood and subsequent combustion of the product gas in gas engines and even gas turbines is possible. The most important aspects of gasification are discussed in section 2.2.1. Small scale gasification/gas engine systems are already today commercially successful, based on favorable support schemes in some countries. They usually run on wood pellets, which is a relatively easy to handle and dry fuel with very low ash content. Similarly to the steam turbines and the gas engines running on biogas or biomethane, their power output can be changed relatively quickly which enables ancillary services. As the gasification process itself is less flexible, product gas not used in the engine is burned instead which increases the heat production.

Similar to the case of combined heat and power plants (CHP) based on biogas, a suited incentive is necessary to realise the inherent flexibility of wood based CHPs within the energy system. Without e.g. a flexibility premium or another appropriate price system, economic considerations favour continuous operation of the CHP at full load with the heat share only being economically and environmentally valorized during the heating season, unless there is a continuous heat demand (e.g. industrial heat).

Apart from the pathways discussed so far, there are also more conventional options to use existing CHPs and heat plants in a more efficient way and to use other types of biomass fuels, such as municipal waste and bio-oils. Investments in peak load heat boilers for district heating systems can enable the use of CHPs for maximum power production even if heat demand is high, and heat delivery would otherwise be prioritized. At certain times it might even be advisable to run CHPs in condensing mode, when electricity is in high demand and there is too little variable power produced resulting to very high power prices.

2.2 EMERGING TECHNOLOGIES WHICH HAVE BEEN TECHNICALLY DEMONSTRATED AT LARGER SCALE

In this section, technologies are presented, which have been demonstrated as complete process chain with real feedstock with all process steps at least in pilot scale, i.e. at technical readiness level TRL 7 or higher. Some of them have been operated for years under commercial conditions, but the boundary conditions, usually market conditions, did not yet allow a multiplication of these processes at other sites. Therefore, the technologies presented in the following are a set of reliable means to cope with the challenges of the future energy systems asking for more flexibility. With suitable incentive systems, these technologies could be rolled out within a few years.

2.2.1 Large scale gasification for flexible heat and electricity production (positive ancillary services)

As discussed in section 2.1.3, standardized small scale gasification based CHPs running on high quality feedstock (dried wood pellets with very low ash and sulfur content) have meanwhile a significant market share. For less expensive feedstock, e.g. wood chips from forest residues, a number of gasification processes have been operating successfully since years at scales up to few 10 MW thermal input. For wood, in many regions, especially in continental Europe, without access to harbors or inland ports, a few 10 MW is the upper limit of wood supply as above the increasing costs for the wood logistics exceed the savings due to economy of scale. At this scale and due to the less standardized feedstock, significantly more engineering effort is needed to adapt the process to the boundary conditions at the respective sites.

Further, more process steps are needed to handle all in- and outgoing material and energy flows which increases complexity and capital costs. For the gasification process, the feedstock has to be prepared accordingly by producing chips with narrow size distribution avoiding high ratio of slenderness to enable the handling with less danger of blockages etc. As residues from forestry are relatively humid, the chips then have to be dried first at least at the air. Too high humidity sincerely limits the efficiency of the process as chemical energy is consumed to evaporate the water. Active drying of the chips to lower water content is technically possible, but needs some extra units and is therefore subject of the process optimization for a given site.

The wood chips are fed to the gasifier, in which they are brought in contact with a gasifying agent at > 800°C. As the gasification is an endothermic process, heat has to be introduced which is either realized by addition of a sub-stoichiometric amount of air or oxygen and thus internal partial combustion of the feedstock, or by heat transport from an external combustion chamber, usually by means of circulating hot bed material. While in the first case, the flue gas of the internal combustion acts as gasifying agent, in the latter case steam is added. There are manifold ways to bring the solid feedstock, the gasifying agent and the heat into contact; therefore, the exact composition of the product gas differs significantly between the various gasifier types. Still, the main components are carbon monoxide, carbon dioxide, hydrogen, steam and hydrocarbons (e.g., methane, ethylene, aromatic compounds) accompanied by tars, dust and sulfur species. In case of air as gasifying agent, the nitrogen fraction can reach 50%.

After water condensation and removal of tars and dust, this burnable gas can be converted in gas engines to produce heat and power. In the > 1 MW scale, overall electrical efficiencies of 25%-30% are reached. Typical examples for these technologies are the Skive plant and the Viking gasifier in Volund, both in Denmark, the FICFB gasifiers in Güssing and Oberwart, both in Austria, the Dutch Milena gasifier concept (realized in India), the Pyroforce gasifier in Stans in Switzerland.

Figure 4: Güssing Dual Fluidized Bed Steam Gasifier, Austria (Source: Bioenergy and Sustainable Energies GmbH)

The start-up time of a gasifier is in the range of hours to one day, therefore operation should be continuous with moderate load change. The gas engine itself can however be ramped up and down between 0 % and 100% within 5 min which offers the same options for ancillary service as the other biomass based CHPs. Additional flexibility could be gained within poly-generation schemes where the gasifier is operated continuously, and the product gas is fed with varying shares to a gas engine (CHP) and a synthesis step to produce e.g. methane (see section 2.2.3).

2.2.2 Pyrolysis oil and its stabilization (positive ancillary services; long-term flexibility)

Pyrolysis is a process similar to gasification where the raw material (wood, straw) is heated in the absence of a gasifying agent with the aim to maximize the yield of liquid products. Therefore, the temperature range is at 450-600°C, i.e. lower than in gasifiers. The necessary heat is usually provided by the combustion of the burnable gases and/or of the carbon-rich solids left over after the pyrolysis. Around two thirds of the weight of the raw materials ends up as pyrolysis oil that consists of hydrocarbons and more reactive oxygenates. This oil is energy-rich and can be stored for some time, transported and can be used in combustions, turbines or gasification as other liquid fuels. The relatively high energy density allows for decentral small pyrolysis units close to the feedstock combined with central large-scale processes for further conversion. Due to the high oxygen contents in the many functional groups in the hydrocarbons, the oil continues chemical reactions and changes its properties like viscosity etc. Therefore, it cannot be stored for longer time or be used immediately as fuel in internal combustion engines, but needs some stabilization and deoxygenation which can be reached by catalytic hydro-treating, which allows saturation of reactive double bonds and removal of oxygen from the molecules. While the first commercial pyrolysis plants are operating (TRL 8, e.g. in Hengelo/NL), the oil stabilization is still under development. Due to the similarity with hydro-treating in oil refineries, the up-scaling of the oil stabilization step is expected to follow soon.

2.2.3 Methane, liquid energy carriers and chemicals from gasification of dry biomass (long-term flexibility)

As already discussed in section 2.2.1, gasification of wood or torrefied biomass delivers a product gas whose main components are hydrogen and carbon monoxide, i.e. species that are also the main constituents of synthesis gas in petrochemical industry. This opens the pathway to produce methane and other valuable energy carriers and chemicals such as Fischer-Tropsch Diesel, kerosene, gasoline, methanol, di-methyl-ether and similar molecules. While the suitable catalysts and operation conditions (pressure, temperature) differ for these synthesis reactions, all of them necessitate an appropriate upstream gas cleaning. Here, steam content has to be condensed, and dust, chlorine, sulfur species, and tars have to be removed, partly to sub-ppm range. Biomass based processes are 1-2 orders of magnitudes smaller than fossil coal, gas or oil based processes due to the decentral feedstock, therefore the process concepts from coal industry and petro-chemistry hardly can be used for financial reasons. As a result, several combinations of gasifier types, gas cleaning concepts and reactor types are developed and tested up to demonstration scale.

Figure 5: GoBiGas Plant, Goteborg (Source: www.goteborgenergi.se)

The most developed process is the production of renewable methane (also referred to as Bio-SNG, Synthetic Natural Gas), where two process concepts were developed up to demo-scale. Within the EU project *BioSNG*, a pilot and demonstration plant with a fluidized bed methanation reactor at 1 MW scale (TRL 7) was built and operated in Güssing/Austria; more prominent, a fully automated 20 MW plant in Gothenburg/Sweden (*GoBiGas* project) at TRL 8 was erected and operated with a series of fixed bed methanation reactors. Both process concepts reach an efficiency from wood to SNG higher than 61%. While technically a great success, both plants are not operated anymore due to financial boundary conditions, i.e. high wood prices compared to the value given to the renewable methane.

Processes to larger molecules than methane usually need significantly higher pressures than methanation (5-16 bar) and even better process control due to inherent selectivity challenge. As a result, costs are higher and efficiencies are usually lower. Still, with the *BioTFuel* plant in northern France, meanwhile the first process to produce Fischer-Tropsch-Diesel at TRL 8-9 is built.

2.2.4 Power-to-Gas with biogas (negative ancillary services)

The inherent CO_2 content in biogas from anaerobic digestion offers the possibility to convert it with hydrogen to additional methane. This can be useful, if in a region more electricity is produced from PV, wind turbines and hydropower than can be consumed or transported away with the existing infrastructure. In such situation, instead of turning down the renewable power plants, within negative ancillary service (referred to as Power-to-Gas) the otherwise not usable electricity can be used in a water electrolysis producing hydrogen (and oxygen). In principle, the hydrogen can be used right away, e.g. for mobility or for injection into the gas grid (today's upper limit 0.5-4%, depending on the country). If the hydrogen consumption is too low and the storage infrastructure not sufficient, converting the hydrogen to methane opens the natural gas grid as very large storage option and the manifold well-developed applications of (then renewable) natural gas.

Figure 6: Audi e-gas production in Werlte (Source: Audi media centre)

Similar to the processes described in section 2.2.3, there are several process options under development, of which few are realized in demonstration scale. Both micro-organisms (at around 35-65°C) and chemical catalysts (usually nickel catalyst at 300-550°C) can catalyze the methanation reaction. To bring catalysts and gaseous reactants into contact, different reactor types are developed, of which the stirred bubble column (for biological), as well as fixed bed and fluidized bed catalytic methanation have reached the demonstration scale (1 MW or larger, e.g. in Werlte/Germany or Dietikon/Switzerland). In principle, the cleaned biogas can be converted directly with hydrogen; some of the processes use CO_2 that was separated from biogas before with one of the technologies described in section 2.1.1. Recent research aims at decreasing costs, increasing of the efficiency by better heat integration with high temperature steam electrolysis and flexibilization of the plants. This helps to improve the so far difficult economic boundary conditions and to handle the situation that sufficiently cheap renewable hydrogen is not available all year.

2.3 TECHNOLOGIES UNDER DEVELOPMENT

In this chapter, a number of biomass based energy technologies is described that have not reached demonstration scale, but have the potential to reach that scale in a few years and could offer important additional flexibility.

2.3.1 Power-to-X with product gas and/or (flexible) BECCS

As described in section 2.2.1, the product gas of gasification processes contains besides hydrogen and carbon monoxide also CO_2. Moreover, when used for syntheses such as methanation, methanol synthesis or Fischer Tropsch, most of the oxygen in the product gas has to leave the system as CO_2, as the synthesis products contain no or only little oxygen, and the hydrogen amount is too low in most combinations of gasification and hydrocarbon synthesis to allow conversion of oxygen to water. As a result, processes that convert product gas from biomass gasification to hydrocarbons emit, similar to biogas plants, significant amounts of biogenic CO_2. As the plants have taken up the CO_2 beforehand to grow, this emission is climate-neutral. Also all processes with biomass combustion emit biogenic CO_2 in the flue gas, however then diluted with nitrogen and remaining oxygen.

There are, besides of using CO_2 in beverage industry or in greenhouses, two options for better use of biogenic CO_2. With appropriate infrastructure, the CO_2 can be collected and transported to a suitable sequestration site, e.g. depleted gas fields in Norway. This BECCS (Bioenergy with Carbon Capture and Storage) concept would present negative CO_2 emissions, which could help to balance other greenhouse gas emissions that cannot be replaced. Many scenarios to limit the climate change consider negative emissions as necessary.

Figure 7: Sunfire GmbH – Company site view – Power to Liquid (Source: Sunfire GmbH)

For combustion processes, specific CO_2 capture plants with connected costs and energy consumption are needed. However, in the production of biomethane from biogas (cf. to section 2.1.1) and in the production of hydrocarbons from gasification product gas (see section 2.2.3), as well as from ethanol production, already inherently CO_2 is separated, i.e. a relatively pure biogenic CO_2 stream is available with no or little additional cost and energy effort.

On the other hand, when renewable hydrogen is available, the inherent flow of biogenic CO_2 from both anaerobic digestion and biomass gasification could be used for energy storage by synthesis of chemical and energy carriers as discussed in sections 2.2.4 and 2.2.3. This increases significantly the potential for Power-to-Gas processes without the need to capture CO_2 from flue gases or even the atmosphere (which both are under development as well, but connected to important costs and energy consumption). Such a process needs additional investments in electrolyzer capacity (local hydrogen storage) and capacity for synthesis. This leads to a balance between operating hours, mean sustainable electricity price and production costs.

In principle, it is even possible to flexibly combine these two options to use the biogenic CO_2 by applying Power-to-Gas when renewable hydrogen is available (e.g. in summer), while collecting the CO_2 for negative emissions when renewable electricity is scarce and expensive (e.g. in winter) and therefore renewable hydrogen is not available at reasonable costs.

To increase the amount of captured biogenic CO_2 from gasification processes, two further approaches are discussed, but still in technical development. One is the production of pure hydrogen from gasification gas, which asks for converting the hydrocarbon content (methane, ethylene, benzene) by reforming to carbon monoxide (CO) and hydrogen, and the subsequent water gas shift of CO to CO_2 and additional hydrogen. This is however a relatively complex process with many steps.

Further, in direct gasifiers, the combustion takes place in the same vessel as the gasification reaction, i.e. the flue gas is contained in the product gas from the gasification (while in indirect gasifiers these two processes occur in two different vessels and the flue gas is released separately). This means the CO_2 originating from the combustion to produce the heat for the endothermic gasification (usually about one third of the biogenic carbon) can be captured as well. To avoid the downstream separation of nitrogen and CO_2, direct gasifiers with the aim of CO_2 capture should be operated with pure oxygen and steam as gasifying agent, which increases again the cost and energy effort.

2.3.2 Hydrothermal processes to produce storable energy carriers from wet biomass

As discussed in section 2.1.1, many feedstocks (e.g. sewage sludge, manure, algae, agricultural and food processing residues) contain significant amount of water, such that combustion does not make sense, as the energy content is too low to cover the needed enthalpy of evaporation. Therefore, these feedstocks have to be dried before use (which increases the cost and energy effort), or they are converted by biological processes in aqueous phase. Under these conditions, usually full conversion is not possible and a digestate remains containing still carbon and the nutrients. In the last two decades, several processes have been developed that aim at high conversions without the need to evaporate the water. The solution is the choice of hydrothermal conditions, i.e. relatively high pressures and temperatures which allow for nearly complete conversion. Usually the water then reaches nearly or fully super-critical conditions, a thermodynamic phase that allows to avoid the evaporation. Different operation conditions lead to a variety of products ranging from solid via liquid to gases (carbon monoxide and hydrogen, if no catalyst is applied; methane and CO_2 with suited catalyst).

2.3.3 New option for waste water handling

Organic matter in wastewater is an interesting bioenergy source because it has a large availability, an interesting biomass content and needs to be handled and cleaned anyway. At a low TRL level, research is ongoing in electricity production and use in (industrial) waste water treatment. By using microbial fuel cells it is possible to produce directly electricity (or hydrogen) from waste water. Another option is to increase the speed of waste water cleaning and to increase the amount of biogas from anaerobic digestion by adding electricity. When those technologies develop, more knowhow will be available on the possibilities to increase electricity production or demand depending on the actual electricity situation.

Sewage sludge can be converted into an energy carrier with a lower water content by thermal processes like torwash (see section 2.3.2). Instead of anaerobic digestion of this sludge to methane, research is done on stopping the process earlier and producing the fatty acids chemicals.

3 Conclusions and outlook

There are many ways and suited technologies for sustainable biomass to support the energy system by its inherent flexibility, given that biomass offers more options for controlled use, conversion to energy carriers and storage than other renewable sources of electricity (PV, wind, hydropower). Figure 8 below shows how many different pathways exist from feedstock to applications including the options for changing place and time of using the bioenergy. As discussed in chapter 2, for many of the pathways even several process options exist.

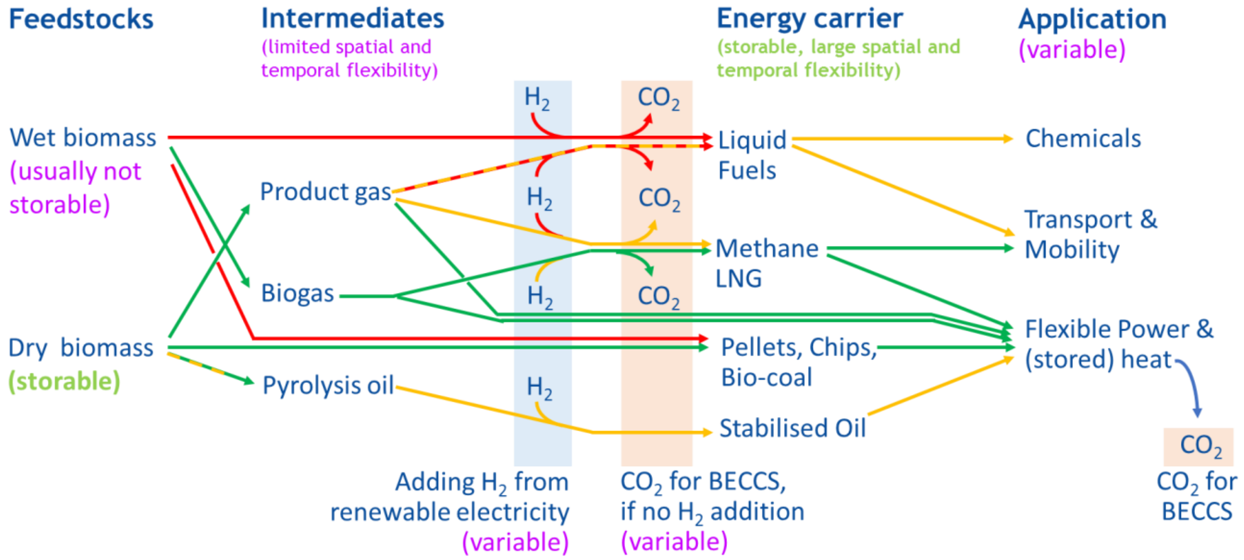

Figure 8: The network of flexible technologies in biomass related energy conversions. Green arrows indicate technologies which are already applied; yellow arrows indicate technologies which have been demonstrated technically, but do not yet have a working business case; red arrows indicate technologies under development.

Figure 8 shows clearly that by far not all of the technically possible and successfully demonstrated process options are regularly applied. While burning biomass or biomass based intermediates and energy carriers for production of heat or combined heat and power is quite common, the flexibility of these units for **positive ancillary services** is only rarely exploited; mostly in countries where suited incentives such as a flexibility premium exist.

Negative ancillary service, i.e. the flexible up-take of electricity that cannot be used otherwise at time and site of its production by e.g. Power-to-Gas or Power-to-Liquid type processes, is technically solved and was successfully demonstrated only for biogas-upgrading by methanation of the CO_2 content. Here, the second commercial scale plant is under construction. Flexible hydrogen addition to wood gasification gas or within hydrothermal gasification or liquefaction is still under development.

Long term flexibility, i.e. the conversion of biomass to energy carriers that can be easily transported or stored within existing infrastructure, is quite common for biogas upgrading by CO_2 separation. The conversion of wood to non-solid energy carriers such as methane, stabilized pyrolysis oil, Fischer-Tropsch Diesel or similar has been demonstrated, but most have not found a good business case yet.

As a common observation, the processes that work in most countries are starting from waste streams that have to be treated but cannot easily be valorized otherwise, e.g. sewage sludge to biogas to biomethane. Also, the production of heat and electricity from biogas and wood is applied at many places, but usually with financial support schemes. The inherent flexibility of biomass CHPs for ancillary services that is discussed in chapter 2 is most often not used, as without specific incentive, economics dictates continuous operation at maximum load. The country-specific aspects of flexible bioenergy use are discussed in more detail in the IEA Bioenergy Report “Expectation and implementation of flexible bioenergy in different countries", IEA Bioenergy Task 44, March 2021[1].

The flexible use of woody feedstock is so far limited from two sides: on the one hand, simple combustion to cover heat needs is a financially more attractive alternative to more complex conversion processes, as long as there is sufficient heat demand. On the other hand, due to the value of energy wood and the more complex processes, energy carriers based on wood have a higher price difference to fossil energy carriers than those starting from biogas from waste inputs.

With the further increasing share of variable renewables like PV and wind in the energy system, the flexibility of bioenergy - besides electricity production on demand also e.g. the synergies with Power-to-X processes - will become more and more necessary and therefore more valuable. Especially the upcoming hydrogen strategies in several countries will open many new options for synergies, as can be seen from the multiple options to include renewable hydrogen in bioenergy value chains, see Figure 8. Also the new IEA energy outlook shows the substantial role for flexible bioenergy expected in the future.

The broad use of bioenergy flexibility, i.e. positive and negative ancillary services for the electricity grid and options for storage and transport within existing infrastructure, will depend on a suitable market design and for some period also support schemes to anticipate for upcoming higher flexibility needs in the energy system and to allow the stakeholders to decide for the better investments. IEA Bioenergy Task 44 publishes on its webpage a list of Best Practice examples which profit from suitable technical, economic and regulatory boundary conditions to maintain their operation.

[1] https://www.ieabioenergy.com/blog/publications/new-publication-expectation-and-implementation-of-flexible-bioenergy-in-different-countries/

4 Appendix - Overview of individual flexible bioenergy technologies

4.1 BIOGAS UPGRADING (BIOMETHANE PRODUCTION BY CO2 REMOVAL)

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	The CO_2 contained in biogas is removed to produce a gas stream, which can be injected in the natural gas grid (CH_4 content above legal requirements, e.g. > 96%). This is operated via scrubbing, chemical absorption, pressure swing adsorption (PSA) or membrane separation. Scrubbing: CO_2 is removed by absorption in a solvent (water or organic). Chemical absorption: CO_2 is removed by reaction with a specific chemical. PSA: CO_2 is removed by adsorption on a specific material and removed by change of pressure. Membrane separation: CO_2 is removed by selective permeation through a specific material. All the technologies mentioned here, can successfully perform the operation; selection of the most suitable technology follows site-specific considerations. Important: CH_4 losses to atmosphere have to be minimized.	[1–4]	The legal limit for both minimal CH_4 and maximal CO_2 must be fulfilled. Biogas must be cleaned also from other components (e.g. S containing compounds) and dried. Desulfurization is usually necessary before CO_2 separation.
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	Water scrubbing: 0.1-0.2 m^3 H_2O/Nm^3 biogas is required to reach >95%; CH_4 losses: 1 %. Applied at large scale. Chemical absorption (with amines): production of biomethane with purity >99 % CH_4, losses lower than 0.1 %. Contemporary separation of H_2S (up to 300 ppm). Applied in ca. 20 % of the upgrading facilities worldwide. PSA: CH_4 recovery between >98%, with 1-2% losses in the off-gas. If losses are higher, off-gas must be further treated. Offered commercially: product quality >99% CH_4 and >99 CH_4 recovery. Membrane separation: In single stage configuration, 92-96 % purity achievable. To reduce losses more stages are used and 0.5% loss is reached. The necessary purity depends on gas network requirements. If off gas is used efficiently in the process, the loss percentage is less important.	[5–8], [14] [15]	According to the technology, it may be possible to use the CO_2 collected in further processes like carbon capture and utilization (CCU) and carbon capture and storage (CCS).

What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	Biomethane production allows storage of the energy carrier in the gas grid and thus the flexible use of the biomass (possible use of biomass in a different time than at the production). This is the most important feature in terms of flexibility. Rump-up/-down depend on the specific technology: Water scrubbing: rapid ramp up/down, particularly in the once through configuration. Chemical absorption (with amines): quick start-up, time required depending on the activation of the regeneration section. PSA: immediate start, cyclic operation requiring at least 4 units (adsorption + regeneration + intermediate stages). Membrane separation: immediate start-up, possibility to directly recycle the product gas when out of specification. Furthermore, membrane separation does not require chemicals, and allows for easy scale up, thanks to modularity (scale up performed with several units).	[2,4]	The out-of-specification start-up gas can be recovered by recycling, minimizing the amount of biomethane wasted. Ramp-up/-down might be interesting in special situations, e.g. if it can reduce biogas storage needs or biogas flaring.
What is the TRL? How many similar plants exist? Where is the example plant located?	Water scrubbing: commercial plants available (TRL 9), > 200 units installed worldwide. Chemical absorption (with amines): commercial technology (TRL 9) > 100 units installed in the world. PSA: mature technology (TRL 9). 21 % market share (>100 units installed). Membrane separation: units commercially available. The market share has been growing rapidly since 2015 and is in 2019 comparable to water scrubber (TRL 9).	[2,5, 7–9] [16]	All technologies here presented are commercially available; however, R&D is still ongoing to decrease costs by new materials or process configurations.
What are the R&D needs?	Increase in process efficiency, increase in size with consequent reduction of costs. Cost efficient small-scale applications for farm applications. Improvements of the CO_2 purification units to create a market also for the side product (CO_2). For membranes: development of tailored materials for the separation in specific applications.	[10]	
What are expectations, what experiences were collected?	Rapidly evolving market, driven by the economic potential of biogas grid injection vs. electricity production in gas engines. Additional profit by CO_2 sales can further boost the market, favoring the solution that provide pure CO_2. Further expansion	[2,4, 11]	

	of the technology must follow the creation of awareness of the potential of biogas plants for the production of renewable gas, involving the entire process chain, from feedstock collection to gas injection. But feedstock potentials and competitive uses should also be taken into account. Furthermore, awareness of the profitability of the business case must be created with the decision makers who are not always aware of the potential of biogas upgrading.		
Indicate the capital costs and the fixed operation costs.	Water scrubbing: 1500 €/(Nm^3/h) capital cost, operating costs 0.2-0.3 kWh/Nm^3 for compression and pumping of the solvent (2-3% of the capital cost). Chemical absorption (with amines): investment 3200 €/(Nm^3/h) for capacity up to 1500 (Nm^3/h); 1800 €/(Nm^3/h) for larger scale. Costs for chemicals are negligible (if the desulfurization is reliable), energy costs for liquid pumping and gas compression amount to 0.12-0.15 kWh/Nm^3, energy cost for the regeneration is 0.55 kWh/Nm^3. PSA: capital cost: 2700 € per Nm^3/h up to 600 Nm^3/h treated gas, reduced to 1500 € per Nm^3/h for plants of 2000 Nm^3/h capacity. Operation expenditures linked to the electricity needed for compression: 0.24–0.6 kWh/Nm^3. Membrane separation: Investment costs (membrane modules) range from 2500 to 6000 € per Nm^3/h for capacities 100 to 400 Nm^3/h. Above 1000 Nm^3/h capacity, the investment cost is ca. 2000 € per Nm^3/h. Operative expenditures are related mainly to the periodic replacement of membrane (every 5 to 10 years), pressurization of biogas and pretreatment (ca 0.2–0.38 kWh/Nm^3). Furthermore, maintenance amounts to 3-4% of the investment cost. Total costs for standard upgrading capacities (~ 700 m3/h) are in general between 10-20 €/MWh. Cost increases with lower capacities. Also costs for feed-in will raise. Upgrading and feed-in costs can raise from 41-47 €/MWh (250 m^3 raw gas/h) to 24-27 €/MWh (750 m^3 raw gas/h).	[2,4, 5, 11–13] [17]	
What is the underlying business case or incentives for the plant operation?	The business cased is based on the possibility of injecting the biomethane in the natural gas grid, with increased profit compared to the direct use of biogas in electricity production (e.g. in internal combustion engines). Biomethane is usually recognized a higher price than natural gas	[2,9]	Currently the development of biogas upgrading depends strongly on the incentive policy and its

	(according to local incentives). Because electricity is becoming more sustainable and less CO_2 intensive, using biogas for the gas network is increasingly interesting from the point of view of CO_2 reduction. Financial incentives can help with this transition.		expansion is thus strongly differing country by country

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4.2 PYROLYSIS OIL STABILIZATION

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	With the pyrolysis process solid biomass can be converted into oil. This oil is still reactive and contains a lot of oxygen compounds. With hydrogenation, this oil can be stabilized, and oxygen can be removed. The final product can be mixed with or replace currently used fossil oil products. Treatment of oil with hydrogen is a commercial process used for e.g. transport fuels in refineries. Main difference with treating pyrolysis oil is the much higher hydrogen consumption, water production and lower sulphur content. Main characteristics of hydrogenation are catalyst, pressure and number of reactors. Many catalyst and conditions are already tested on lab. scale. Currently sulphided catalysts, predominantly alumina-supported NiMo and CoMo catalysts are the preferred choice for pyrolysis oil (adding of H_2S might be needed). Future developments can go in the direction of only stabilization and limited oxygen removal or in the direction of oxygen removal and drop-in fuel for current used fossil fuels both depending on market developments.	[8]	The development of stabilization by hydrogenation depends on the development of the pyrolysis process and the pyrolysis oil production.
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	Fast pyrolysis is a process in which organic materials are rapidly heated to 450 - 600 °C in the absence of air. Under these conditions, organic vapors, pyrolysis gases and charcoal are produced. The vapors are condensed to bio-oil. Typically, 60-75 wt.% of the feedstock is converted into oil. After this pyrolysis, the oil is combined with hydrogen at 255° – 410°C and ~140 bar and is converted to hydrocarbons, water, and gas over a fixed bed reactor. Depending upon the reactivity of the catalytic pyrolysis oil, two beds may be needed. In a two reactor approach the first is a mild reactor for most reactive components followed by a reactor with more severe conditions.	[1], [7]	Fast pyrolysis is in the market introduction phase. Stabilization by hydrogenation is a next step.
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	Because hydrogen is used for stabilization, it follows the electrolyser characteristics if H_2 storage is available. If more oxygen is removed, more hydrogen is fixed		Three types of flexibility. [1] Power grid (with H_2 storage). [2) Flexible electricity

	in improved liquid fuel[2]. Stabilized pyrolysis oil can be stored for a long time and used as a flexible fuel[3].		production using the liquid fuel. (3) Sustainable liquid fuel availability.
What is the TRL? How many similar plants exist? Where is the example plant located?	Starting with pyrolysis plants: **BTG-BTL technology**: Malaysia 2 t/h EFB for Genting (2005); Empyro plant in Hengelo (Netherlands) 5 t/h wood (2017); Lieksa (Finland) 5 t/h (being build, 2021) and 3 more are ordered; Gävle (Sweden) Kastet pyrolysis plant using 4-4.5 t/h sawdust (startup 2021). The Kastet oil will be processed further in the Preem oil refinery in Lysekil. **VTT technology**: Valmet plant in Joensuu (Finland) 10 t/h (2013). **Ensyn technology:** 1.7 t/h; 3.5 t/h and in Port Cartier 9 tons/h all in Canada. **Kior Technology**: Columbus (Mississippi/USA) 21 t/h (2014) with a combination of pyrolysis and FCC cracking (installation dormant). TRL level pyrolysis depending on technology 6-9. Hydrogenation estimated TRL level 3-5	[1], [2], [3], [4], [9]	Stabilization of pyrolysis oil is not demonstrated on a commercial scale[4]. Because it has a lot in common with commercial oil hydrogenation, this might not be a big problem.
What are the R&D needs?	Catalyst special developed for different types of pyrolysis oil and optimized for specific outputs (e.g. max. gasoline fraction). Also, research is done to other H_2 sources like formic acid.	[10]	
What are expectations, what experiences were collected?	Pyrolysis oil can be produced from different types of solid biomass. Stabilization and hydrogenation is possible. Product might split up in two layers. One layer of “oil” and one with water and in water soluble compounds.		
Indicate the capital costs and the fixed operation costs.	Cost for a 20 mln l oil/y pyrolysis plant 25 mln €. Input 5 tons/h output 20 mln l/y of 19 MJ/l LHV pyrolysis oil. Makes also steam and electricity.	[4]	No cost data for stabilization found

[2] Removing oxygen and adding hydrogen increases the energy content of the oil. In this way a surplus of sustainable electricity can be converted in additional liquid fuel energy.
[3] Publication [11] describes a system of solar cells and biocrude for electricity production.
[4] TNO found no reference to a commercial project

What is the underlying business case or incentives for the plant operation?	Main reason is the production of low CO_2 emission sustainable fuel and making use of financial incentives or meeting obligations. A liquid fuel is easier to store and to transport and cleaner in combustion. Stabilization makes longer storage times possible. Hydrogenation makes it possible to make high quality transport fuels or blending products for these fuels.		

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4.3 HYDROTHERMAL TREATMENT OF WET BIOMASS (HTC, HTL, HTG)

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Hydrothermal treatment of wet biomass (HTP), or wet torrefaction, is a way to convert biomass waste streams into solid (HTC), liquid (HTL) or gaseous (HTG) energy carriers.		
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	HTC takes place at temperatures from 240 °C (low T) or 250-800 °C (high T) and 2 MPa. This results after several hours in a solid HTC biochar [1]. Source [4] mentions for HTC 180-350 °C and 2-10 MPa. HTL takes place at 280-370 °C (low T) or 300-600 °C (high T) and 10-25 MPa results after a few seconds in oil which can be improved to a transport fuel by increasing the C/H ratio. Energy efficiency 88% [2]. The same source mentions a potential of 6.5 EJ oil and 2.1 PJ gas from all type of USA waste streams and in 2045 (worldwide potential factor 5.6 higher) [2]. Source [4] mentions for HTL 250 -450 °C and 4-20 MPa [9]. It also mentions that next to water other solvents can be used like hexane or methanol. Efficiencies are also mentioned in [16]: an oil yield of 45% on mass basis and 85% on energy basis. For HTG there are three circumstances 300-500 °C (near critical) with CH_4 production; 300-500 °C (supercritical, called also SCWG [3]) with syngas H_2 C1-C4 gases. For SCWG efficiencies of 60-80% are reported in [5] both with catalyst and various pressures in a few seconds. The last is aqueous reforming at 220-250 °C and 1.5-5 MPa and several hours of reaction time. This produces H_2 and CO_2 and minor C1-C6. In HTG water is not only a solvent but also reacts with the biomass to produce the gaseous hydrocarbons [4]. All HTP processes produce wastewater with organic compounds which can be used for anaerobic digestion into methane.	[1], [2], [3], [4], [5], [9], [16]	
What are its flexibility characteristics? (e.g. ramp up/down rates,	The main flexibility HTP processes give, is that they make from biomass and biomass waste, with a high energy efficiency, a better energy carrier: lower water content, higher heating value and better to transport and to store. Depending on the process a solid "fuel"		

turndown ratio etc.)	is produced, liquids are produces which can be converted in i.e. transport fuels. Gasses like SNG or syngas can be produced and used as source for further chemical processing. So HTP makes the use of biomass time and location independent. It delivers a substitute for fossil fuels like coal, oil and natural gas. Part of the carbon can be separated as CO_2 or converted with hydrogen (for instance made from a surplus of sustainable electricity) into additional energy carrier.		
What is the TRL? How many similar plants exist? Where is the example plant located?	The Ingelia company from Valencia (Spain) has built several HTC plants [21]. The first plant was finalized in 2010 (6000 tons biowaste/y) and extended to 14,000 tons in 2015. A next plant, cost 4 mln £, for CPL Industries started in 2018 in Immingham (UK), and a second one in Foynes, Ireland, to produce biocoal. In Oostende (Belgium) a plant is in preparation of 21,200 tons of waste/y (according to its licence application). Other countries with commercial agreements mentioned on the Ingelia website are Poland, Portugal and Canada. Other companies are also involved in HTC plants. TerreNova from Düsseldorf did put an installation into operation, which makes a solid fuel from sewage sludge in Kaiserslautern, Germany, in 2010. Since 2016 another HTC installation is operating in Jining, China, which makes 3000 t/y of biocoal for incineration from 14 000 t of sewage sludge [23]. Given the number of plants TRL level for this HTC process is about 9. After several old pilot plant attempts for instance at Pittsburgh Energy Research Centre of U.S Bureau of Mines [9], HTL has reached, depending on the specific process, TRL 6-8. Aarhus University in Denmark has a 100 l/h HTL pilot plant and, Aalborg University in Denmark has a 30 kg/h Continuous Bench Scale 1 (CBS1) HTL facility [10]. Both universities are participating in the EU HyFlexFuel (Hydrothermal liquefaction: Enhanced performance and feedstock flexibility for efficient biofuel production) project [17]. A commercial scale HTL plant in Teesside in North East England is under development. This first Cat-HTR™ site will be able to process 80,000 ton of plastic waste per year [11]. Before this plant several pilot plants of 100, 1000 and 10,000 tons slurry/y were built in Somersby Australia [12]. On the same location a Commercial Stage 1 plant is on track for commission in Q1 2021 which can process 5,000 ton of post-consumer biomass and residues (producing	[4], [6], [7], [8], [9], [10], [11], [12], [14], [15], [16], [17], [18], [19], [17], [21], [23]	TRL levels TNO estimates. TNO stopped searching after finding a substantial number of HTP plants, so there might be more than here described.

	approximately 10,000 barrels) [12]. The Southern Oil Refining opened a HTL pilot plant in Gladstone Queensland Australia (16 mln $AUS) in 2017. From i.e. old tyres, sugar cane and green waste it is intended to produce one million liters of fuel within three years for navy ships [14]. A Hydrofaction demo plant is being built by Silva Green Fuel in Silva, Norway, for 59 mln € and a Capacity of 4000 l/day. In the first period it will use mainly residual products from the forest. The opening is expected in autumn 2021 [15] [16]. In Vancouver, Canada, a HTL plant is planned to start up in 2020 which produces oil (finally used in diesel fuel) and natural gas from wastewater sludge. The Genifuel – Metro Vancouver plant has a capacity of 2 dry tons/day. In 2021 a 3 dry tons/day should follow in Martinez, California [19]. For HTG the TRL level is around 4. Often mentioned is the SCWG Verena pilot plant of 100 kg/h max 20% dry biomass in Karlsruhe Germany in 2003 [4], [6], [7]. Also, the Paul Scherrer Institut (PSI), Villigen, Switzerland experienced with a 1 kg/h and a 50 kg/h HTG installation with a catalytic fixed bed [18]. In the Netherlands thermal pressure hydrolyses at (140~165°C) is used at a commercial scale as a pretreatment for wastewater sludge. It increases the amount of methane from digestion and makes dewatering to lower water content possible [8]		
What are the R&D needs?	For biochar removing of corrosive compounds if used as fuel and removing of toxic compounds if used as soil improver. SCWG has three main problems: costs, char/coke formation and plugging by salts (salts have a low solubility in supercritical water). Options are salts removal and kind of moving reactor bed [5] A problem of anaerobic digestion of the wastewater is that some compounds are difficult to break down.	[4]	
What are expectations, what experiences were collected?	Several details on the different routes can be found in [18].	[18]	
Indicate the capital costs and the fixed operation costs.	HTC total capital investments depends on the biomass source and size. According to a 2014 publication and based on model calculations investments can vary between 7-21 mln € for 11 to 56 MW_{HHV} solid biomass input. Specific costs can vary from 8-15 €/GJ [4].	[4], [22]	

	In [22] calculations are made for a 7000 tons dry mass/y graph marc HTC plant. They calculated a total capital investment of 1.77 mln €$_{2015}$ and annual processing costs of 0.83 €$_{2015}$. With an annual production of 5300 tons of hydrochar pellets this translates to 200 €/ton or 8.3 €/GJ HHV, which is comparable with wood pellets. Due to the high cost SCWG is currently only profitable for biomass streams with high disposal costs or as part of a more complex installation.		
What is the underlying business case or incentives for the plant operation?	HTC biochar can be used as a solid biofuel with better storage and transport properties. It can also be used as a soil improver. And finally, as high porous carbon, it might be used for its specific properties for instance in batteries. Dewatering of sewage sludge, to make it better and cheaper transportable and combustible, is also an incentive. Also, the EU policy to decline landfill of waste is mentioned. Several HTL (demo) plants focus on making sustainable transport fuels from waste streams. They use the large price difference between feedstock and product, but also need financial stimulation for low CO_2 fuels.	[4]	

4.3.1 References

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4.3.2 Appendix - Hydrothermal processes

Some figures and tables which might be helpful for understanding the HTS processes.

Table 1 Main HTP and different operating conditions for obtaining highly valued products (taken from Shen, 2020).

Processes	Temperature (T, °C)	Pressure (MPa)	Reaction time	Catalyst	Main products
HTC					
Low T	250	2	Several hours	Not essential	Char
High T	250–800	2	Several hours	Optional	Char
HTL					
Low T	280–370	10–25	Few seconds	Optional	Oil
High T	300–600	10–25	Few seconds	Alkaline salts: Na_2CO_3, KCl, KOH; Heterogeneous catalysts under high pressure H_2	Increasing oil yield; Improved to transport fuel by increasing C/H ratio
HTG					
Near-critical	300–500	Various	Few seconds	Metal catalyst and alkaline salts	CH_4
Supercritical	500–800	Various	Few seconds	Metal catalyst and alkaline salts	Syngas H_2 with minor CO_2, C1–C4 gases
Aqueous phase reforming	220–250	1.5–5	Several hours	Pt/Al_2O_3, Pt/ZrO_2, Rh, Ni and on SiO_2, etc.	H_2 and CO_2 with minor C1–C6 alkanes

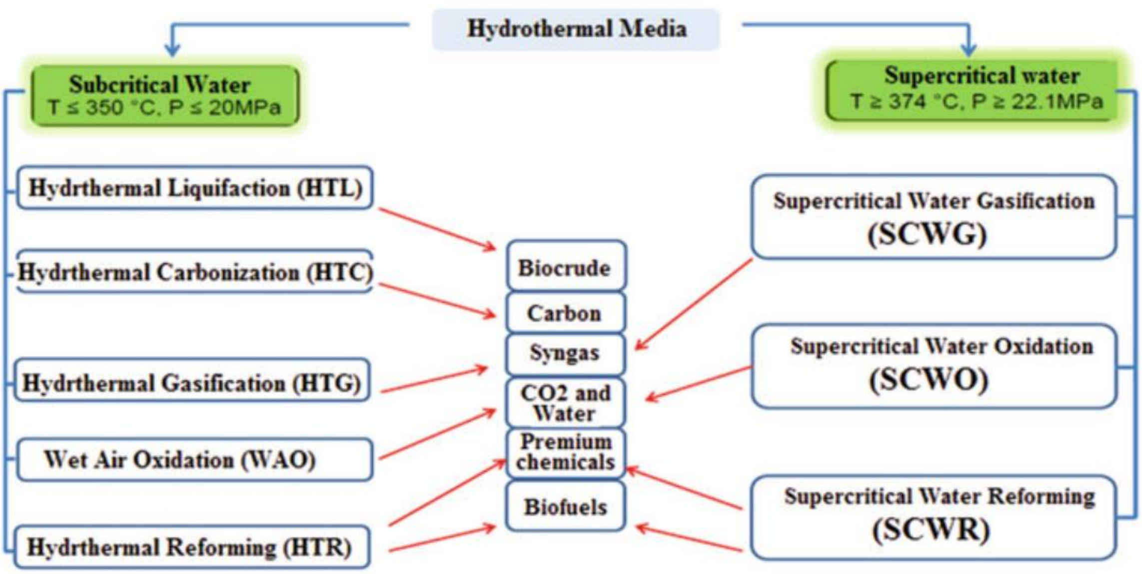

Figure 9 Hydrothermal processing technologies (taken from Barcelo´, 2020)

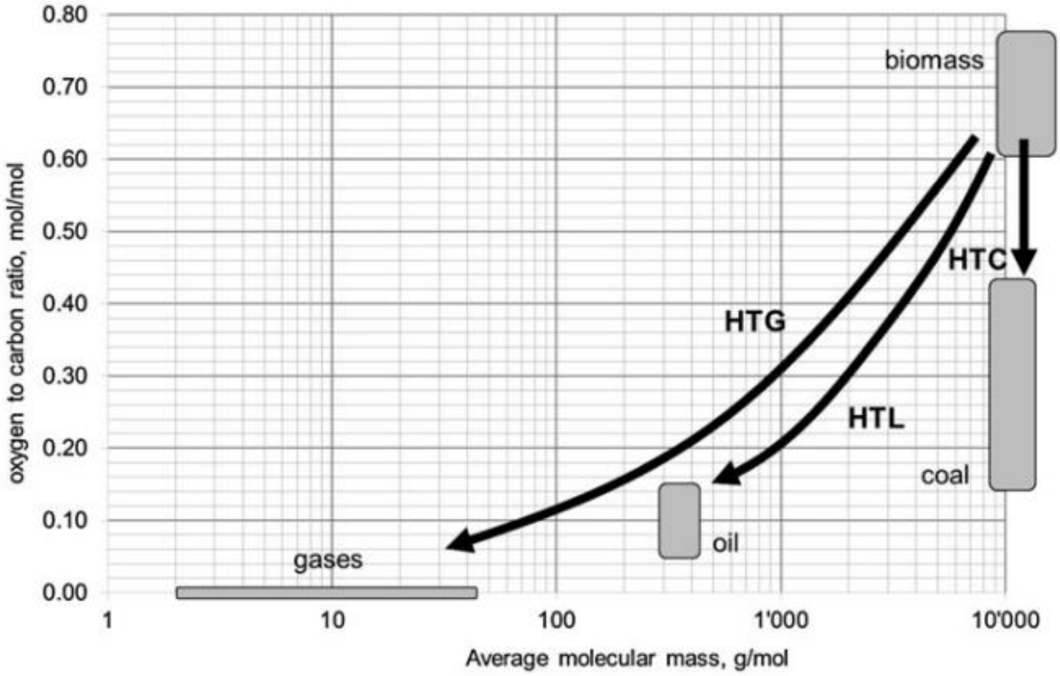

Figure 10 The three hydrothermal conversion paths and reducing of the molecule structure (taken form Vogel, 2019).

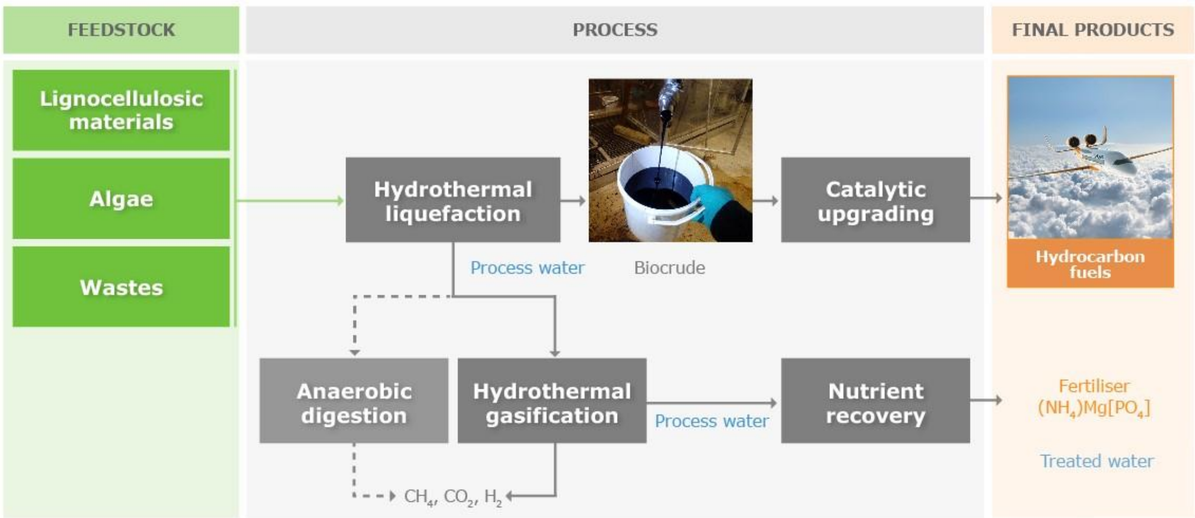

Figure 11 The HyFlexFuel process: Liquid drop-in fuels are produced from different types of feedstock via hydrothermal liquefaction and catalytic upgrading. Organic components of the residual aqueous phase are energetically valorized through hydrothermal gasification and anaerobic digestion. Valuable inorganic nutrients are recovered as marketable fertilizers. [17]. Source: https://www.hyflexfuel.eu/wp-content/uploads/2018/06/HyFlexFuel_Flyer.pdf.

4.4 BTL, WOOD TO SNG/BTL VIA GASIFICATION

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Thermal gasification produces a synthesis gas from a variety of lignocellulose and other biomass feedstocks. The produced synthesis gas, composed mainly of CO, CO_2, H_2, CH_4 and higher hydrocarbons, can be further used to produce a range of products such as biomethane, oxygenates such as Methanol, Ethanol and Dimethyl Ether (DME), synthetic long chain hydrocarbons such as Fischer-Tropsch (FT) Diesel, Gasoline or Kerosene. Also, hydrogen and a mix of higher alcohols can be produced. This gasification is performed in the presence of various oxidizing agents, such as air, oxygen, steam. In case of use of steam, the yield to H_2 is increased, but part of the biomass must be burned to provide the required heat to the endothermic reforming reaction. There are several different types of gasifiers. Entrained flow gasifiers are suited for liquid and pulverized feedstocks, while fluidized bed gasifiers are suited for feedstocks with larger particle sizes such as wood chips or pellets. For production of bio-methane, an indirectly heated gasifier system (dual fluidized bed) may be preferred as it generates considerable amount of methane already in the gasifier itself, as well as that an investment in an air separation unit (for oxygen supply) is avoided. Downstream of the gasifier, the raw gas is conditioned and treated to remove impurities (e.g., tars, particles, S-containing compounds) also other process steps can be put in, like reforming of the higher hydrocarbons, hydrogen enrichment by the water-gas-shift reaction (WGS) and CO_2 removal. The CO_2 is available for CCS/CCU. The CH_4 content of the gas stream can be increased by methanation of the CO and (remaining) CO_2 with the H_2 present or by addition of H_2 originated from other sources (e.g. energy storage in PtG applications). The CO/H_2 ratio can be adjusted for further processing in a Fischer-Tropsch unit to produce a liquid fuel (biomass to liquid process BtL)	[1], [2], [3], [4]	Inter-mediate treatments may in some concepts be applied to facilitate the handling of the feedstock. For example, the original feedstock can be transformed into a liquid (bio-pyrolysis) at the distributed production place and transported in this form a central location for the of final conversion.
What are its technical performance characteristics? (e.g.	Feedstocks can be solids in form of woody biomass, wood wastes, MSW, agricultural residues (straw), and liquids in form of black liquor from pulp making, pyrolysis liquids, etc. Gasification units operates in scale from 10 MW up to 100 MW or larger. The	[1], [2], [4], [5], [6],	Plants are usually at larger scale than anaerobic

feedstock(s), output(s), scale, efficiency)	overall energy conversion efficiency (from feedstock as received to final product) is typically in the range of 40-70 % on an energy basis (based on the Lower Heating Value - LHV). Efficient utilization of by-products like steam and heat can increase the overall energy efficiency of the plant by up to 5-10 %-units, when integrated with district heating or with combined heat and power production. The product gas composition also depends on the technology used. A summary of the product gas compositions is reported in [5]. A typical low temperature gasification (850°C) gas composition is: 20-40 % H_2, 10-30% CO_2, 20-30% CO, <10% CH_4. With the SER (sorption enhanced reforming, where CAO is added in the gasifier to remove CO_2 directly), H_2 content can increase up to 70%. For the BtL process, high temperature gasification is used, leading to syngas consisting of CO, H_2, CO_2. Normally, 7 t of biomass are required to produce 1 t of liquid fuel. Example: The high temperature (>1100 °C) pilot gasifier in the Bioliq process has 5 MW input. This corresponds to a throughput of biomass oil of 700-1000 kg/h. The installation uses bio-syn-crude made from mixing pyrolysis oil with suspended pyrolysis coke, both products from via fast pyrolysis of biomass. This entrained flow gasifier has a gas composition of 26–35 vol % H_2, 27–39 vol % CO, 14–28 vol % CO_2, < 1 vol % CH_4, N_2 used for flushing is rest. 8 ton of biomass are required to produce 1 t of liquid fuel. In 2019/2020 the methanol/DME installation, after the gasifier, produced 800 l fuel, which was blended to gasoline standard fuel and tested in engines.	[15]	digestion, due to the requirement for utilities and process integration, and due to more favorable feedstock logistics
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	Converting wood and similar feedstocks into more common energy carriers, for which an efficient infrastructure (transport storage, end user technologies) exists, significantly expands the geographical, temporal and application range. Startup of a gasification plant requires several days from cold conditions due to limits in heat-up rate, and several hours from hot stand-by. Since products are storable or can be fed to a gas grid with storage capacity, neither the demand for, nor economics of variable load operation is high. However, some plants offer flexibility in terms of change of load within certain margins. As mentioned previously, flexible addition of hydrogen by Power-to-Gas may be	[1], [7], [16]	

	possible. Example: the start-up of the bioliquid entrained flow gasifier equipped with a cooling screen takes less than half a day. From the time of ignition, the high-pressure entrained flow gasifier of the Bioliq process is ready to deliver synthesis gas to the subsequent process steps within approx. 1-2 hours. The Load flexibility is 70-100% thermal fuel Input. Any BtL process offers the flexibility to store hydrogen, but at the same time, with insufficient H_2 available, this might just as well lead to negative emissions (the CO_2 surplus could be stored). Due to the high investment costs, the gasifier is preferably used continuously. Depending on the design, flexibility is possible regarding the feedstocks. The plant outputs does have a great flexibility and can be transported well and stored for a long time. It is possible to build in extra flexibility on the synthesis side, different products, additional hydrogen supply or CCS, but investments for this do count towards the production costs, even if they are only used partly.		
What is the TRL? How many similar plants exist? Where is the example plant located?	Gasification and BtL technologies are in the demonstration/piloting phase. More than 40 plants are in operation or in construction worldwide. The TRL of these plants is 5-8. The commercial role out is in general limited due to the economics in the scale up. In 2021 a demo plant with 15 MWth input (3 t/h torrefied wood) was successful operated at Dunkrik in France for several weeks, and the gas of the gasifier was converted via Fischer-Tropsch synthesis into high-quality aviation fuel, diesel and naphtha. The torrefied wood was produced by a second demo plant in Compiègne [17, 18].	[1], [2], [4], [7], [8]	
What are the R&D needs?	The R&D needs for this technology lie in 4 aspects: (1) increase of technology readiness to commercial scale, (2) improvement of process integration, (3) development of convenient gas cleaning technologies (4) handling of low-quality feedstocks. Here a certain trade off can be considered: a more robust synthesis allows for simpler gas cleaning; higher investment in gas cleaning allows for more sophisticated synthesis steps. (1) The technologies are proven up to TRL 6-8. In order to reach full maturity, further development and demonstration at full scale is required. Longer operation time and larger	[2], [9], [10], [19], [20]	Although parts of the production process are comparable with oil- and gas-based processes, it must be realized that BtL processes will not reach the

	scale will give rise to issues that cannot be considered in smaller test facilities. (2) Detailed process chain analysis is required to optimize the economic performance of the process, by coupling with appropriate production units, allowing for efficient heat management and raw material supply. In particular, efficient strategies for the collection of hard biomass from the surrounding regions or ship logistics are important to guarantee process profit. (3) Gas cleaning technologies must be refined to have a lower economic impact on the product cost. In particular, development of high temperature scrubbers and filters can improve the process integration, reducing the need for heat exchangers. (4) There is an economic driving force to use lower quality, low-cost feedstocks (residues, post-recycling wastes) and to have a high feedstock flexibility. The knowledge level concerning gasification of inhomogeneous biomass feedstocks with varying quality is currently not high enough. Use of lower quality feedstocks is followed by challenges in fuel feeding, managing tar and soot formation, varying ash properties, finding suitable reactor lining materials, and avoiding poisoning in gas upgrading [19].		same production scale. So BtL research can learn from fossil fuel but should not adapt the same approach.
What are expectations, what experiences were collected?	The main technological issues are addressed; the target products can be successfully obtained. Currently, gasification-based plants are in operation, where the business case is favorable, mainly in CHP or process heat production. The cases aimed to the production of biofuels and chemicals (H_2, CH_4 and liquids) are not competitive in the current situation. A change in CO_2 policy and pricing can substantially modify the analysis and make these plants economically sustainable. The expectation is thus of a possible further development of the technology, following new energy policies.	[7]	
Indicate the capital costs and the fixed operation costs.	H_2 production: selling price for NPV=0: 2.70 €/kg (based on DFB gasifier). Capital cost approx. 65 mln € for a capacity of 50 MW, forming approx. 5% of the annualized total costs. The highest share of OPEX is due to raw material (ca. 40% of the costs). Costs for SER-based H_2 production are significant higher due to costs in bed material handling.	[1], [2], [6], [10], [11], [12]	Reference prices: H_2: 1.05 €/kg (large scale); 2.5 €/kg (small scale)

	SNG production: total costs ca. 0.20-0.40 €/Nm^3. Approx. 10 % of the total costs due to capital expenditures, remaining due to running costs. Cost of SNG production via wood gasification is currently 60% higher than biogas via fermentation. BtL: total cost ca. 1 €/kg of produced synthetic fuel. Approx. 60 % of the costs is due to biomass collection and handling. A recent IEA report mentions a range from 0.6-1.7 €/kg of produced synthetic fuel components via the gasification route. The range is related to the feedstock. Capex for biomethane and methanol is in the range of 2000-3000 €/kW product output, and for FT-fuels and gasoline hydrocarbons it is in the range of 2600-4500 €/kW product output. It also gives cost reduction possibilities in investment and operating costs and in financing and lifetime. Reduction of feedstock costs is judged to be more limited [6].		CH_4: 0.2 €/Nm^3 Fuels: 0.5 €/kg
What is the underlying business case or incentives for the plant operation?	The underlying business case is based on the utilization of cheap biomass in a plant placed at close distance to the production site. This makes the wood-to-SNG/BtL processes currently profitable only at limited locations with particularly favorable conditions. In the near future, the processes can become profitable in case of introduction of sufficient incentives on CO_2 utilization or on avoided emissions. Gasification has important benefits. It has a high energy efficiency, a low CO_2 emission (with CCS even negative) and already a high TRL level. Furthermore, it can handle a large variety of feedstocks (from wood residues to waste streams) and depending on the chosen synthesis plant, it can produce valuable liquid fuels or chemicals. Depending on feedstock availability it can be built on “large” scale and integrated with existing infrastructure and industries. The short term, large scale and low CO_2 aspects makes it interesting for governmental policy or oil/chemical companies, although it goes along with substantial investments. Possible future development involves the use of the bioSNG plants for energy storage, by addition of renewable energy to the gas stream. In this case, increased production with limited additional costs can improve the business case.	[2], [13], [14] [21]	

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4.5 FLEXIBLE POLYGENERATION (FUEL/HEAT/POWER), I.E. SWITCHING BETWEEN FUEL PRODUCTION AND CHP OPERATION

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Polygeneration energy systems have the potential to provide a flexible, high-efficiency, and low-emissions alternative for power generation and chemical synthesis from fossil fuels. However, the potential of flexible polygeneration is far less into full play as expected. Reasons could be: • majority of companies operate polygeneration plants according to a fixed power-to-heat ratio for easy control. • the current energy policy in different countries to drive the sustainable energy development places too much emphasis on power generation. Various incentives to promote RES (renewable energy sources) are causing a greater temporal and spatial imbalance between supply and demand. This means that current design, planning and policy-making methodologies fail to adequately consider the sustainability of different energy products in the system in coordination. Biomass-based flexible polygeneration is important for the future, because beside power, heating and cooling it can produce gas and liquid fuels for transportation	[1] [2] [3-6]	Problems with tar formation and ash fusion
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	Polygeneration has a varied range of fuel inputs that can be applied and combined (e.g. biomass with solar): coal, natural gas, biomass, solar, other renewables (e.g. wind), biomass (hemicellulose, lignin and cellulose, palm oil residues, fiber of coconut, solid waste, straw). There is a wide variety of outputs: heating, cooling, electricity, H_2, methanol, urea, oil, gas, char, desalinated water, synthetic-fuel, chemicals…) The reported overall efficiency in the literature varies from: 50% up to 95.84%	[10] [8,9]	
What are its flexibility characteristics?	The system built can be very flexible and strong in operating for different conditions, depending on the used feedstock and outputs.	[10]	

(e.g. ramp up/down rates, turndown ratio etc.)	The ramp up and down rates and turndown ratio strongly depend on the systems used and the specific operating characteristics of the process equipment.		
What is the TRL? How many similar plants exist? Where is the example plant located?	The TRL for flexible (!) polygeneration is between 3-5. Combined Heat and Power (CHP) are mature technologies with high technology readiness levels (TRLs) of 8–9 and are widely used to convert biomass to energy. Other processes — such as pyrolysis and gasification — are still in the development-to-deployment stage with TRLs of 6–7 for heat and power production. But, focused on one product, gasification to methane has also reached 6-7 (Gobi plant), and pyrolysis to fuel oil is even higher 8-9. Gasification and pyrolysis for liquid biofuel synthesis, to be used in engines, have a TRL of around 4–5. Biorefineries, specifically low-quality feedstock and thermochemical-based ones, are at the early research and development phase with TRLs of 3–4. Various forms and types of polygeneration are found in literature. The existing polygeneration operations are not carried out on a commercial scale. Flexible polygeneration systems available in the literature are largely theoretical studies. A few experimental and pilot plants of polygeneration are also considered in a few studies: • 190 kW biomass fixed bed gasifier (location: Danyang, Jiangsu province of China), • smart polygeneration microgrid (location: Thermochemical Power Group, University of Genoa, Via Montallegro 1, Genoa, Italy), • solar thermal polygeneration plant in United Arab Emirates, • overall thermal efficiency of the trigeneration system is 63% (can run on neat plant oils, 9.9 kW), • biomass gasification plant (location: Austria, Oberwart, 8.5 MW fuel / 2.8 MW el).	[22] [10] [11] [12] [13] [7] [16] [21]	TRL for flexible polygenera-tion depends on the used technologies the feedstock used and the produced outputs.
What are the R&D needs?	The plant design of polygeneration to date has mainly focused on the use of coal, even though renewable-based polygeneration has a higher capacity.	[10]	

	R&D could continue to develop advanced guidance and control systems, to achieve optimal integration of thermodynamic cycles in order to increase the electrical conversion efficiency. More R&D is needed to develop hybrid systems that combine biomass, biogas with hydrogen production, PV or concentrated solar systems, heat pumps, micro gas turbine and fuel cells. Further R&D is needed to integrate, optimize and demonstrate such systems at large scale.	[17]	
What are expectations, what experiences were collected?	Biomass-based polygeneration from the sun has various advantages such as reducing carbon emissions, increasing energy efficiency and overcoming the problem of scarcity of fossil fuels compared to stand-alone units. The outermost regions which are decentralized with polygeneration can increase energy access in areas that are difficult to access electricity. Most types of renewable energy cannot be carried away at any further place in producing energy; this is significantly different from fossil fuels. Solid fuels, such as biomass, have similarities with coal, such as hydrocarbons consisting of lignocellulose and cellulose. However, the complexity involved in gasification and combustion is different during operations.	[10]	
Indicate the capital costs and the fixed operation costs.	The capital cost and the fixed operation costs strongly depend on the type of polygeneration plant. However, the complexity involved in gasification and combustion of biomass is more complicated. Tar formation and ash fusion are also problems that arise when biomass is used. Study of a Flex Fuel Polygeneration plant that uses a combination of the primary energy sources natural gas and renewable natural gas: • capital Costs ($MM) $326.6 - $273.7 • operating Costs ($MM) $32.5 - $22.8 Smart polygeneration grid, experiments carried out on the test rig: • Fixed operation costs 0.07€/kWh – 0.290 €/kWh • Total operation costs 0.25€/kWh – 0.62€/kWh Oil palm biomass polygeneration plant enhanced cost of energy (COE) 1.1-1.3 $/kW.	[10] [18] [13] [19]	
What is the underlying	Flexible polygeneration offers an alternative to relying on grid electricity. It allows businesses to generate	[20]	

business case or incentives for the plant operation?	their own energy output on site, for both heating and cooling purposes, and have a stable, reliable and affordable electricity supply. Flexible Polygeneration is a cost saving and environmentally friendly energy alternative. Its supporters, nevertheless, highlight difficulties in embracing this technology and a lack of incentives for its use. Because market conditions (which can be highly variable) greatly affect the optimal process topologies, it makes sense to pay closer attention to flexible polygeneration systems. These systems can change the relative amounts of each product produced or feedstock used periodically (yearly, seasonally, weekly, or even daily) in order to respond to market conditions and make more profit than a static, unchanging plant would.	[23]	

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4.6 FAST RAMPING UP/DOWN A BIOMASS POWER PLANT

E.g. gas motor, gas turbines running on biomethane, MeOH, pellets, bio-oil etc.

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Currently, two general approaches for flexible fast ramping up/down of biomass CHP plants might be differentiated: **1) Conventional "solid-fuel" CHP-plants:** Conversion of the biomass fuel via total combustion and utilization of hot flue gases to produce power and heat. Generally, the produced power is immediately consumed. Important flexibility factors are the range of load settings and/or potential heat storage tanks. **2) Conventional biogas plants** Conversion of biomass to biogas by biochemical processes (biogas: CH_4, CO_2, N_2, O_2, H_2S, H_2, NH_3) **3) Advanced flexible CHP-plants based on syngas:** Conversion of (solid*) biomass fuels to the secondary energy carrier "biomethane or SNG" **. Subsequently, conversion of gas to heat and power. The secondary energy carrier "Biomethane or SNG" might be distributed via the natural gas grid and used in decentralized CHP plants for power and heat production. Flexible CHP-plants are generally characterized by a high-power quotient (PQ): $PQ = \frac{P_{nom}}{P_{rated}} = \frac{Nominal\ Power\ capacity}{Rated\ capacity}$ Rated capacity (P_{rated}) $P_{rated} = \frac{W_{el,annual}}{t_{annual}} = \frac{anual\ electrity\ generation}{hours\ of\ one\ year}$	1) &2) [1], [3], [4], [7], [9] 3) [2], [4], [7], [9] [6]	3) beside gas engines (as suggested in [2]) also other technologies for CHP production would be possible, e.g. gas turbines with a heat recovery unit for hot water and/or steam production. Also a combination with a steam cycle would be possible via a HRSG. Another option would be SOFC-fuel cells [5] * also, biogas could be further converted to Biomethane ** in principle, conversion to a liquid secondary energy carrier is also possible, but due to economic reasons currently only minor relevance [4]
What are its technical performance characteristics ? (e.g. feedstock(s), output(s), scale, efficiency)	1) Biomass CHP plants based on steam cycles (Rankine cycle) or ORC-processes (Organic Rankine Cycle). Most relevant types of turbines: Extraction turbines (and back pressure turbines). Feedstock: Woody biomass (wood chips, bark, landscaping residues), waste wood Scale: > 5MW$_{el}$ (steam: Ø ~2-10 MW$_{el}$, ORC: Ø ~1 MW$_{el}$) 2) Biogas plants	1) [1], [3], [4], [9] 2 & 3)	3) Example for

<table>
<tr><th>Question</th><th>Answer</th><th>Ref.</th><th>Remarks/ comments</th></tr>
<tr><td></td><td>Utilization of biogas in block-type systems with gas engines

<u>Feedstock:</u>

Energy crops, liquid manure, waste

3) Biomass gasification plants in combination with CHP plants (e.g. block-type systems with gas engines, gas turbines with heat recovery systems, or CCGT (combined cycle gas turbine). Conversion of biomass fuels to biomethane (= secondary energy carrier) by thermo-chemical (or biological) gasification of fuels (syngas), cleaning of syngas and subsequent methanation cleaned syngas.

<u>Feedstock:</u>

Biomass (note: conversion to CH_4 is in principal possible for all types of biomass fuels)

<u>Scale:</u>

Small-scale to large-scale possible (upscaling by operating a whole swarm of distributed, local CHP plants).

<u>Efficiencies:</u>

Conversion of biomass to Methane: 66%

Conversion of Biomethane to el. power (via gas engine): 40% (to Heat: 50%)</td><td>[2],
[4],
[9]
[10]</td><td>Switzerland: Based on [2]:

Fuel energy (Biomass): 22.8 TWh → Conversion to 15 TWh Methane → Conversion to 6 TWh power and 7.5 TWh Heat (80% (~5TWh) of power supply in the winter season)
η_{el}: 26.3%
η_{therm}: 33.0%
$\eta_{overall}$: 59.3%

Remark: Instead of biomethane also methanol might be produced as a secondary energy carrier</td></tr>
<tr><td>What are its flexibility characteristics ? (e.g. ramp up/down rates, turndown ratio etc.)</td><td>The main objective is the flexible supply of heat and power on demand with a high time resolution (short-term demand of power should be covered either positively or negatively).

1) Power supply based on steam or ORC-processes:

<u>Combustion system (furnace & boiler):</u>
Ramp up/down: 1 h to 1 day (depending on cold start, warm start, hot start).
Ramp down: -.
Turndown ratio: poor (long term).
Minimum (part) load: ~40%-50%.
<u>Turbine:</u>
Ramp up/down: ~30s to 50% of load.
Turndown ratio: few seconds.
Minimum (part) load: 0% (with steam bypass).
Extraction turbines most suitable for flexible adaption of share of heat and power output (e.g.</td><td>1)
[1]</td><td>1) -3) Arrangement: Several units in parallel (operation and control of a number of decentralized plants or even all available plants as a “plant cluster” or CHP swarm [10])

→ Highest flexibility, smoothing of limitations of single plants possible.</td></tr>
</table>

Question	Answer	Ref.	Remarks/ comments
	summer vs. winter season); flexibility: 100%-88% of power production (long time option). District heating system used as a thermal storage for times with decreased power demand (e.g. operation of turbine with steam bypass); flexibility: 100% - 10% of power production (short time option). 2* & 3) Power supply based on gas engines when residual loads due to lack of power from PV and/or wind occur. ▪ Ramp up: Seconds to 1 Minute, max. 5 minutes for cold starts (depending on the plant size and design). ▪ Ramp down: few seconds. ▪ Turndown ratio: good.	2 & 3) [2], [4]	* important flexibility criteria: gas storage and design of CHP units
What is the TRL? How many similar plants exist? Where is the example plant located?	1) TRL 7-8: Many plants exist, but currently the operation mode is thermal driven (subsidies for electrical power). <u>Example:</u> Bioenergy Waechtersbach GmbH (ORC 1.2 MW_{el}, 4.8MW_{th}). 2) Flexible biogas plants: TRL 7-8: In Germany around 2800 plants receive the flexibility premium*. 3) Biomethane of solid biomass: TRL 2: Single R&D projects showed principal feasibility (based on simulations).	[3] [4] [2]	*number refers to 2016
What are the R&D needs?	1) Power supply based on steam or ORC-processes: Controllability of furnace, boiler, turbine (specifically and in interaction with each other). Roll of (thermal and/or electrical) energy storages (flexibility and economic aspects). 3) Conversion of Biomethane for flexible power generation: i) New business models for CO_2 neutral electricity production. ii) Design of decentralized CHP swarms. iii) Controlling or energy management concepts of decentralized CHP swarms.	[1]-[4] [2]	
What are expectations,	1) Flexible operation currently economically not feasible (without additional incentives).	[1], [3],	

Question	Answer	Ref.	Remarks/ comments
what experiences were collected?	3) In principal the feasibility of the concept for flexible power generation was demonstrated.	[4] [2]	
Indicate the capital costs and the fixed operation costs.	Solid fuel biomass plants: Additional costs for flexibility: - Automation technology (5 k€-500 k€). - Additional heat buffer (0.1-1.2 mln €). Additional costs for (turbine) bypass installation marginally (amortization in about 2 years expected), general cost indications currently hardly possible. Exemplary <u>revenues</u>: Negative control capacity*: • 0.21 ct/kWh – 0.64 ct/kWh. Positive control capacity**: • 0.0 ct/kWh – 0.02 ct/kWh. Biogas plants General: Flexibilization costs increase with increasing power quotient (PQ): - PQ 1.5 (rated capacity of 800 kW): 33 k€ additional capital related costs per year for 10 years. - PQ2.1 (rated capacity of 800kW): 99 -118 k€ additional capital related costs per year for 10 years.	[4], [8] [3] [4], [6]	* low prices refer to TCC (tertiary control capacity), high prices refer to SCC (secondary control capacity) ** low prices refer to SCC, high prices refer to TCC Compared to biogas higher efforts for flexibility of solid fuel CHPs (e.g. biogas plants already offer a gas storage)
What is the underlying business case or incentives for the plant operation?	1 & 2) Higher revenues for power production in the framework of “control capacity production on the spot and balancing market” (revenues higher as shorter the time-frame)*. 3) Biomethane: In principal as 1 & 2) but economic constraint even higher → without reflection of CO_2-values in the business models (or prices) not competitive.	1) [3], [4] 3) [2]	* Traditional operation concept represents base-load-oriented production, commonly supported by fixed “feed-in tariffs (FIT)”. Flexible operation with direct marketing is typically supported by “sliding feed-in premiums (FPI)”.

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4.6.2 Appendix – Flexible power supply

Flexibility parameters

List of important flexibility parameters:

- Range of loads: minimum and maximum load
- Ramp up/down loads
- Turn down ratio
- Start-up times: Cold start, warm start and hot start*

*Differentiation of starting conditions (Source: https://de.wikipedia.org/wiki/Kohlekraftwerk)

- Cold start: Ramp up after stand by phases longer than 48 h
- Warm start: Ramp up after stand by phases between 8 h and 48 h
- Hot start: Ramp up after stand-by phases less than 8 hours

Five major kinds of actions can be identified to increase the flexibility of the power system [4]:

1. increase in flexible power generation by dispatchable RES (primarily bioenergy) and conventional energy sources (primarily natural gas power plants, but the flexibility of coal power plants and combined heat and power (CHP) plants can also be enhanced);
2. use of power storage systems and increased sector coupling (through power-to-gas, power-to-heat and power-to-mobility concepts);
3. demand side management;
4. grid extension for interregional transport and balancing; and
5. an improved integration of European electricity grids and markets (transnational transport and balancing)

Flexibilization opportunities

Following table summarizes technical flexibilization opportunities for biogas and solid biomass CHP plants according to [4]

Table 2 Overview of technical flexibilisation opportunities for different bioelectricity technologies (based on [11, 19, 36, 37, 49])

Bioelectricity technology	Power variation range "eOut" (%)	Timescale for power variation "ramp up"	Timescale for power variation "ramp down"	Technical potential for flexible bioelectricity supply[1] (TWh_{el})
Biogas plants	0–100	≤ 5 min (0% to nominal load)	≤ 5 min (nominal load to 0%)	40
Solid biomass CHP	0–100	0.3% point per min for 30–100%	1% point per min for 30–100%	10
Solid biomass gasification plants	0–100	1% point per min for 50–100%	10% points per min for 50–100%	10

[1]For estimating the technical potential for future flexibility provision from solid biomass plants, their current CHP electricity production level of 18 TWh_{el} provides an upper limit [36]; taking flexibility restrictions and a likely future reduction in production into account, the technical potential may amount to ca. 10 TWh_{el}

Flexible power production for biogas plants according to [10].

Table 1 Different kinds of flexible power for biogas, data based on Smart Bioenergy, Chapter Biogas [30]

Provision/shift	Marketing	Additional technical demands
Up to 5 min	Secondary control reserve (to balance the net frequency)	Control gateway, CHP adjusted to start stop operation
5–15 min	Minute reserve (to balance the net frequency)	Control gateway, CHP adjusted to start stop operation
15 min–6 h	Spot market—intraday (balance forecast errors, larger plant malfunctions, etc.)	Gas storage capacity, additional CHP capacity
6–24 h	Spot market—day-ahead (balance residual loads)	Additional CHP capacity, heat storage, additional gas storage capacityPotentially: process control, feeding management, adjustment of substrate and gas management systems
1–7 days	Spot market—day-ahead (balance residual loads, in particular macro weather situation)	Additional CHP capacity, heat storage, additional gas storage capacity, process control, feeding management, adjustment of substrate and gas management systems, long-term substrate storage
7–90 days	Spot- and derivative markets (balancing residual load, seasonal demand)	Additional CHP capacity, additional gas storage capacity, heat storage, process control, feeding management, adjustment of substrate and gas management systems, long-term substrate storage

Flexible power supply based on solid biofuels according to [10].

Table 2 Types and time frames of increasing flexible power supply based on solid biofuels, data based on Smart Bioenergy, Ch. 4 [106]

Flexibility time frame	Flexibility type (market)	Additional technical demands
<15 min	Secondary + tertiary control reserve (to balance the net frequency)	Steam bypass and/or storage (for steam cycle power plants); gas storage (for gasification + gas engine)
15 min–6 h	Intraday (balance forecast errors, larger plant malfunctions, etc.)	Advanced control strategies, heat storage
6–24 h	Day-ahead (balance residual loads)	Advanced control strategies, heat storage
1–7 days	Day-ahead (balance residual loads, in particular macro weather situation)	Long-term heat storage with high capacity
7–90 days	Day-ahead (balance residual load, seasonal demand)	Long-term heat storage with high capacity
90–365 days	Day-ahead	Increasing efficiency in part load operation, e.g., by applying constructive changes in combustion chamber or using modular designs

4.7 FAST RAMPING UP/DOWN BIOMASS HEAT PRODUCTION FROM STORED BIOMASS

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Supply of process heat* using thermo oil or steam (temperature level about 300°C**) and change from fossil fuel to renewable fuel-based systems (e.g. biogenic fuels or residues). In principal two options: 1. Systems with heat storage tank. 2. Systems without heat storage tank. Especially for systems without a heat storage tank the overall thermal load is reached by cascadic configurations of several combustion units.	[1] [2]	*Typical or often produced by CHP applications. Most of process heat demand in EU28 >500°C ([2] [4]).
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	Heat supply Thermal heat production via fuel combustion* (thermochemical conversion) in a specific furnace (combustion system). The design of the combustion system depends mainly on the used fuels and their characteristics and on the plant size. → Direct heating: Heat transfer directly from hot flue gases to the process (high temperature process heat, > 500°C). → Indirect heating: Heat transfer from hot flue gases to hot water/steam or to thermo oil (via heat exchanger/boiler) (process heat supply typically in the range of 200°C to 300°C, up to 400°C). Feedstock: Woody and non-woody biomass and residues. For the latter: Physical and chemical properties; increased ash content, emissions (esp. PM, NOx), potential fuel treatment (e.g. pelletizing) relevant for boiler and system design. Mixtures with wood enable also feedstocks with unfavorable properties (e.g. ash melding, fouling, etc.). Control concept (typical configuration): a) Cascadic operation of several units b) Only one combustion system	[1] [2]	In the EU28: 84% of the process heat is consumed in five industrial sectors: 1) Iron & steel 2) Chemical & petrochemical 3) Non-metallic minerals 4) Pulp, paper and printing 5) Food, beverages and tobacco *>90% of bioenergy generation relies on combustion [7]; Types of combustion of solid fuels: Directly or as part of gasification or pyrolysis processes (see Appendix).

Question	Answer	Ref.	Remarks/ comments
	c) a) & b) with integrated heat storage tank <u>Emissions:</u> Relevant emission limits for CO, VOC, PM, NOx (depending on fuels and plant size); flue gas recirculation and secondary emission abatement systems typically (e.g. ESP, SCR or SNCR).		
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	<u>Flexibility characteristics:</u> i) Compensation of formerly used fossil fuel boilers and decreased (or even no) need of fossil peak load boiler in the biomass fueled operation. Minor demand, or demand changes (e.g. short term) are covered by heat supply of a storage tank or by cascadic use of combustion systems. ii) Decoupling of heat supply and process heat supply via thermo oil circulation system (with or without heat storage options). iii) Frequently, the combustion system limits the flexibility of process heat supply (especially in the case without heat storage tank)*. <u>Combustion system (furnace & boiler):</u> ▪ Ramp up/down: 1 h to 1 day (depending on cold start, warm start, hot start). ▪ Ramp down: -. ▪ Turndown ratio: poor (long term). ▪ Minimum (part) load: ~40%-50%.	[1] [1] [5], [6]	* In the case of CHP systems based on steam: variable heat supply based on used turbine system (e.g. extraction turbines or back-pressure turbines with bypass).
What is the TRL? How many similar plants exist? Where is the example plant located?	TRL 7-8* <u>Example:</u> Process heat for a bakery (Schafisheim, Switzerland) via hot water/steam and thermo oil		*so far economic aspects are most relevant obstacles (especially competitiveness with gas and electricity tariffs for industry)
What are the R&D needs?	Adapted control concepts in combination with specific heat storage tank designs for configurations of biomass systems for minimized fossil fuel demand (peak load –	[1]	*<u>Examples:</u> Establishment of biorefineries in the chemical &

Question	Answer	Ref.	Remarks/ comments
	bivalent operation or even monovalent operation without fossil fueled peak load boiler). Controlling concepts and system configurations which enable fast load changes. R&D regarding business models or framework conditions* which make biomass-based systems competitive with fossil fuel systems. Develop strategies for further biomass process heat in industry. Develop and optimize cost-effective and sustainable biomass supply-chains.	[2]	petrochemical industry 8 Integration of steel plants with biomass upgrading (e.g. torrefaction) and production of chemicals [11].
What are expectations, what experiences were collected?	Technically, process heat supply based on biomass heating systems is feasible, however in comparison with fossil fuel combustion systems they are more complex (e.g. fuel logistic and storage, system components, emission requirements, ash management concept) and consequently, up to now, most frequently economically not advantageous (without subsidies).	[1], [2]	Economical valorization of CO_2 savings (carbon taxes) are mentioned as potential measure to increase biomass process heat supply (however global competitiveness of large industries should be respected) (e.g. [9]) Reduction of costs of upgraded biomass are also mentioned [10].
Indicate the capital costs and the fixed operation costs.	Range of wood fired heating systems (only heat supply): • Investment costs: 323-827$/kW$_{th}$. • Annual operating and maintenance costs (without fuel costs): 69-127$/kW$_{th}$. Costs of CHP-systems: see Fig. Appendix; specific investment costs depend on technology and electric capacity. Most relevant for biomass: steam turbines, ORC turbines, internal combustion engines (based on syngas from gasification).	[2]	Costs are quite variable and depend on: Conversion technology, type of emission control, feedstock storage capacity, potential pre-postprocessing of biomass.
What is the underlying	The business case is often not predominantly economically driven, but more based on	[1], [2]	Chemical & petrochemical

Question	Answer	Ref.	Remarks/ comments
business case or incentives for the plant operation?	idealistic considerations; e.g. marketing activities of companies, like a sustainable bakery with environmentally friendly production processes.		industry: Biorefineries are regarded as a promoter of biomass process heat since the production of chemicals and polymers gain an additional value [8].

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4.7.2 Appendix

Industrial process heat

Data about industrial according to [2] (data from [3]).

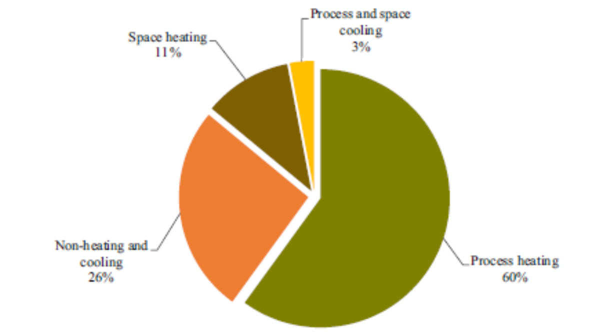

Fig. 3. Share of the different end-uses in the final energy demand in industry for EU28 in 2012 (Data source: [28]).

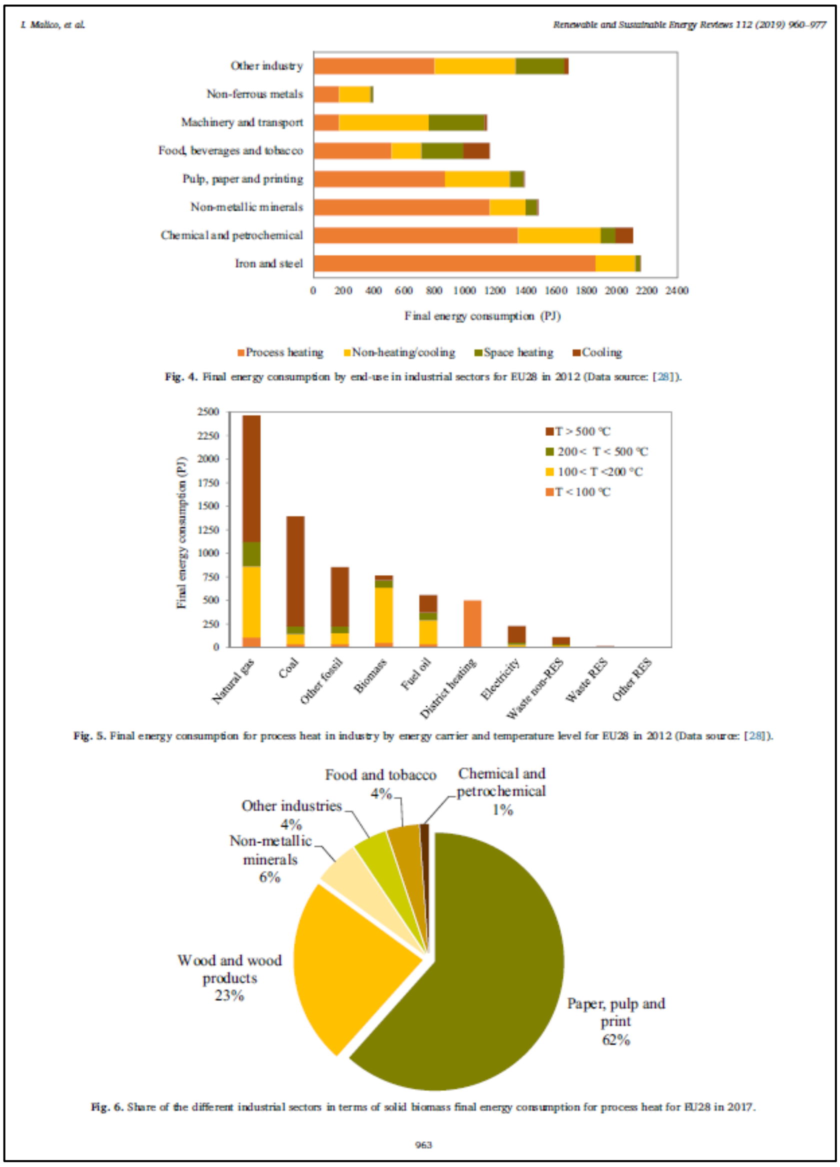
I. Malico, et al.
Renewable and Sustainable Energy Reviews 112 (2019) 960–977

Fig. 4. Final energy consumption by end-use in industrial sectors for EU28 in 2012 (Data source: [28]).

Fig. 5. Final energy consumption for process heat in industry by energy carrier and temperature level for EU28 in 2012 (Data source: [28]).

Fig. 6. Share of the different industrial sectors in terms of solid biomass final energy consumption for process heat for EU28 in 2017.

963

Possibilities of thermochemical conversion of solid fuels for heat production according to [2]:

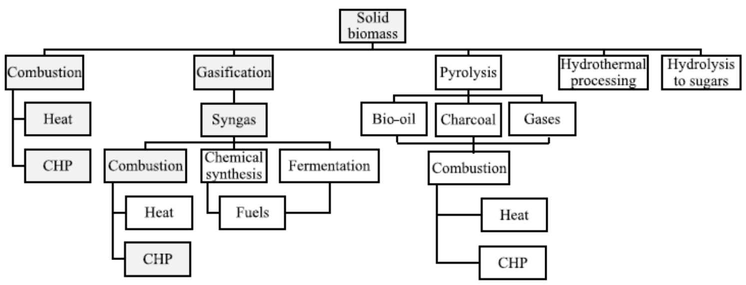

Fig. 12. Thermochemical paths for production of fuels, heat and CHP (solid fill indicates the technologies that are in a commercial stage and generally used).

Cost indications of (only) biomass heating and CHP systems according to [2]:

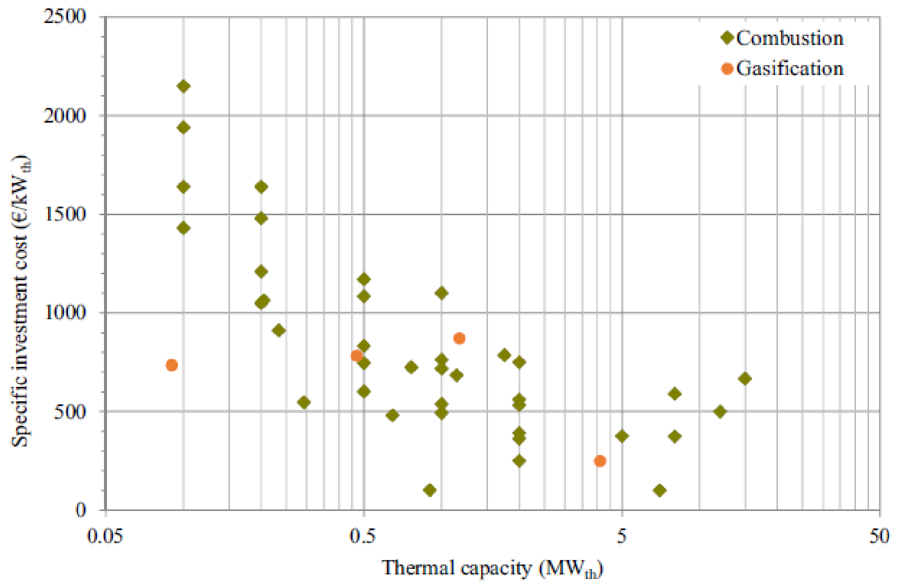

Fig. 13. Specific investment costs of biomass heating systems as a function of capacity (Data source: [60,147,150–153]).

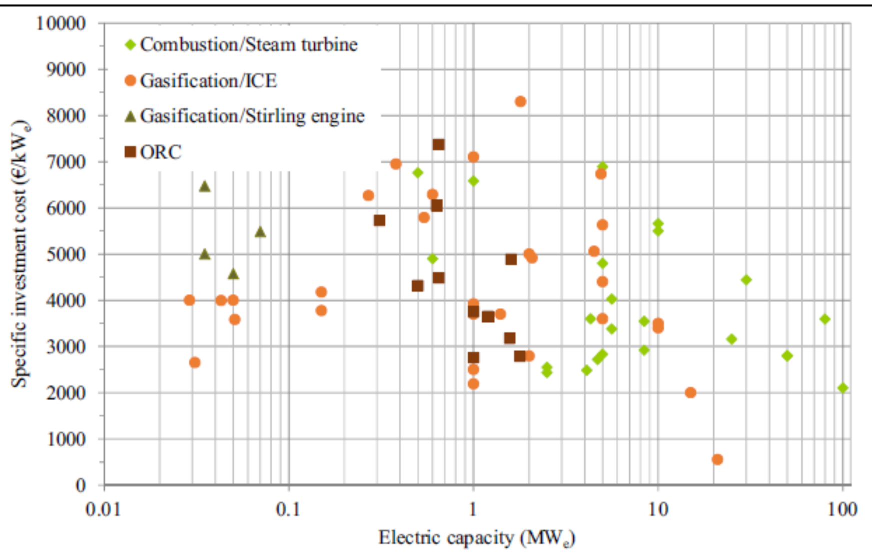

Fig. 14. Specific investment cost of biomass CHP systems as a function of capacity (Data source: [60,144,150–153,173–184]).

Flexibility parameters

Flexibility parameters for "Fast ramping up/down biomass heat production from stored biomass"

- Share of fossil fuelled peak load boiler (optimal: 100% of heat demand covered by the biomass system, no fossil fuelled peak load boiler necessary)
- Heat supply at the desired temperature level (thermo oil or steam)
- Load settings of the boiler
- Start-up times (cold start and warm start)
- Range of load (minimum and maximum load)

Question:

- Are those requirements achievable by systems without a thermal storage system?
- If no: What are important requirements for systems including thermal heat storage tanks (dimensions, control concept, etc. …)?
-

Examples

Examples of processes that offer flexibility to the energy system.

Long term flexibility service	**Short term flexibility service**	
Storage as chem. energy carriers: *e.g. pellets, biomethane/SNG/LNG, liquid hydrocarbons (MeOH, FT, DME), etc.*	Back-up/Peak generation of heat and/or power	Demand response, *i.e. taking up electricity that cannot be transferred or used otherwise*
Biogas upgrading, *e.g. membranes, scrubbers, …*	Flexible polygeneration (fuel/heat/power), *i.e. switching between fuel production and CHP operation*	Biogas upgrading with H_2 *(biological & catalytic methanation)*
Pyrolysis oil stabilization, *e.g. by hydrogenation*	Fast ramping up/down a biomass power plant, *e.g. gas motor, gas turbines running on biomethane, methanol, pellets etc.*	Flexible H_2 addition to enhance biofuel production, *e.g.* H_2 *enhanced BtL, Wood-to-SNG*
Thermal treatment (e.g. torrefaction)	Fast ramping up/down biomass heat production from stored biomass	Chemicals from stored bio-CO_2/CO and H_2, *e.g. methanol, FT-Diesel, methane, DME*
Hydrothermal treatment of wet biomass *(HTC, HTL, HTG)*	Biomass CHP with flexible power to heat ratio	Chemicals from CO_2 and H_2 *(biological process)*
BtL, Wood to SNG via gasification, biofuels by enzymatic processes	Microbial fuel cell running on wastewater	Electrons in fermentation

4.8 BIOMASS CHP WITH FLEXIBLE POWER TO HEAT RATIO

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Today's combined heat and power plants to produce energy from solid biomass are designed to provide either electrical power on a fixed level or to meet heat demand. The main existing types are working with a water steam cycle (with typical electrical power of more than 1 up to 20 MWel), Organic Rankine cycle (ORC) with 0.1 to 5 MWel, or a combination of gasification and gas engines with usually less than 500 kWel [1]. A high potential for further flexibilization of bioenergy from solid biomass may be achievable by implementation of small-scale CHP systems. Due to their size and low thermal inertia, these systems are considered to be highly flexible. As for solid biomass CHP plants, the technical potential for flexible bioelectricity supply is strongly dependent on the actual technology used [2].	[1], [2]	
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	• In steam-cycle-based power plants, a common way for negative control power is the bypassing of steam around the turbine, providing additional heat to heat grids or storages. • In power plants based on the Organic Rankine Cycle (ORC), relatively high flexibility. • In gasification-based CHP systems, relatively high flexibility.	[1]	
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	• Biogas plant: ≤ 5 min (0% to nominal load, ramp up), ≤ 5 min (nominal load to 0%, ramp down). • Solid biomass CHP: 0.3% point per min for 30–100% (ramp up), 1% point per min for 30–100% (ramp down). • Solid biomass gasification plants: 1% point per min for 50–100% (ramp up) 10% points per min for 50–100% (ramp down).		

What is the TRL? How many similar plants exist? Where is the example plant located?	Most CHP plants have a fixed power to heat ratio, in the moment there are not many plants with variable ratio. Plants: • A micro CHP-system for charcoal (fast controllability and the possibility for a power shift between thermal and electrical power. It can modulate from 18 to 100 % in normal operation and 36-100 % in power shift operation, location TU Chemnitz (Germany) [3]. • Harnosand (Sweden) 11.7 MWe/26 MW power to heat ratio 0.45-0.49, bubbling fluidized bed (BFB) [4]. In development are SOFC, e.g. with bio oil the heat-to-power ratio of the proposed system varies between 0.05 and 7.5 [5].	[3], [4], [5]	
What are the R&D needs?	For new biogas plants, a flexible mode of operation should in principle be ensured by e.g. the rule (in Germany) that funding is limited to annual electricity generation corresponding to a power rating of 50% of the installed electric capacity, as introduced in EEG 2014 [9]. The bigger challenge is therefore setting effective incentives for existing plants to switch to flexible modes of production, if this is associated with additional costs [2].	[2], [9]	
What are expectations, what experiences were collected?	The two major technologies which are available for large CHP-plants (more than 120 MW power output) are: •Condensing steam turbine with steam extraction. The heat to power ratio can be regulated by changing the amount of steam which is extracted. This technology is suitable if steam is available from other processes, and when fuels that are intended for indirect combustion are being used (for example oil or coal). •Combined Cycle with backpressure or condensing extraction steam turbine. This technology allows for direct combustion of gas in a gas turbine, and includes, in the same way as a CCGT, a gas turbine process and a steam turbine process. The heat can be produces either by applying a backpressure steam turbine or by steam extraction. Backpressure steam		

	turbines are used when a high heat to power ratio is wanted, while steam extraction is used for moderate to low heat to power ratios. Steam extraction allows a flexible heat to power ratio, while backpressure steam turbines imply a predetermined heat to power ratio.		
Indicate the capital costs and the fixed operation costs.	The results show that the operating strategies of cogeneration plants have a significant impact on their operating costs and profitability. The minimum heat demand of 40% is identified for which the CHP plant can be economically operated under the current conditions of power markets. Obviously, the profit of the cogeneration plant increases if the useful heat demand is higher than this value. The average prices recorded in the power markets were used to solve the optimization problem. The proposed model in [6] could be improved in future research by using an algorithm in which predicted prices are used.	[6]	
What is the underlying business case or incentives for the plant operation?	The potential capacities to flexibly provide combined heat and power are quite high, as today many small-scale boilers for biomass are used and almost as many could be switched to CHP Technologies [2]. The results indicate that product flexibility with variable plant product ratios (heat/electricity primary frequency response) and thermal flexibility have the highest value for the cogeneration plant (up to 16.5 M€ increased revenue for a 250 MWel plant), while operational flexibility (ramp rate) has a comparatively small impact (<1.4 M€). A wide load span and plant versatility, e.g. electricity and heat generating potential between 0 and 139% of nominal capacity, is beneficial in future energy system contexts, but has a marginal value in the current system. Electricity price volatility is a main driver that increases the value of flexibility and promotes operating strategies that follow the electricity price profile rather than the heat demand. Larger number of hours with high electricity price (Fig. 5) that makes combined electricity and heat generation profitable [7]. Flexibility in heat load enables electricity-following operational strategies [7]	[2], [7]	

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4.9 MICROBIAL FUEL CELL RUNNING ON WASTEWATER

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	A microbial fuel cell (MFC) can break down organic and other compounds in wastewater (WW) and can convert the breakdown energy directly in electricity. The technology is not in the demo phase although long time test has been done with stacked MFCs on real wastewater. Combined with WW treatment facilities, MFCs can improve the energy balance because it produces more electricity than sludge digestion and a gas engine. If the technology (and materials) improve it can be an addition to a WW treatment facility. Removal rates are currently not high enough to replace it completely. In future the system might give good results on waste streams from the food industry and can also work on WW. The hydrogen ions at the cathode might be used to produce biofuels such as ethanol, methane and hydrogen.	[1], [2], [5]	
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	Microbial fuel cells (MFC) are bacteria catalyzed fuel cells. They produce electricity from oxidation of organic and other compounds in wastewater and hydrogen ions which go through the membrane to the cathode space. A city with 100,000 population generating 16.4 million m^3 of wastewater over a year with a potential to produce 2.3 MW[5] of electricity (based on 300 mg/L BOD concentration[6]) which can be harvested in MFCs. Reported power outputs are 142-6530 mW/m^2.	[1] [2] [7]	
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	The technology is not that far developed that flexibility characteristics can be determined. In large scale test higher electricity production can be reached by pumping more wastewater through the installation.	[5]	

[5] 2.3 mln W/(16.4 mln m3/y *1/(365*24))= ~ 1230 Whe/m^3. Advanced wastewater treatment costs 310-400 Wh/m^3 [2]. [3] Germany 35.2 kWhe/ population equiv.
Wastewater treatment requires about 0.5e2 kWh/m3 which depends on the process and wastewater composition and interestingly, it contains about 3-10 times the energy required to treat it.

[6] 300 mg BOD/l= 0.3 kg/m^3. If we take COD= 2.3 BOD (factor varies up to 4) this is 0.69 kg COD/m^3. If anaerobic digestion produces 1 kWh/kg COD, one m^3 can produce 690 Wh. MFC potential 4 kWh/kg COD. Andere bron 1.66: 0.5 kg COD= 500 Wh. [3] noemt 1 kwhe/kg COD, but theoretical 3.86 can be reached. Reactor volumes: Anaerobic digestion 400 w/m3 volume; MFC 40 W/m3 (stacked 250 W/m3 reached) [2]

What is the TRL? How many similar plants exist? Where is the example plant located?	Concrete research started in the 1980s. After 2000 the microbial electrochemical technology (MET) platform became more concrete and MCF is one of the technologies. A 2018 publication mentions: Microbial Fuel Cell technology is currently at the laboratory level stage of analysis and evaluation [4]. Many lab tests are done with synthetic wastewater. Several large-scale test has been done with (stacked) MCFs of 45 (Germany), 72, 90, 200, and 250 L on real wastewater. The largest is a 1 m^3 MCF with 50 modules operated in Beijing, China. Depending on the specific system TRL level is 4-5.	[1] [2] [4] [5]	TRL level based on 2018 publication [4]
What are the R&D needs?	MFC reactors are still very small and removal rate range in lab conditions is between 0.005-5 kg COD/m^3/d. COD removal rate too low (for instance 60% in 8 days) and electricity production is currently low compared to potential biogas production. Currently expensive materials for the electrodes are needed: cheaper materials needed and higher contact area per m^3 anode space for the bacteria.		
What are expectations, what experiences were collected?	With a 45 l pilot MFC with 4 chambers on real wastewater the best results were a COD, TSS and nitrogen removal of 24%, 40% and 28%, respectively. Institute of Urban Water Management and Environmental Engineering, Ruhr-Universität Bochum.	[3]	7 months period
Indicate the capital costs and the fixed operation costs.	Objective: Organic removal rate of 5-10 kg COD (chemical oxygen demand) per m^3 MFC reactor/day is ~ equal to cost of 0.5 \$/m^3 wastewater. Positive energy balance and selling surplus of electricity. Also, reduction of the amount of sludge and lower disposal costs. Cost study 2008: Lab scale: cost 0.2 euro/m^3 wastewater (capital 0.4; offset -0.2). Large scale future: profit 0.3 euro/m^3 (capital 0.1; offset -0.4).	[2]	Costs from [2] fig 7
What is the underlying business case or incentives for the plant operation?	Wastewater treatment cost about 3-4% (~110 TWh/y) of the electricity consumption in the USA. Already anaerobic treatment costs less energy than aerobic treatment. It is possible to generate energy by digestion of the (carbon components) in the sludge. Microbial fuel cells (MFC) can break down carbon component in an anaerobic plant and directly generate electricity from it. It also leads to less sludge. A MFC can directly work on wastewater, but also on sludge (mixed with water).	[2]	Demand 0.5-2 kWh/m^3 wastewater. MFC produces theoretical ~ 2 kWh/m^3 (0.5/2=factor 4 times).

	MFC can be integrated in existing treatment plants (even at a domestic scale) or used separately. Depending on the situation MCF can (theoretical) produce up to 4 times the energy demand for wastewater treating.		

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4.10 BIOGAS UPGRADING WITH H2 (BIOLOGICAL & CATALYTIC METHANATION)

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	The CO_2 contained in biogas is converted to methane via a reaction with H_2. The reactor for this operation can be catalytic or biological. In the former case, the reactor is operated at 200-600 ˚C, in the latter at 35-70˚C. Often, further upgrading is necessary to recycle/convert unreacted gas and to reach gas grid injection specification.	[1–4]	Need for an appropriate gas cleaning to avoid catalyst deactivation.
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	The reactor works with a CO_2:H_2 mixture of 1:4 mol:mol. CO_2 can be originated from raw biogas, sewage sludge digestion, fermentation or direct capture from air. Cleaned biogas can be immediately used without prior separation of the CO_2. The scale depends on the biogas source; usually 1 or a few MW. The product is mainly CH_4 as the reaction is highly selective. The reaction is strongly exothermic and limited by thermodynamics, so that full conversion is difficult to achieve. Catalytic methanation reactors convert 80-90 % of the CO_2, so that a recycle of unreacted H_2 and CO_2 is necessary. This is usually operated via separation of CH_4 from H_2 and CO_2 through membranes. Alternatively, intermediate water condensation and a second reactor allow sufficiently high conversion to reach the injection specification of the natural gas grid. Biological reactors can reach higher conversion if not mass transfer limited. The efficiency of the system is around 83% LHV based or 78% HHV based (energy content of methane vs. hydrogen) at high conversion of H_2 (sufficient for grid injection). At lower hydrogen conversion, efficiency is higher due to the exothermic character of the reaction. The remaining energy is released as reaction heat and as condensation heat of the produced water.		Possibility to further process the released heat according to operation temperature (e.g. coupling with efficient SOE/high temperature electrolysis), district heating in case of catalytic methanation).
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	The flexibility aspect is twofold: i) raw biogas can be converted to a versatile energy carrier with transport and storage infrastructure and efficient use technologies. ii) electricity which cannot be used otherwise can be converted to hydrogen that then is stored for weeks up to months as methane in the grid. To allow incorporation of stochastic electricity, the technology has operation flexibility: <u>Catalytic reactors</u>: cold start–up in a few hours, start from hot standby < 30 min; possibility to operate at partial load (up to 20% of the nominal load). For fixed bed reactors, flexibility is possible by shift of the hotspot region. For		The out-of-specification start-up gas can be recovered by recycling, minimizing the amount of SNG wasted.

	fluidized bed reactors, flexibility originated by the large range of fluidization possible (interplay of flow rate and pressure). <u>Biological reactors:</u> cold start-up in 1 hour, short H_2 feed interruptions possible without problem (still need to keep the bacteria active).		
What is the TRL? How many similar plants exist? Where is the example plant located?	Cooled fixed bed reactors: TRL 7-8. Several plants existing in the world. Example of demonstration units: Werlte (D, 3 MW_{CH4}), Falkenhagen (D, ≤ 500 kW_{CH4}), Stuttgart (D, ≤ 150 kW_{CH4}), Foulum (DK, ≤ 50 kW_{CH4}). Fluidized bed reactors: TRL 6-7. Pilot and demo plants: Güssing (A, ≤ 1 MW_{CH4}), Villigen (CH, ≤ 200 kW_{CH4}). Biological reactors: TRL 7. Four demo plants (≤ 500 kW_{CH4}) existing in the world. Examples: Solothurn (CH), Allendorf (D), Avedøre (DK), Golden (US); commercial scale plant (≥ 1 MW_{CH4}) planned in Dietikon (CH).	[2–6]	
What are the R&D needs?	Reduction in electrolyser cost, optimization of the gas cleaning, sector coupling to increase the global efficiency and use of resources. Demonstrate dynamics and part-load for all technologies in sufficiently large scale (TRL 8). Use synergies with biogas sites: heat use, e.g. for high efficient high-temperature or steam electrolysis, fermenter, heating etc.	[6]	
What are expectations, what experiences were collected?	Technically feasible process, strong economic constraints. The main limitation for the development of the technology is the high cost of H_2. Further development of the technology is expected to provide electrolysers at lower prices and with higher efficiency. CAPEX of the methanation unit are also expected to decrease with large scale applications.	[7–9]	
Indicate the capital costs and the fixed operation costs.	OPEX are dominated by H_2 costs (up to 60%) and raw biogas costs (up to 30%). No consistent data or comparison are available for capital costs, but indications: Catalytic methanation at 1 MW scale: 1000-1500 €/kW_{CH4} Biological methanation: similar (no big differences) Electrolyser: 500 (future) - 1500 €/kW_{el} (today)	[8]	
What is the underlying business case or incentives for the plant operation?	The business cased is based on the operation of the methanation plant with (relatively) cheaper biogas to produce more valuable biomethane. Profitable operation can be achieved with low price of electricity and a sufficiently high spread between biogas and biomethane prices. Further, the system allows seasonal shift of energy, if hydrogen is consumed in summer, but the upgraded	[8]	

	biomethane is stored in the grid and used later. So far, no market incentives exist for this, but are expected in future.		

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4.11 CHEMICALS FROM STORED BIO-CO2/CO AND H2

<table>
<tr><th>Question</th><th>Answer</th><th>Ref.</th><th>Remarks/ comments</th></tr>
<tr><td>Briefly describe the existing or potential future process</td><td>The CO_2 collected from a biogenic source is stored and used as a starting material for the reaction with H_2 produced from excess renewable electricity. The product of the reaction are liquid fuels, such as methanol, di-methyl-ether (DME), gasoline, diesel or jet fuel.

Converting hydrogen into more common energy carriers, for which an efficient infrastructure (transport storage, end user technologies) exists, significantly expands the geographical, temporal and application range.

According to the desired product, a different catalyst and reactor type is used.

Methanol is a key intermediate in chemical industry as well as a final product, which can be used in internal combustion engines or as an additive for gasoline.

DME is an optimal diesel substitute and can be either directly synthesized from CO_2 or produced from methanol de-hydration.

Higher hydrocarbons can be synthesized directly from CO_2 in the modified Fischer-Tropsch synthesis (FTS) or from processing of methanol (methanol to gasoline MTG and further treatment).

Common features of the processes are:
• They produce heat, so that the reactors must efficiently release it.
• The desired products are obtained only in a limited temperature window (due to equilibrium limitation or selectivity issues), thus accurate temperature control is necessary.
• The products are formed at high pressure.

Besides methanol synthesis, the reactions considered are generally non-selective, thus further processing is needed, including separation and recycle of the unreacted species and purification of the products. In the case of</td><td>[1–4]</td><td>The processes operate with the CO_2 obtained from biogas upgrading (i.e. after separation of the valuable biomethane). The main drawback in case of direct use of biogas as feedstock is the processing of the methane contained in the biogas. This remains inert in the reaction, causing additional compression costs, increasing the equipment volume required and complicating the heat integration.</td></tr>
</table>

	fuel production through the Fischer-Tropsch synthesis, the raw reaction product must be further treated to obtain the final desired fuels.		
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	Methanol: high conversion and selectivity possible, however low conversion per pass attainable with the current technology. The demonstration plants currently available are in the order of magnitude of 1000 tons/y MeOH produced. The processes with recycle require electrical energy for the operation of the recycle compressor, thus decreasing the efficiency of the whole system. No plant so far is directly biogas-fed, but all operate directly from CO_2. DME: similar characteristics as the methanol plants. FTS: the plants produce a wide range of products and the CO_2 conversion per pass is limited, requiring for recycle and further treatment of the product mixture. In particular, when feeding pure CO_2, the reactions yields mainly unsaturated hydrocarbons, which need to be converted into paraffines in order to be used as fuel. CO_2 can be reduced to CO by endothermic reverse water gas shift reaction (RWGS) before the synthesis step, allowing the removal of water. In the BtL process, biomass can be first converted to a mixture of CO and H_2 (biosyngas and then fed in a standard FT reactor). In this case, the product follows a standard FTS distribution. The available scale of the BtL plants is in the order of 3000 t/y.	[5–10]	
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	Large scale plants show poor flexibility characteristics, as ramp up and down times are relatively long (need to bring to steady-state reactors with recycle streams). CO_2-to-chemicals processes are more suitable for continuous chemical manufacturing than for energy storage of intermittent energy. New and more flexible reactors are being studied, but are currently at low TRL.	[1]	
What is the TRL? How many similar plants exist? Where is the example plant located?	Methanol: TRL 6-9, various plants exists (e.g. Mitsui Chemicals in Japan and Carbon Recycling International in Iceland, Carbon2Chem in Germany). Liquid fuels: in demonstration, TRL 6-7 for BtL (e.g. plant exist in Karlsruhe and Freiberg D), TRL 2-4 for Jet Fuels (demonstration units realized	[1]	

	e.g. in the framework of the European projects Solar-Jet and Sun-to-Liquids).		
What are the R&D needs?	Process intensification to realize more robust and flexible processes; realization of intermediate processes for an easier handling and transportation of the biomass (e.g. in the form of bio-oil); development of new catalysts for the selective production of the desired compounds; reduction of equipment cost to have a lower product cost (at least to reach a similar price as the alternative routes from fossil fuels); reduction of operation costs through determination of possible process integration.	[1,11–13]	
What are expectations, what experiences were collected?	Processes are technically feasible; however, the economical operations is made difficult by various factors. Among these: the cost of electricity, the difficulties in collecting large quantities of CO_2 or biomass, the difficulty in manufacturing a single product with high market value. In general, to reach full maturity, the processes need to be simplified compared to the existent industrial productions and be adapted to the specific locations where biomass or excess electricity are available.	[1-14] [15]	
Indicate the capital costs and the fixed operation costs.	Methanol: for a large plant with recycle (ca. 1000 kg/d) the costs are as following: • Capital costs: ca. 500 €/(t_{MeOH}/y). • Operation costs: ca 700 €/t_{MeOH} On top of these costs, the prices of CO_2 and H_2 have to be taken into account, making the business case highly site-dependent. BtL: ca. 1 €/L of product. This is divided in: 60 % of biomass preparation and handling, 20 % operation cost. The remaining is the share of capital cost.	[12] [15]	The data for methanol are estimation for the operation of real-size plant (much larger than existing demonstration units). Data for BtL are estimation from the data of the existent plants
What is the underlying business case or incentives for the plant operation?	The underlining business case depends on the incentives for the consumption of CO_2 and on the price of electricity (and thus of H_2). Most of the processes here analyzed are currently 4-6 times more costly than the existing fossil-based alternatives. The operation of the biomass based processes can be profitable if at least one of the following conditions are realized: • The products are given a higher market price due to their renewable nature (to compensate for higher production costs).	[1,16,17]	

	• The cost of electricity is low (difficult to realize with the current technology, as the intrinsic inflexibility of the large plants does not allow for fully exploiting the times of low electricity price). • An incentive for the consumption of CO_2 is given (i.e. a negative price is given to CO_2 to favor its use as a feedstock). • Under these conditions, a process can be set up with profit. This is the case of the George Olah plant in Iceland, which can operate thanks to the low price of geothermic energy.		

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4.12 CHEMICALS FROM CO2 AND H2 (BIOLOGICAL PROCESS)

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Chemicals and synfuels can be produced from CO_2 and H_2. There are two main production ways: thermochemical or catalytic and biological. This factsheet focuses on biological processes. Both, CO_2 and H_2 can be produced with gasification of biomass. It is also possible to use the surplus of CO_2 from biogas or biofuel production. The potential is the same as for the chemical route. By adding hydrogen to biomass CO_2, the amount of energy carrier produced from biomass can approximately double. This factsheet focuses on 3 processes. 1) Making more methane, 2) Stopping methane production to collect the fatty acids and 3) making other products.		The second process is mentioned because it is related to the first. Fatty acids are produced before the methanation step in which additional methane can be produced with H_2
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	1) Biological methanation uses biological catalysts, i.e. methanogenic microorganisms, to catalyze the methanation reaction. For the optimal growth conditions these reactors work normally at temperatures between 37 and 65 ◦C and pressures from 1 to 15 bars. The Soloturn demo plant reported an electricity to methane efficiency of 76% (HHV basis) and 43-45% if the heat surplus at 60 °C is not used locally [3]. 2) Another way of producing chemicals with biomass is by blocking the methanogenesis reaction in biomass digestion reactors. In this way the volatile fatty acids will not be converted into methane and can be separated and sold as chemical feedstocks, for instance for biodegradable plastics. The energy recovery in fatty acid, and some H_2, is in the same range as with biogas (60-80% based on the lower heating value) [14]. 3) The company LanzaTech from Chicago has developed a biological process, a gas fermentation platform, which convert CO_2/CO and hydrogen in other products. Although they use the process for gasses from the steel industry, they also use gas from the gasification of biowaste [17], [18].	[3], [14], [17], [18]	Because there are three different processes. 1), 2) and 3) is used to distinguish them

What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	1) The flexibility of a good storable gas with an already available infrastructure is better than of a large waste stream. In case of adding hydrogen there is first the reaction time of the electrolyser (and the hydrogen storage capacity) secondly the reaction of the microorganism on the added hydrogen. The Soloturn demo plant could cope with load changes from 40 to 95 % with rates between 1.8 and 4.2 %/min without loss of quality [3]. According to [8] an electrolyser can respond to a power switch of 25% of its maximum capacity to stable hydrogen production within 1 second. Only when it starts at zero, but is already at temperature, a 25% increase can take longer (15 seconds) because hydrogen pressure has to be built up.	[3], [8]	The electrolyser can follow the electricity balance very quickly. With a small hydrogen storage, the biological plant can follow also.
What is the TRL? How many similar plants exist? Where is the example plant located?	1) TRL level for biological methanation is about 9. Electrochaea has built three commercial scale pilot plants for power to methane until 2019 [6]. These are stirred tank projects, which use CO_2 from biogas from wastewater digestion. The first test where at the Aarhus University's Biogas Research Center in Foulum, Denmark. Later on, it demonstrated the technology with the first one in the BioCat Project at BIOFOS wastewater treatment facility in Avedøre, near Copenhagen (gas injection into the grid in September 2019) [2]. This installation has a 1 MWe electrolyser and produces 550 kW (HHV) methane. Also, for the Store&Go project a plant started methane production (325 kW HHV) in May 2019 in Solothurn, Switzerland [3]. The last project is with SoCALGas and NREL in Golden Colorado USA (~125 kW HHV) [6], [7]. MicrobEnergy part of Viessmann has developed the BION process. Since 2015 a pilot plant is running in Allendorf (Germany): 0.3 MW electrolyser and 0.17 MW HHV CH_4 [12]. In 2020 it was decided to build a 13 mln € plant in Limeco (Switzerland) with a 2.5 MW electrolyser and a CH_4 output of around 1.45 MW HHV [13]. Biogas with 35% CO_2 will be fed into the reactor to be converted into CH_4. Electrochaea is involved in the development of a 46 l trickle-bed reactor (0.7 - 0.15 kW methane HHV basis). It was first tested in Regensburg in 2019 and later transferred to Ibbenbüren (Germany) to produces methane for injection in the national gas grid (the Orbit	[2], [3], [4], [6], [7], [9], [10], [12], [13], [17], [18].	TRL level estimates by TNO. Also, the steel gas plants of LanzaTech are mentioned because they are part of the same technology development.

	project stopped in December 2020); this reactor development has a lower TRL level. [4]. There are a number of other initiatives. A publication from 2019 mentions 38 active power to methane projects with a total production of 6 MW CH_4 (LHV) [9], [10]. 2) Based on literature the TRL level for fatty acid production by blocking the methanogenesis is around 3-4. 3) At the Jingtang Steel Mill in Caofeidian in Hebei Province in China a production plant started with a capacity of 46000 ton ethanol/y in May 2018 [17]. In 2020 a 16000 ton fuel grade ethanol/y plant did get the green light at a MRPL refinery in Mangalore in the State of Karnataka, India. This biomass gasification plant uses agricultural waste and will also produce biochar as fertilizer for the local community [18]. In Ghent (Belgium) ArcelorMitall and LanzaTech started building a 63000 ton ethanol/y plant using carbon monoxide from blast furnace gas and hydrogen. Because a third large plant is being build, the LanzaTech gas fermentation platform has reached TRL 9 [18].		
What are the R&D needs?	1) Main issue is getting the best methanogenic archaea for the reactor conditions and the optimal mix of nutrients, with lower costs. The archaea should stay alive when the reactor is not used. Another challenge is the low hydrogen gas-to-liquid mass transfer especially at 65 °C, which leads to lower space-time yields and the requirement of bigger reactor dimensions. So, research is done to several reactor types: Trickle-Bed Reactors (TBR), Continuous Stirred Tank Reactors (CSTR), Bubble Column Reactors (BCR), and Membrane Reactors (MR). In the reactors foam formation due to high cell densities of methanogenic archaea might give problems [1]. 2) Important are the right microorganism (depending on biomass source and desired fatty acids), PH, Redox potential, temperature (for instance for blocking the methanogenesis bacteria), and additives [15], [16]. Also, separation of the fatty acid from the waste stream is an issue. One source mentions fouling problems with membrane separation [14]. Finally, accumulation of total ammonia nitrogen	[1].[14], [15], [16].	

	(TAN) and volatile fatty acids (FVA's) might give problems [15]. 3) No specific information for the LanzaTech gas fermentation platform.		
What are expectations, what experiences were collected?	1) Stable methane concentrates > 90% in the output were reached [3]. Archaea stayed alive if the reactor was not used and directly started converting again when new hydrogen and CO_2 were added. 2) A substantial number of biowastes have been tested on lab scale for fatty acid production [16].	[3], [16].	
Indicate the capital costs and the fixed operation costs.	1) Current investment costs for a 5 MW CH_4 output methanation reactor are estimated at 600-900 €$_{2017}$/kW. Costs are expected to go down in future [3], [11]. Operating costs highly depends on electricity or hydrogen prices. In 2050 SNG production costs can be around 0.1 €/kWh (LHV) [11]. 2) Investment cost are estimated in $\$_{2016}$ at 65 mln \$ for 1.1 mln m^3/d wastewater sludge to 7-17 mln \$ for 200-250 wet tons/d food waste, swine sludge or fat oil and grease. Theoretical production costs of lactic or butyric acid are estimated on 0.5-0.8 \$/kg for wastewater sludge and 0.5-1.5 \$/kg for the other biomass sources. Market prices of the products is estimated at 1.4-2.4 \$/kg [14]. 3) The Steelanol plant in Ghent of 63000 ton ethanol/y request an investment of 165 mln € [19].	[11], [14], [19].	
What is the underlying business case or incentives for the plant operation?	1) Bio-methane from this plant is more expensive than natural gas. Business cases are built on the higher value companies, "green" consumers or governments which aree willing to pay for gas with no additional CO_2 emissions. 2) The value of a liquid feedstock is higher than biogas. But this liquid feedstock market must be willing to pay additional for the biobased origin. If developments are successful price might become competitive crude oil based feedstock. 3) For the steel industry it is a way to reduce their carbon dioxide emission. The Indian government reduces the air polluting emissions from burning of agricultural waste, generates additional income for local farmers and also		

	contributes to reach their 20% ethanol blending mandate by 2030 [17]		

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4.13 ELECTRONS IN FERMENTATION; ELECTROBIOLOGY

Question	Answer	Ref.	Remarks/ comments
Briefly describe the existing or potential future process	Electrolysis-enhanced anaerobic digestion (eAD) is used to improve the biogas production in a digester by adding electricity. Examples are published for co-digestion of manure [1] and digestion of wastewater [2], [3]. Also, Electro-fermentation (EF) is mentioned as more general technology name. Electrolysis creates oxygen and hydrogen. Oxygen causes micro-aerobic conditions which facilities hydrolyses (and more chemical oxygen demand (COD) removal) and reduce H_2S formation. Hydrogen is partly converted into methane. Not converted hydrogen becomes part of the biogas. Instead of methane eAD can be used to produce a larger number of other products like fatty acids when methane formation is suppressed.	[1], [2], [3]	Production of fatty acids is already mentioned in "Chemicals from CO_2 and H_2". This technology overlaps with the research field of "Microbial fuel cell". Here electricity can be added, in the fuel cell case electricity is extracted. Both are part of the research field of microbial electrochemistry.
What are its technical performance characteristics? (e.g. feedstock(s), output(s), scale, efficiency)	On a mixture of cow manure and switch grass COD removal raised from 0.6 to 0.9 COD/d and methane production raised with 26% [1]. Adding 2.8-3.5 V to wastewater sludge (0.2-0.3 W/l) increased methane production with 10-25% [3]. In general information in literature about the efficiency and energetic losses is limited [7].	[1], [3], [7]	
What are its flexibility characteristics? (e.g. ramp up/down rates, turndown ratio etc.)	No data available. Currently the focus is on more production of methane or liquid valuable products.		
What is the TRL? How many similar plants exist? Where is the	Only laboratory research: TRL level is estimated at 3-4 [6]. No sample plants; experiences with	[6]	

example plant located?	reactors on liter scale or smaller.		
What are the R&D needs?	According to [3], [5] the exact mechanism is not known, but there are several possible mechanism. There are test done with a membrane between anode and cathode, and later mixing of the streams and without a membrane. Better know how about why and when might increase development of this technology. Also exploring the role of electroactive microbes might increase the role of eAD [3].	[3], [5]	
What are expectations, what experiences were collected?	Electricity or electron transfer can improve the production of methane or other valuable products in fermentation. Further optimization and know how about the mechanism and more models are needed. Models "to witness the response of microbial consortia to harsh environmental changes, and the mechanism of microbial cooperation for metabolism under such conditions" [7].	[7]	
Indicate the capital costs and the fixed operation costs.	There is no clear picture of the costs. Focus is on lower cost of the anodes and lower costs of the membrane. The literature mentions for instance: "The economic feasibility of direct interspecies electron transfer stimulation in AD reactors is still questionable" [7].	[7]	
What is the underlying business case or incentives for the plant operation?	There are a lot of technology developments focusing on anaerobic digestion, see other factsheets with for instance making fatty acids or producing electricity. But finally, the amount of waste-feedstock is limited, and it is important to avoid food and feed production. Techno-economical assessments will be important for investors to decide which technology to choose [4].	[4]	

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