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Energy from biomass

Bioenergy resource base, provision technologies and integration concepts in energy systems with net zero climate gas emissions

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Summary. — Bioenergy is the most relevant renewable energy source today. Many technologies and concepts are implemented to provide heat, power and transport fuels. While biomass is a limited resource, so bioenergy provision needs integration, not only in the energy system but also in sustainable supply systems. The use of residual and waste materials will increase and needs mobilisation strategies and utilisation technologies. Due to different biomass potentials, energy infrastructure and energy strategies in different countries, even under the transformation towards more and more renewable energy-based energy systems the areas of bioenergy application remain diverse. However, flexible and hybrid concepts are gaining importance in all energy sectors; further technology development and digitalisation are pioneers. Additionally, the interaction with hydrogen and negative emissions is relevant in the long term and needs to be researched now.

1. – Introduction

Bioenergy is defined as energy derived from biomass. Biomass is a raw material of biological origin excluding material embedded in geological formations or transformed to fossilized material. Biomass can be processed into solid, liquid or gaseous fuels or stored

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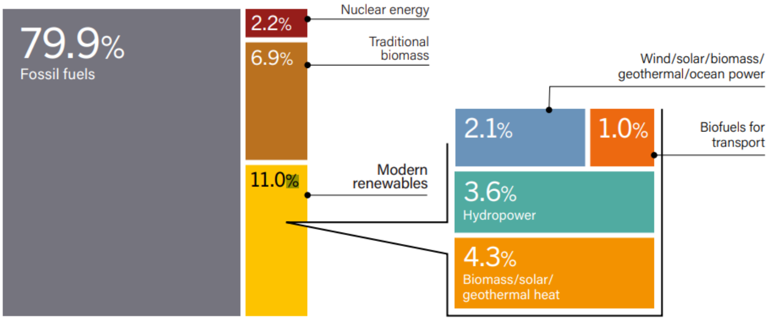

Fig. 1. – Estimated renewable share of total final energy consumption, 2018 [1].

energy in biomass can be directly converted into other forms of energy (*e.g.*, heat, light) (ISO 13065:2015).

Energy from biomass currently contributes on a worldwide basis 10% in 2018 to the gross primary energy demand (see fig. 1).

Due to geographical, economic, and climatic differences, the share of biomass energy in relation to total energy consumption differs widely between different countries, ranging from less than 1% in some industrialized countries like the United Kingdom to significantly more than 50% in some developing countries in Africa and Asia. Biomass is by far the most important renewable energy source, being significantly larger in energetic terms than the second largest, hydropower.

Cooking with biofuel is extremely rare today in rich countries although there is significant use of biofuel for space heating in regions with easy access to forests. However, because urban households tend to rely less on biofuels than rural households do. In a global context, the use of biomass in open fireplaces is still dominating the resource demand.

In parallel, the demand for electric energy is increasing in industrialized as well as in developing countries. Therefore, electricity production from biomass is often seen as an important future market for biomass worldwide. The same is also true for the production of transportation fuels from biomass.

2. – Biomass potentials

In principle, a wide range of resources can be used for energetic purposes, including biomass from agricultural and silvicultural primary production as well as by-products and residues from downstream industries and municipal wastes.

One important parameter for describing the biomass potential is the type of potential. Literature distinguishes between a multitude of different terms such as theoretical, technical, economic, sustainable, and realizable/available potential. The most frequently used types of potentials are:

> "The theoretical potential is the theoretical energy supply in a given region that can be used physically within a specific period of time (*e.g.*, the energy

> stored in the whole plant mass). It is determined solely by the given physical utilisation boundaries and thus delineates the upper limit of the theoretically realisable energy supply" [2].
>
> "The technical potential describes the portion of the theoretical potential that can be used, taking into account the given technical restrictions (*e.g.*, recovery rates, conversion losses). Additionally, the given structural and legal environmental or other limitations are taken into consideration since they are regarded, similar to the technical restrictions, as "insurmountable" (*e.g.*, legally [nature] protection areas, legally/administratively: cross compliance regulation, societal: considering food production and material utilisation). As a result, it describes —primarily from a technical point of view— time and location dependent, possible contribution of the biomass to energy supply" [2].

Many studies deal with the following question: what amount of biomass is available for energetic use now and in the future?. However, those studies cover a wide range of results and also changed over the time. The main differences among these studies are the consideration of different biomass, and also the expectation on land availability. However, compared to former trends the expectation for biomass from arable land are decreasing [3] and focusing on degraded land.

Biogenic residues and wastes are seen as becoming more important for energy generation. The majority of those biomasses has a low energy density and is therefore not transported over long distances (there are exception, *e.g.*, used cooking oil or recovered wood). For Germany, the bioenergy potential of biogenic residues and wastes is estimated at 0.93–1.22 EJ (0.54 EJ already in use, 0.39–0.68 unused). This corresponds to at least 7% of the national primary energy consumption [4].

Beside a necessary resource quality, the question of the origin and the according life path arises for the supply of biogenic resources —for material as well as for energetic use— in the context of available resource potentials. For instance, there is a significant influence in this regard whether a certain resource comes as residual material or is specifically cultivated. The latter as well has influence on direct or indirect land use changes. In the case of biofuels, transparency in the sustainability of the supply has already started with the help of certification systems. This assessment and certification framework shall be extended beyond biofuels in the future and shall have influence on potential assumptions accordingly [5].

3. – Bioenergy provision

Biomass consists primarily of carbon, hydrogen and oxygen (as well as other elements) and is produced in the photosynthesis of plants. The overall principle of energy generation from biomass is —the same as from fossil fuels— the oxygenation of carbon hydrates, which is an exothermal reaction. Heat released from the oxygenation is the base for our energy provision. It can be used for heating or further processed to electricity or

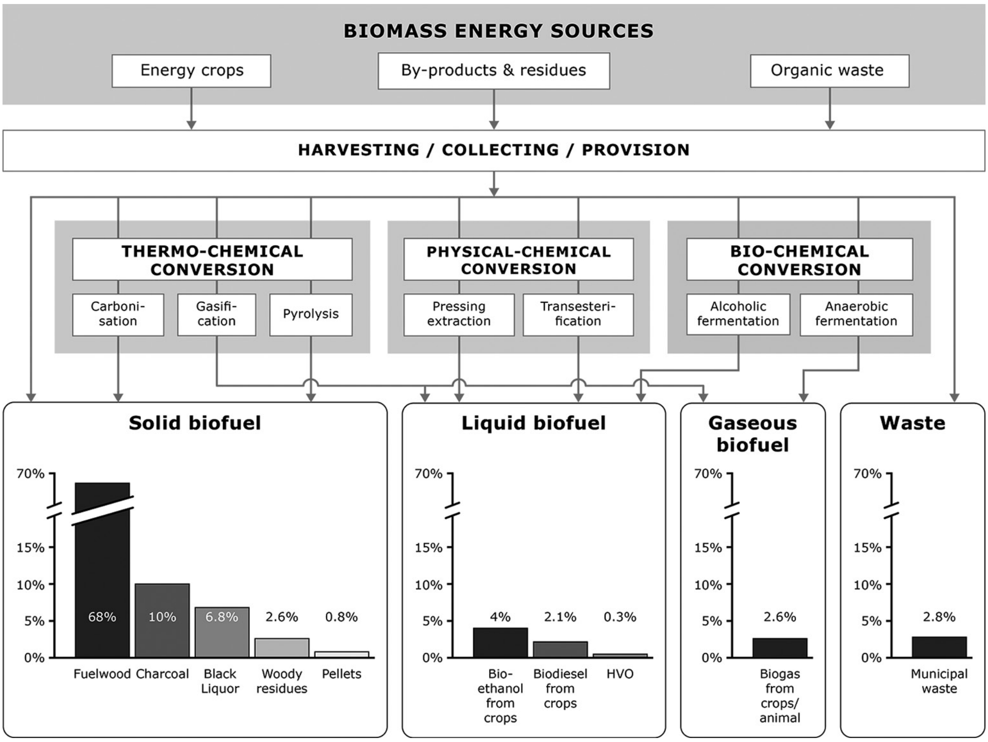

Fig. 2. – Bioenergy carriers [6].

mobility. The CO_2 from biomass or biofuel oxygenation does not have global warming effects if the biomass use is balanced with the biomass growing.

Most biomass used for energetic purposes is directly combusted to produce heat and/or power, but huge varieties of additional possibilities are available to provide environmentally sound heat and/or electricity as well as transportation fuels from organic material. The most important conversion routes available now or in the near future will be discussed according to the framework shown in fig. 2.

It is useful to consider two major forms of biomass fuel: unprocessed and processed. For unprocessed biofuel in which the material is used essentially in its natural form (as harvested) direct combustion usually supplies heat for cooking, space heating, or electricity production, although there are also small- and large-scale industrial applications for steam raising and other processes requiring low-to-medium temperature process heat.

Processed biofuels with clearly defined fuel characteristics allow for a technically easy and environmentally sound conversion into the desired useful energy. Such biofuels can then be traded easily and used with fewer problems to meet a supply task efficiently and comfortably. To ensure this, the following conversion routes are available (fig. 2).

– Thermo-chemical conversion summarizes all conversion processes of biomass into a solid, liquid or gaseous fuel based on heat. Therefore, gasification, pyrolysis and charcoal production count to these processes. From these possibilities, only charcoal production is state of the art and widely used so far. However, gasification in connection with electricity production is a promising option, which might become available in the near future.

– A physical-chemical conversion process provides liquid fuels based on physical (like pressing) and chemical (like esterification) processes. The most frequently used process so far is the vegetable oil production from oil seed and the transesterification of this vegetable oil to Fatty Acid Methyl Ester (FAME) as a substitute for petroleum-based diesel fuel.

– Bio-chemical conversion summarizes conversion processes based on biological processes. The most important possibilities are alcohol production from biomass containing sugar, starch and/or celluloses and biogas production from organic waste material. Both technologies are state of the art and widely used for energy provision.

Heat production is so far the most important use for biomass fuel worldwide. Direct combustion devices are widely distributed with thermal capacities ranging from a few kW in household stoves up to heating plants with several tens of MW. The conversion efficiencies vary from 8 to 18% for simple three stone stoves up to approximately 95% and above for modern heating units with high-end condensing boiler technology.

Within the biofuels, a distinction has been made between conventional and advanced biofuels. While conventional or first-generation biofuels are based on food and feed crops, the advanced biofuels use residues and waste biomass (2nd generation) or algae as feedstock (3rd generation). Apart from feedstock, conventional and advanced biofuels differ in technology maturity and GHG reduction. The technology of conventional biofuels such as biodiesel from oil crops, bioethanol from starch or sugar crops and biogas from anaerobic digestion is considered mature and is used commercially. The technology of advanced biofuels such as cellulosic ethanol, Btl, Bio-SG, methanol, bio butanol, DME or OME, hydrogen from gasification of woody biomass or biogas reforming is in research, demonstration or early commercial stage (see fig. 3).

Advanced biofuels additionally offer the prospect of requiring less land, lowering the competition between food/feed and fuel, improving the GHG balances due to the usage of residues and waste and thus reducing sustainability concerns for biofuels. Special interest for advance fuels is announced from the aviation sector. While road and trail transport can be electrified, directly by using net electricity or indirectly by using power-based fuels (Ptx fuels), the aviation sector will require liquid fuels in mid and long term. Thus, biofuels are one alternative to reduce GHG emissions in air transport.

A wide range of biojet fuels have been tested successfully. Technical standards/Certification for five biojet fuels have been established:

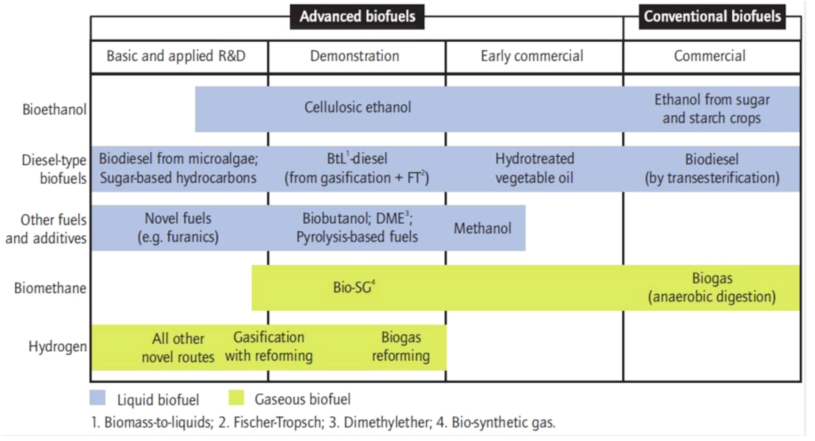

Fig. 3. – Maturity of biofuel technology [7].

- HEFA/HVO (Hydro processed Esters and Fatty Acids/Hydrogenated vegetable oil)
- FT-diesel (Fischer-Tropsch-diesel)
- SIP fuels (Renewable Synthesized Iso-Paraffinic fuel; renewable farnesane hydrocarbon)
- ATJ fuels (Alcohol to Jet Fuel)
- HPO (Hydrogenated Pyrolysis Oils; or: Hydrotreated Depolymerised Cellulosic Jet (HDCJ))

They can be applied as drop-in fuels without major changes in infrastructure or aircraft engines.

4. – Integration of bioenergy into the energy transition

The energy transition towards net zero energy supply systems is one of the biggest challenges for the next century. For bioenergy, the need for further development arises from the need of a sustainable biomasses sourcing and from increasing supply of fluctuating electricity from wind and PV [8].

The ongoing energy transition is mainly driven by reductions in the cost of wind and solar energy, and political efforts to reduce greenhouse gas emissions. Although substantial deployment of variable renewable energy (VRE) is an important part of the overall transformation, rapid changes in the energy mix may pose challenges to the resilience of the electricity grid, particularly in times of weather-related stress [9].

Flexible bioenergy can be arranged in different ways. However, biogas technologies already offer the possibility of short reaction times and buffering properties of gas storage that balance short- as well as long-term fluctuations. The system services comprise the provision of control energy and the offer of increased residual load coverage in times when fluctuating energies such as photovoltaic and wind power are not sufficiently available. On the energy markets, flexibly used bioenergy can thus achieve higher electricity market revenues. Additionally, innovative combined heat and power plants can combine an optimized heat supply with a stable power supply, even with a very high share of renewable energies.

In order to achieve these goals, flexibility requires the provision of corresponding capacities for power generation, remote control of the bioenergy plant via network-based communication and intelligent control concepts, also from the field of artificial intelligence. The efficiency of the flexibilization of block-type thermal power stations and biogas plants is described by the following dimensions, which can be determined for each unit: ramp (plant-specific load ramps), range (amplitude or control range between maximum and minimum plant output) and duration (maximum remaining in a certain load condition). In an "external" control loop, see fig. 4, external information from the higher-level network (*e.g.*, availability of other renewable energies, network utilization and energy market information) is digitally processed with internal plant information (*e.g.*, load situation, filling level and process parameters) in order to flexibly adapt the operating status of the plant along the dimensions ramp, range and duration to the current requirements via an "internal" control loop [10].

Bioenergy plants can primarily meet longer-term balancing requirements (fluctuations within 24 hours up to seasonal fluctuations), as they can use the fuel as a chemical energy store to supply electricity and heat as required. The associated information and communication technology have to meet a wide range of requirements, from network-based communication and standardized interfaces to decentralized and central information processing in order to optimally control the flexibility of the plant. Central data storage and digital information processing can take place via secure cloud services over the Internet.

Another approach is to build hybrid concepts of bioenergy with other renewable energies for certain supply systems. Especially in the heating sector many different combinations of bioenergy with heat pumps, with solar heating systems are possible [12].

Finally, also the interplay of hydrogen with bioenergy provides interesting options for the interplay of VRE and bioenergy. While the generation of hydrogen from biomass is only relevant for some niche applications, renewable hydrogen is an interesting option to increase biofuel yields or to build additional hybrid supply systems [13].

5. – BECCS

Finally, bioenergy can also contribute to accelerate for net zero climate gas emissions: Combining biomass for energy production purposes with CO_2 capture and storage (Biogenic Carbon, Capture and Storage) can be a cost-effective technology for reducing the atmospheric CO_2 concentration. For doing so, CO_2 capture can be realised 1) during biological processing (*e.g.*, fermentation), 2) in pre-combustion CO_2 separation when gasifying biomass to produce hydrogen-rich syngas ("producer gas"), 3) in post-combustion CO_2 capture as downstream unit in biomass combustion plants and oxyfuel-combustion

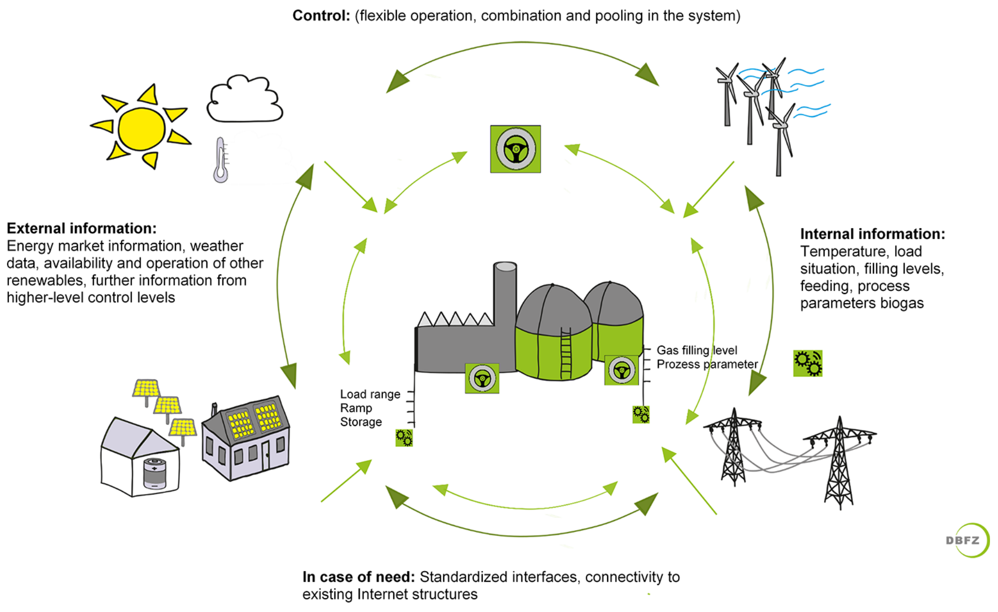

Fig. 4. – System elements and data flows for the flexibilization of bioenergy plants using modern information and communication technology [11].

CO_2 capture (*i.e.*, combustion of the energy carrier in pure oxygen rather than in air) when producing power and heat based [14].

This biogenic CO_2 is not burdened with climate-relevant emissions though the environmental impacts of BCCS technology pathways may vary greatly depending on design and characteristics of the processes. Once CO_2 is separated, it has to be compressed to obtain the necessary pressure for transporting the CO_2 to dedicated storage sites. Such suitable formations can be saline aquifers, depleted oil and natural gas fields, or unminable coal seams. Effective and safe long-term CO_2 storage is crucial with regard to storage site selection in order to prevent CO_2 leaking back into the atmosphere. Alternatively, instead of storing CO_2 underground, it can also serve as input to various applications that can commercially utilise CO_2 (*e.g.*, for greenhouses or algae cultivation; within enhanced commodity production (such as urea) or for the chemical industry). For BCCUS technologies, high-variability potential environmental impacts were found to be dependent on the choice of CCU technologies and CO_2 utilisation pathways [15].

The net-zero-energy road map of the IEA has included those different additional demands for bioenergy and presented a long-term vision in July 2021 [16].

6. – Conclusion

Bioenergy provision is embedded in national and regional energy systems, industrial infrastructure, land uses and value chains. Countries differ concerning biophysical conditions for bioenergy and other energy sources, geological CO_2 storage capacity, gas and electricity grids, public transport infrastructure, etc. A country-specific energy system transformation strategy for climate-friendly energy systems needs to frame the role of bioenergy. Due to different biomass potentials, energy infrastructure and energy strategies in different countries, the attractiveness of different bioenergy options differs among countries. We expect, that even under the transformation towards more and more renewable-energy–based energy systems the areas of bioenergy application remain diverse. However, flexible and hybrid concepts are gaining importance in all energy sectors. Further technology development (especially particulate matter) and digitalisation (predictive controls, interface standardisation) are pioneers. Additionally, the interaction with hydrogen and negative emissions is relevant in the long term and needs to be researched now.

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