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Five cornerstones to unlock the potential of flexible bioenergy

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Introduction

This paper is a summary of IEA Bioenergy Technology Collaboration Programme Task 44 to encourage collaboration and knowledge sharing, to raise awareness for the important potential of flexible bioenergy in sustainable energy system integration, and to explore issues and solutions to fully realise this potential. The target audience of this paper are people interested in energy policy, renewable energy, energy networks, as well as energy industry, fuel producers, regulators, operators, scientists and informed stakeholders.

A large portfolio of innovative technologies is needed to achieve sustainable development goals (SDGs) (Frankl 2020[i]). Achieving least-cost reliable and sustainable energy systems is a global challenge. Renewable energy sources are key for all energy sectors to achieve climate neutral energy supply till mid of century at the latest (IEA Net Zero by 2050 2021[ii]). Driven by favourable policy environments, market opportunities and substantial cost reductions, variable renewable energy (VRE) like wind and solar photo-voltaic (PV) are increasingly important energy sources to expand energy access and enable electrification based on clean energy. This essentially changes the structure and operation of the power systems, but also influences the renewable energy provision for heat and transport sector.

Bioenergy, which was in the past mainly applied for heating and cooking, is now a key option in fields where alternative renewable energy sources are difficult or costly to provide. Those options for bioenergy are for example seen in the aviation sector, heavy duty transport, in high temperature industry heat, but also in enhancing renewable energy supply systems for residential heating during cold seasons or for electricity, especially if it comes to higher provision from variable renewable energy (VRE) like wind and solar photo-voltaic (PV).

This paper describes the current role of flexible bioenergy in the energy system and identifies potentials and bottlenecks, future pathways and the need for further work, analyses, communication and collaboration.

The broad potential of flexible bioenergy

On the aggregate level, energy system flexibility is defined as the ability to effectively cope with variations in the supply or demand of energy. In this context, flexible bioenergy is defined as ***deployment of sustainable biomass to provide multiple services and benefits to the energy system under varying operating conditions and/or loads contributing to energy security*** (Schipfer et al., submitted). The definition of flexible bioenergy includes:

- utilizing sustainable biomass feedstocks of varying types and qualities depending, for example, on feedstock availability or accessibility due to meteorological or seasonal conditions or the impacts of climate change;
- trade and storage of bioenergy carriers such as wood pellets, biomethane and bioethanol, over longer periods to meet energy demand during winter months;
- flexible generation of power for grid stability and ancillary services for power systems;
- flexible and/or poly-generation of power, heat and fuels, according to market demand and trends, for example, matching seasonal demand patterns between power and heat or continuous changes in output shares of heat for residential heating and biofuels;
- flexible provision and processing of biogenic CO_2 converted to synthetic fuels (with for example hydrogen from PV or wind surpluses) or captured and stored (bioenergy carbon capture and storage (BECCS)).

Flexible bioenergy can support energy transformation in all energy sectors, but it might also bring benefits to agricultural value chains or industry, and also build an important element of a sustainable bio-economy, when using the biogenic residues in energy applications or for production of intermediates that can be used for energy or material purposes.

Energy supply systems with increasing shares of fluctuating renewables can be served with bioenergy in different conversion levels compensating fluctuating renewables but also increasing the value of hydrogen (Figure 1).

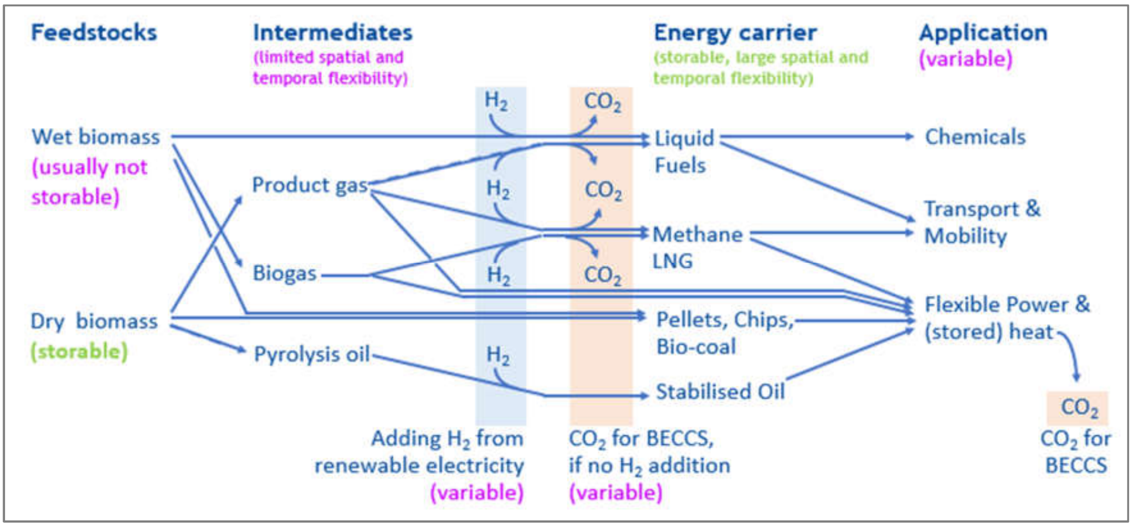

Figure 1: The network of flexible technologies in biomass related energy conversions (Source: Schildhauer et al. 2021[iii]; https://task44.ieabioenergy.com/wp-content/uploads/sites/12/2021/08/IEA-Task-44-report-Technologies-for-Flexible-Bioenergy.pdf)

While dry biomass such as wood or straw can be stored without decay or even further dried with solar thermal energy, biomass sortiments with high moisture content can form CO_2 and/or methane due to uncontrolled activity of micro-organisms. To use the energetic content of wet biomass (green wastes, food production residues, sewage sludge, manure), this has to happen in a controlled way, i.e. by well-known anaerobic digestion or fermentation to form biogas, alcohols or similar molecules. Alternatively, biomass with high moisture can be converted in hydrothermal processes (partly still under development) either to a mixture of methane and CO_2 or to liquid or solid energy carriers, e.g. by torrefaction.

Similar to biogas, also product gas from gasification and oil fractions from pyrolysis are intermediates that cannot be stored for longer time due to missing storage infrastructure or changing quality. Therefore, they all have to be converted to more standardised energy carriers for which quality specifications and (storage/distribution) infrastructure exists. These energy carriers can then be used for many energy services, offering a high degree of flexibility with respect to time, place and type of application including covering of electricity demand peaks.

In times with high share of fluctuating renewable electricity production and the emerging need for CO_2-negative emissions, it is an important feature of bioenergy that the production of most energy carriers allows either the addition of hydrogen from electrolysis or the removal of biogenic CO_2. While the latter can be sequestrated to realise negative CO_2 emissions, the former enables storage of electricity for weeks or months and sector coupling (e.g. Power-to-Gas). The reason lies in the fact that compared to the energy carriers, biomass contains too much oxygen and/or too few hydrogen molecules in its structure. The challenge for technologies developed is now to enable the hydrogen addition or CO_2 removal in a flexible manner to be able to adapt to the needs of the overall energy system where the flexibility also includes part load operation.

Flexible operation to serve the electricity sector

An increasing but also rapidly changing electricity provision is largely universal and make flexible resources in the power system essential to ensure that consumers can use electricity when needed.

Flexibility requirements change with increasing integration of VRE in the electricity system. IEA (2020[iv]) defined six phases of system integration of VRE (see Box 1). Rather than looking at specific shares of VRE deployment, the phases are defined by the typical sequence of challenges faced by system operators when more and more VRE sources are connected to the grid (Arnesen et al. 2019[v]). From Phase 3 on, investment in flexibility becomes a more and more relevant issue, which also has to consider the different time-horizons that needs to be covered: from short term flexibility, which mainly addresses power system stability to longer term stability requirements relating to weather and climatic conditions, as well as the availability of appropriate capacity and resources (Table 1).

IEA's "Six phases of system integration"

- Phase 1: No relevant impact on system integration
- Phase 2: Drawing on existing system flexibility
- Phase 3: Investing in flexibility
- Phase 4: Requiring adv. technologies to ensure reliability
- Phase 5: VRE surplus from days to weeks
- Phase 6: Seasonal or inter-annual surpluses of VRE
  -> Seasonal storage and use of synfuels/hydrogen

Box 1: IEA´s phases of integration of renewable energies in the energy system (IEA 2020)

Table: 1 Different timescales of electricity system flexibility (based on IEA 2020)

Flexibility type	Short term			Medium term	Long term	
Time scale	Sub-seconds to seconds	Seconds to minutes	Minutes to hours	Hours to days	Days to months	Months to years
Issue	Ensure system stability	Short term frequency control	More fluctuations in the supply / demand balance	Determining operation schedule in hour- and day-ahead	Longer periods of VRE surplus or deficit	Seasonal and inter-annual availability of VRE
Relevance for heat and power system operation	Dynamic stability	Primary and secondary frequency response	Balancing real time market (power)	Day-ahead and intra-day balan-cing of supply and demand	Scheduling adequacy	Energy system planning, including cogeneration of chemicals & materials

Those requirements are setting the scene to determine which types of flexible bioenergy can contribute most efficiently. For short term flexible operation certain key performance indicators have been defined by Dotzauer et al., which are illustrated in Figure 2. This includes the possibility of delivering energy and power in part load, at which speed (ramp rates) the energy provision can change and how long the maximum load can be delivered.

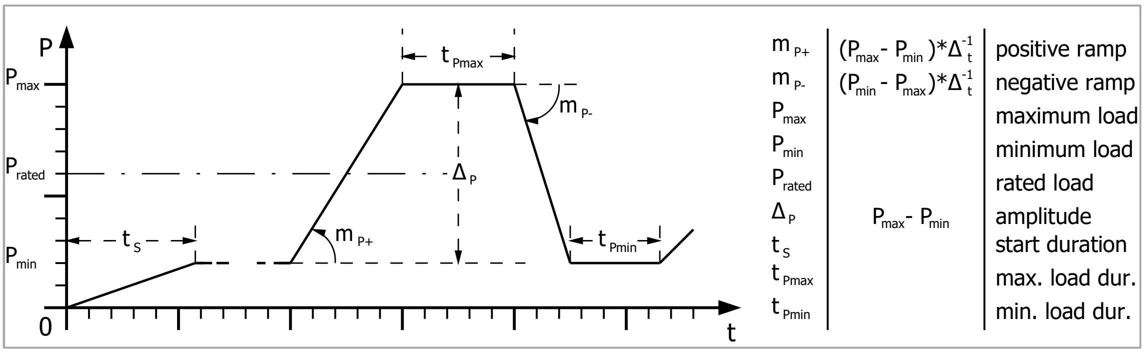

Figure 2. Illustration of direct measurable indicators for flexible power generation by biogas plants (power quotient and baseload ratio are not shown, but calculated based on P_{max}, P_{rated} and P_{min}). Source: Dotzauer et al. 2018[vi]

In addition, the availability of energy infrastructure (electricity grid, gas grid, district heating and cooling systems) as well as the availability of biomass for energy and – complementary - of other flexible renewable sources, such as hydropower, influences the priorities for flexible bioenergy. Finally, also targets for material use of renewable sources, i.e. in the chemical sector, influence the further development. So, it is difficult to define simple recipes or phases of introducing flexible bioenergy. However, at least the differentiation between systems ready to start and systems, which need more development is done in the following. Against this background, as a starting point for the further exploration and integration of flexible bioenergy, information on existing capacities and whether and how they are already used is necessary.

Where to start with flexible bioenergy provision

While flexible bioenergy in the electricity sector is expected to contribute to energy transition, flexibility is also relevant in other sectors. Currently, there are several best cases for flexible bioenergy already established in different countries. A dedicated description of these examples is given under Task 44 website[1]. The already realised flexible bioenergy generation covers both, flexible heat and power generation but also multi-product systems:

- Flexible heat and power generation: District heating systems are designed to provide flexible output of heating and cooling, but could also be better used to provide flexibility to the power grid, e. g. by more optimal use of power production in CHPs and installing units for peak load (both for heat and power using fuels like wood pellets and bio-oil) and units for quick ramp-up like biogas-based gas engines. In Finland, CHPs are also used in condensing mode if needed by installing coolers.

- Multi product systems: In Karlstad, Sweden, CHPs have been developed into bio-combinates producing not only power, heating and cooling, but also liquid fuel and biocoal (or biochar) by attaching a pyrolysis unit. Similarly, wood-based industries like pulp mills and sawmills can be developed to bio-combinates: In pulp mills, lignin can be extracted and used as feedstock for biodiesel, and in sawmills, sawdust can be used for pyrolysis.

- Increasing the resource base by using different feedstocks is an additional option to take advantage from flexibility: Ethanol plants can be developed to use both sugar or starch feedstock as well as lignocellulosic feedstock like straw (see best practice Muswellbrook, Australia). With fermentation or gasification an array of different biogenic feedstocks can be used to produce biogas that can be up-graded to biomethane for transport or used for power production. The biogas can be boosted with renewable hydrogen to increase output (see best practice case Werlte in Germany). Carbon dioxide captured from flue gases at biomass CHPs and pulp mills and from fermentation processes (ethanol plants and biogas plants) can be utilized to produce synthetic fuels together with renewable hydrogen (CCU - carbon capture and utilization). One such example is best practice case Liquid Wind project in Örnsköldsvik, Sweden.

In several countries, a flexibility premium encourages operators of CHP, e.g. biogas-based gas engines, to adapt the electricity production to the needs of the local power systems. This highlights that besides suitable financial or regulatory boundary conditions also adaptations to the technologies themselves are necessary to enable flexibility. This includes e.g. storage options for feedstock or intermediates in case of part load operation, but also more robust and flexible plant design to allow for variations in feedstock (quality) and to adapt the product spectrum (power, heat, chemical energy carriers) to actual demand situations. Further, in all applications more advanced control/automation strategies are needed and as a prerequisite, the suitable instrumentation of the plants. An overview over the respective R&D needs is given in the technology specific annexes of the report "Technologies for Flexible Bioenergy" (Schildhauer et al. 2021[iii]).

[1] https://task44.ieabioenergy.com/best-practices/

How to support the flexible bioenergy implementation

To unlock the manifold potentials of flexible bioenergy for future energy supply, the regulations and market design are seen as key (cf. to IEA Bioenergy Task 44 report Thrän et al. 2021[vii]). The implementation of flexible bioenergy is in its infancy, and the broad range of secondary benefits that bioenergy can offer is currently not very much understood yet. Additionally, the potentials are often described for certain energy sectors only (i.e. electricity) or for certain types of flexibility.

So far, only in some countries policy instruments for flexibility are in place. This is for example the case in the German Renewable Energy Law (EEG), where since 2017 the provision of additional capacities is mandatory for new biogas plants (Thrän et al. 2021, page 52). In Italy, since 2019 Mixed Qualified Virtual Units (UVAM) are supported that represent (eventually distributed) sets of electrical loads, production and storage capacities managed by a Balancing Service Provider (compare Thrän et al. 2021, page 72). Additionally, flexibility is also expected to be stipulated, when biomethane provision is supported (e.g. in Austria and in the US via the low carbon fuel standard).

Overall, only very few and very different policy instruments are in place, mainly focusing on the flexible electricity provision from biogas or biomethane. In the longer term, it can be concluded that additional efforts for implementation of flexible bioenergy might follow if there is a need within the energy system and efforts from including variable renewable energies are seen as a major challenge, especially in countries with limited access to other flexible renewable energies (Thrän et al. 2021).

Effective policy toolkits are needed to foster technologies at different maturity stages (Frankl 2020), including roadmaps to climate neutral energy systems on national level, incentives to introduce renewables and also to guarantee a stable energy supply, as well as research and development for technical concepts combining variable and flexible renewable energies.

How to integrate flexible bioenergy into long term energy system planning

Even if the implementation of flexibly bioenergy is still in an early stage, its need in renewable resource-based energy systems is highlighted in the IEA roadmap for “Net Zero by 2050” that considers the building sector, industry and power system, and forecasts a strong increase especially in latter two (IEA Net Zero by 2050 2021[ii]).

While we can expect an unprecedented expansion of intermittent renewable electricity production in the current decade, valorising flexibility on a business level remains challenging. This observation becomes even more striking, when considering that also long-term energy system modelling and planning does not include proper valorisation functions for the different types of flexibility options. Besides missing definitions and modelling tools, we notice limitations in data availability; this includes data of sufficiently high spatial and temporal resolutions of biomass feedstocks, regarding intermediary bioenergy carrier (solid, gaseous, liquid) markets, storage and stocks and market data especially for heat and bio-based chemicals.

Long-term bioenergy system planning also needs local and regional contextualisation: Flexible 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. The attractiveness of different bioenergy options therefore differs between countries. The value of dispatchable balancing power based on biomass may be high in energy systems with high shares of wind and solar power. Options for managing the variability of wind and solar power, such as demand-side management, storage systems, and (pumped) storage hydropower, represent alternative solutions. The roles of these different options as well as flexible bioenergy will depend on regional conditions, such as the transmission capacity and the availability of biomass and (pumped) storage hydropower.

Thus, bioenergy strategies cannot be developed in isolation from interacting systems like the actual provision and use, including the related investments, infrastructure and stakeholders. This is especially important because the actual biomass and bioenergy use is very different between different global regions and there is a lack of studies from key world regions, such as the BRIC countries as well as from the global South.

Flexible bioenergy also provides interesting synergies for the many upcoming hydrogen strategies. Potential benefits arise not so much from biomass-based hydrogen, but from bio-based processes and biomaterials as a flexible user of renewable hydrogen: hydrogen enrichment of the conversion processes can increase the fuel and product yields of the hydrocarbons in fuels, chemicals or other materials, and are often more efficient than power-to-X processes based on CO_2 that is captured from air or industrial combustions. Again, those potentials need further evaluation and consideration in long term energy planning.

Summary

Flexible bioenergy provides additional value to different energy sectors and can accelerate the transformation towards renewable energy systems. Five cornerstones for the successful implementation of flexible bioenergy systems are necessary

(1) The definition of the flexible bioenergy portfolio is still under debate. Importantly it needs to include not only the electricity sector but also multi-product plants, providing different energy carriers / fuels /chemicals, and hybrid processes in which biomass and other renewable energies and/or hydrogen are integrated.

(2) The policy and market conditions to support flexible bioenergy are still in an early stage. The value of flexibility is often created by cost reduction in the overall energy system. Most important is the development of appropriate support schemes to unlock the potential of flexibility in existing and new plants.

(3) Some best cases are already implemented. Monitoring of their success and multiplication of their experiences is key for a fast transfer in other regions. One relevant initiative in this field is the best case collection on the IEA Bioenergy Task 44 website.

(4) Technology development: the technologies currently in the market and many of those in research are not able to cope with feedstock, load or product flexibility, because in the past the concepts and in particular the control strategies where never designed and developed for highly demanding flexible operation. In particular short-term and medium-term flexibility will need a lot of R&D in the field of Automation and Control. Further, processes integrating renewable hydrogen should be developed in a way that they can cope with phases without hydrogen supply, e.g. in cold seasons due to a lack of renewable electricity for operating water electrolysis. Also, efficiently and flexibly recovering biogenic CO_2 to enable negative emissions may need changes in plant design.

(5) Appropriate consideration in long term energy system planning: the value of flexible bioenergy is often created by optimisation of the overall energy system. Long term energy system planning is often done with energy system modelling. To have the flexible bioenergy options integrated into those models is a precondition to optimise their possible value in sustainable energy transformation.

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