



**IEA Bioenergy**  
*Technology Collaboration Programme*

# Flexible bioenergy providing value to renewable energy integration

Foundation and way forward

IEA Bioenergy: Task 44

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## Introduction

This paper is based on the work of IEA Bioenergy Technology Collaboration Programme Task 44 and provides the status and needs of bioenergy as an enabler for renewable energy integration in sustainable energy systems. It addresses people interested in energy policy, renewable energy, energy networks, as well as energy industry, fuel producers, regulators, operators, scientists and informed stakeholders.

**Achieving climate neutral, least-cost reliable and secure 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 2023). Driven by market opportunities and substantial cost reductions, variable renewable energy (VRE) like wind and solar are increasingly important to expand energy access and enable electrification based on clean energy. This essentially changes not only the structure and operation of the power systems, but also influences the renewable energy provision for heat and transport sector.

**Bioenergy**, which was historically used for heating and cooking, is today the only mature alternative to fossil fuels in sectors such as aviation, heavy-duty transport, and high temperature industrial processes. As the share of VRE continuous to rise, bioenergy will play an increasingly important role in supporting the electricity system reliability - particularly during winter periods, night-time hours, and prolonged cloud-dark doldrums (see Figure 1).

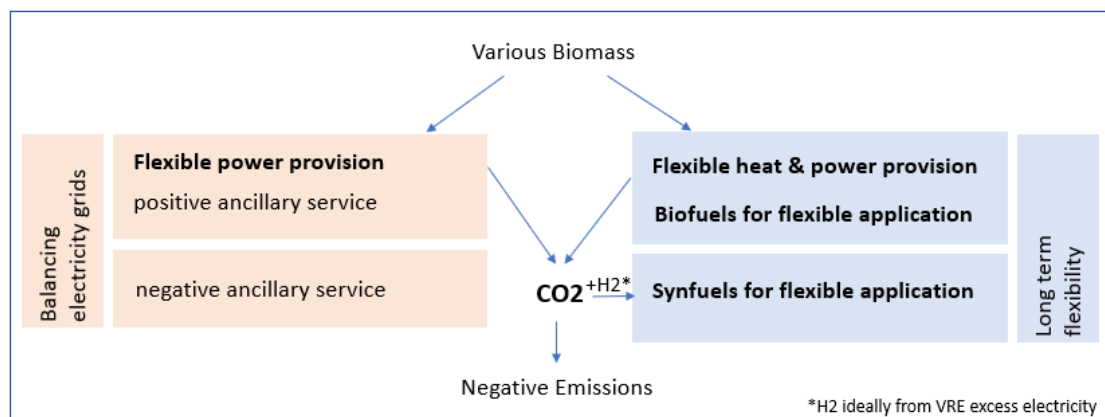


Figure 1: System integration in the renewable energy system and resulting energy and climate system services from bioenergy.

## 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 (Box 1). To serve a sustainable energy system, flexibility can be provided along the value chain of the energy system, at different time scale and geographical scale and with different scopes, such as balancing the system to increase efficiency and resilience (Schipfer et al., 2026).

**Flexibility of an energy system** is the ability to adjust supply, transmission, distribution and storage, and demand, across all relevant time and geographical scales considering all energy vectors, in response to changing conditions or policy objectives.

Box 1: Definition of Flexibility (Inter-TCP 2025).

More specifically, flexible bioenergy includes (see Figure 1):

- **utilizing sustainable biomass feedstocks of varying types** and qualities depending, for example, on feedstock availability or accessibility due to seasonal conditions;
- **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<sub>2</sub>** for various applications (i.e. synthetic renewable fuels or negative emissions).

With regard to energy system integration different markets are relevant:

**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 irradiation. The integration depends heavily on the bioenergy reactor types: anaerobic digestion is slow in flexibility, but if the produced biogas is stored or injected in the gas grid, high short-term flexibility can be realized. In biomass heat and power plants moderate turndown ratios are possible, while gasifiers have typically poor part-load performance. In heating services such as district heating, different biomass-based energy carriers can cover demand peaks, especially during very cold phases.

**Negative ancillary service** with biomass (e.g., for the uptake of surplus electricity, when more is produced than can be consumed at the given location or can be transported away) is less obvious. Currently, only few biomass conversion technologies allow the direct incorporation of electricity for process heat or within electrochemical reactions, but the topic attracts increasing R&D attention. However, when providing hydrogen from surplus electricity, bioenergy processes play a central role in the further processing hydrogen to renewable energy carriers such as methane (Synthetic Natural Gas), methanol, diesel fuel or other hydrocarbons. Those renewable energy carriers offer a key advantage: they can easily be stored and used across multiple energy sectors and support long term flexibility.

**Beyond the electricity market** long term flexibility can be achieved with biomass storage and using it strategically in response to market demand (e.g., focusing on heat and power production in colder seasons). The (seasonal) storability and transportability is proven for wood and some other types of relatively dry and highly dense bioenergy carriers (e.g. pellets from straw or grass, grain etc.). Wet biomass, however, has the tendency to decay or to be converted to CO<sub>2</sub> or methane by microorganisms if left untreated. Examples for such non-stable biomass categories are municipal waste, sewage sludge, manure, food (processing) residues, etc. In consequence, such feedstocks have to be converted to energy carriers with appropriate properties for storage and transport, i.e. by anaerobic digestion or through the combination with renewable hydrogen (see above). Bioenergy technologies can have consi-

derable flexibility in operation, i.e. the capacity of a digester, pyrolyzer, gasifier etc. to convert different feedstocks or biofuels, even in varying compositions.

**Some pathways and conversion technologies enable negative CO<sub>2</sub> emissions:** Biogenic CO<sub>2</sub> is an inherent by-product of all fermentations, anaerobic digestions and biofuels production and is a mature technology and already provides very pure biogenic CO<sub>2</sub>. In addition CO<sub>2</sub> can be recovered from flue gases from biomass combustion in CHPs or pulp and paper plants. The biogenic CO<sub>2</sub> can be added to renewable hydrogen to provide renewable hydrocarbons (as described above) or alternatively be used for negative emissions, when no renewable hydrogen is available (BECCS, Bio-Energy Carbon Capture and Storage). One challenge for technologies developed is now to enable the hydrogen addition or CO<sub>2</sub> 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 (Schildhauer et al. 2025).

**In many countries there is interest in a broad portfolio of flexibility options** (Figure 2). Moreover, efforts mainly are in a research, development and pilot stage; implementation support for those flexibility options is rare. 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) and has recently been increased (Bundesregierung 2025). Flexibility is also expected to be stipulated, when biomethane provision is supported, e.g. EU Methane Strategy with implementing activities in several European countries (Thrän et al 2024), when hybrid energy supply systems are promoted or when biomass storage systems are improved.

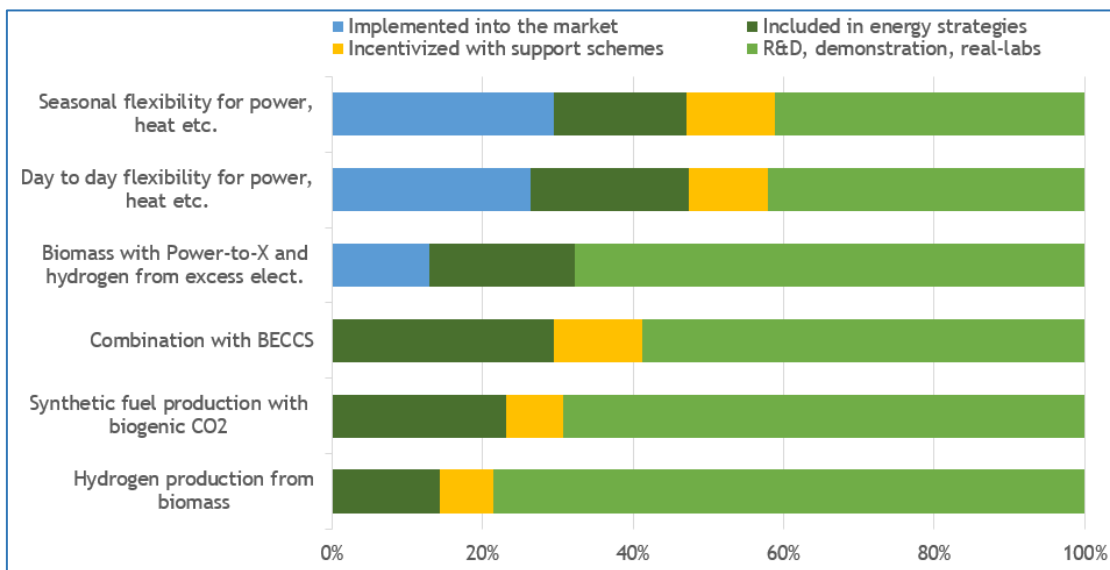


Figure 2: Status of bio-based flexibility option for different energy provision chains in 12 countries and EU. Austria, Australia, Canada, Denmark, EU, Finland, Germany, Italy, the Netherlands, Sweden, Switzerland, Türkiye, UK. Based on results from a survey on implementation of flexible bioenergy policies (data from Thrän et al 2024).

## Added value from flexible bioenergy today and in the future

With increasing expansion of VRE electricity production in the current decade, **first studies show, that flexible bioenergy has already contributed to cost reduction** in the electricity sector, especially in morning and evening hours (when photovoltaic is not available) and in winter periods (Dotzauer & Thrän 2025). The cost reductions highly depend on the specific countries energy system conditions. Tools for analyzing the added value are still in infancy stage and need further development.

**Valorizing flexibility on a business level remains challenging:** As there is no silver bullet for added value generation from flexible bioenergy, consideration of countries energy supply systems is relevant for the attractiveness of different bioenergy flexibility options. This includes biophysical conditions for bioenergy and other energy sources, gas and electricity grids, geological CO<sub>2</sub> storage capacity etc., and also monitoring of the development, as it is for example done in Germany (see Figure 3).

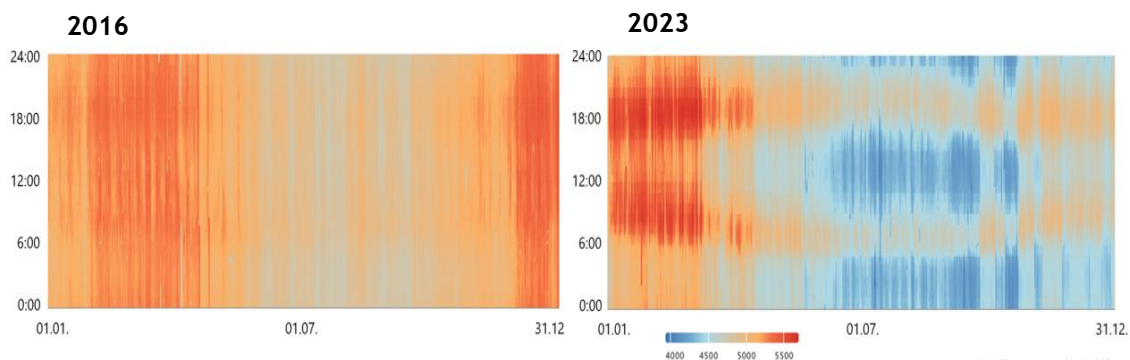


Figure 3: Public net electricity provision in Germany 2016 (left) and 2023 (right). The pattern show for every moment of the day (x-axis for 365 days of the year, y-axis for 24 hours). Source: energy-charts.info.

**Long-term optimization needs appropriate modelling:** Developing optimal flexible bioenergy strategies in renewable energy systems needs proper consideration of the various potentials in long-term energy planning. It is necessary that energy system models include valorization functions for the different types of flexibility options embedded in sufficiently high spatial and temporal resolutions of biomass and other renewable energy, transport, storage and the demand in electricity, heat and different transport modes as well as bio-based materials and CO<sub>2</sub>. Some examples for energy system models with those capacities are given in Box 2.

**Specific national strategies are key:** National bioenergy strategies are key to unlock the valorization potential of flexible bioenergy. While an increasing number of energy system models have flexible bioenergy included, the consideration in national energy strategies is still rare (Thrän et al. 2025). As flexible bioenergy provides interesting synergies with green hydrogen (Henning et al. 2025), the upcoming hydrogen strategies can benefit from the consideration of flexible bioenergy. This is also true for the upcoming strategies on carbon management and negative emissions (Styles et al. 2025). These synergies could become the focal point of national bioenergy strategies in some countries, while other regions other may instead prioritize the modernization of traditional bioenergy use.

## Examples for energy system models addressing flexible bioenergy and system integration

Energy system models aim to support long term energy system planning with possible futures (scenarios), in which the important drivers for the energy transition are well considered. The results from energy system models are what-if-pathways building a solution space and should not be confused with predictions. Important drivers for future energy systems include intended actions (such as social and environmental targets), possible technical solutions (such as the many flexibility options with bioenergy, mentioned in the last chapter), and additional implications (such as effects from climate change), all of which require systematic consideration.

Energy system modelling can express potential valorization of flexible bioenergy in future energy systems. Important to note: future energy system models should not focus on flexible bioenergy in isolation, but also carefully consider the important drivers, identify new pathways (e.g., through sector coupling), include high temporal resolution (i.e. for power supply and demand), to deliver real-world flexible solutions. Some examples are as follows:

*(High technological resolution)* Using scenario analysis in the **BENOPT** model with high technological details, Jordan et al. (2023) show that the domestic potential of digestible residues can play an essential role within the energy transition in Germany by providing energy either as flexibility option in the power sector or in hard to electrify areas of the heat sector. By coupling **REMix** and **BENOPTex**, Wullf et al. (2025) demonstrate that biofuel availability reduces e-fuel demand, thereby lowering cost-optimal hydrogen production capacity and grid expansion requirements in Germany.

*(High spatial resolution)* Higher spatial resolution also allows for the consideration of region-specific characteristics and flexibility options. Gøtske et al. (2025) link **PyPSA-Eur** with an **IAM** to enhance the temporal and spatial resolution of VRE representation while retaining a global geographical scope.

*(Sector-coupling)* More standard, but simpler, representation of flexible bioenergy is available in **TIMES** family models (e.g., **TIMES-Europe**, **JRC-EU-TIMES**). **TIMES** models often represent flexibility through sector coupling; however, some model variants have been adapted to operate at higher spatial and temporal resolutions.

*(Flexibility between material and energy use)* Using near-optimal solutions in **PyPSA-Eur**, Millinger et al. (2025) show that the value of renewable carbon in biomass exceeds its value as a direct energy source, which also leads to different flexible bioenergy provision in the longer term.

*(Resilience and risks)* Gutjahr et al. (2025) examine the flexibility between VRE and bioenergy in the German energy system using the risk-averse **stochastic BENOPTex** model. The results show that flexibility, when considering a broader variation of climate condition (i.e. droughts), substantially increase resilience and if not considered appropriate, energy transition might get delays and backfire climate change. Employing the **ZEN model**, De Marco et al. (2025) demonstrate that resilience-oriented planning leads to increased biomass boiler capacities in the heat sector.

While high technical solution always increases the potential value creation of flexible bioenergy, high temporal and spatial solutions as well as risk sensitivity can also reduce the solution space and favors adapted pathways for system integration (i.e. to contribute to resilient heat supply in certain regions).

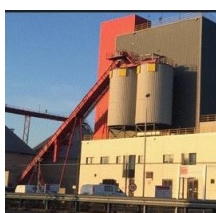
*Box 2: Examples, how flexible bioenergy is addressed in energy system models.*

## Initiatives and best practices

Following the different conditions between the countries, 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 (<https://task44.ieabioenergy.com/best-practices/>).



Below you can find selected examples of the broad portfolio:



**FROM BASE-LOAD BIOMASS CHP TO A FLEXIBLE ENERGY HUB, Land van Cuijk, the Netherlands:** BECC, Bio-Energy Centrale Cuijk, is transforming from a base-load solid biomass power plant to a flexible renewable energy hub, which is steered on optimizing operational margin instead of maximizing electricity output.



**E-GAS GENERATION FROM GREEN HYDROGEN AND BIOGAS, Werlte, Germany,** In Werlte, green hydrogen from renewable electricity electrolysis is converted to methane in a catalytic methanation process using carbon dioxide from a biogas plant. The plant operates when there is an oversupply of wind or photovoltaic power. The final product is grid-ready synthetic natural gas (SNG).



**THE ETHTEC LIGNOCELLULOSIC BIOETHANOL PILOT PLANT, Muswellbrook, Australia:** The plant provides sugars and lignin from lignocellulosic feedstocks, using the sugars in flexible production of ethanol, other liquid biofuels, food additives, bioplastics precursors and other biochemicals. Lignin is used for electricity generation and production of biochemicals.



**PIONEERING INITIATIVE TO PRODUCE RENEWABLE HYDROGEN FROM ETHANOL, São Paulo, Brazil:** This pioneering initiative aims to produce renewable hydrogen from ethanol in two production plants. The agreement includes a hydrogen refuelling station (HRS) for a university bus. Hydrogen reforming from ethanol enables local production of hydrogen and creates temporal and spatial flexibility through an intermediate bioenergy carrier.

**Automation is key.** In all applications advanced control/automation strategies are needed and as a prerequisite, the suitable instrumentation of the plants. 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 were never designed and developed for highly demanding flexible operation. Initiatives for standardization of automated control for both, hardware and software, are emerging in collaboration with several IEA Technology Collaboration Programmes (i.e. SHC TCP).

**Policy incentives can accelerate the implementation.** Many countries have bioenergy policies but do not consider the flexibility potential and the related system services. While investment support can initiate more pilot plant and best practices, the market mechanism for flexibilization and system integration are more complex. Depending on the specific energy policy of a country, technology independent support for flexibility serving dedicated energy

system services (i.e. grid stability, energy system resilience, further processing of green hydrogen) might be easier to implement. Low hanging fruits are for example the consideration of bioenergy when auctioning negative ancillary services.

## Foundation for added value from flexible bioenergy

Flexible bioenergy provides additional value to different energy sectors and can accelerate the transformation towards renewable energy systems. Five cornerstones build the foundation for unlocking the potential:

- 1) **Understanding energy system flexibility as a broad concept** including not only the electricity sector but also contributions to heat supply, transport fuels, grid stability, and energy security. This includes 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) **Unlocking the full technical potential with research and development** on short term and long-term flexibility options for different feedstocks and reactor types, including coupled concepts with different renewables (solar photovoltaics, wind, geothermal, (pumped) hydropower), as well as automation and control systems. 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<sub>2</sub> to enable negative emissions may need changes in plant design.
- 3) **Gaining experiences with pilots:** Demonstrators are necessary to test and improve flexible concepts in pilot operation. These demonstrations are essential to learn more about the technology, but also about business models and enabling policy environments in renewable energy systems.
- 4) **Developing and applying appropriate models and tools to optimize the added value** of flexible bioenergy in today and in future energy systems to provide decision support for country specific flexible bioenergy strategies. Tools and indicators for analyzing the added value are still in infancy stage and need further development. Where long term energy system planning relies on energy system models, these models must be capable of capturing the added value of flexible bioenergy.
- 5) **Implementing effective policy toolkits:** Flexible bioenergy plays different roles depending on a country's specific pathway toward a net-zero energy system. Because of this, policy support schemes also need to be tailored to national circumstances. The value of flexibility often comes from reducing costs across the overall energy system. Therefore, technology-neutral support schemes that reward flexibility services—such as grid stability, energy system resilience, or the further processing of green hydrogen—may often be the most efficient approach. In specific policy instruments supporting biogas, biomethane or other biogenic gases also storage, transport and automation should be considered.

**A foundation to build on:** Researchers and developers will continue advancing flexible bioenergy options, while system modelers will increasingly demonstrate the value these options add to net zero energy systems. Business models can grow, when the value of flexibility is considered in energy policies and support systems. Some best cases are already implemented. When done right, flexible bioenergy offers a huge potential for reducing the costs and increasing the stability of renewable energy systems.

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