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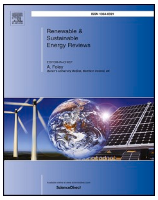

Status of and expectations for flexible bioenergy to support resource efficiency and to accelerate the energy transition

F. Schipfer [a,*], E. Mäki [b], U. Schmieder [c], N. Lange [c], T. Schildhauer [d], C. Hennig [c], D. Thrän [c,e]

[a] *Technische Universität Wien, E370-3, Gusshausstraße 25-29, 1040, Vienna, Austria*
[b] *VTT Technical Research Centre of Finland, Kivimiehentie 3, Espoo, Finland*
[c] *Deutsches Biomasseforschungszentrum, Torgauer Str. 116, 04347, Leipzig, Germany*
[d] *Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland*
[e] *Helmholtz Center for Environmental Research, Permoserstraße 15, 04318, Leipzig, Germany*

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ABSTRACT

We can expect a remarkable expansion and cross-sectoral deployment of PV and wind power in the current decade. The intermittent nature of these renewables, however, will evoke challenges regarding matching energy supply and demand. Studies and strategies that aim to solve this challenge tend to neglect the flexibility potential of modern and sustainable bioenergy, despite this being the leading renewable energy resource today. We explore the current status of, and stakeholder expectations for, bioenergy flexibility, drawing on recent questionnaire data gathered in the IEA Bioenergy TCP, including some of the authors of this study, to provide a technological and deployment status review for eleven countries. We present a wide range of commercially available bioenergy technologies that can offer flexibility services. We find that sustainable biomass can be deployed for multiple services and benefits to the energy system under varying operating conditions and loads, contributing to energy security beyond the power grid. Yet, practical deployment continues to be seen as little more than a niche innovation mainly due to limited 'landscape pressure' and considerable challenges in translating systemic, macro-economic and societal gains into an economic profit on a business level. Considering the large variety of flexibility services, we highlight that markets and frameworks have to be designed to sufficiently reflect the qualities and limitations of the different commodities or services. Therefore, we advocate for a heterodox energy economic debate to help settle fundamental questions about the effectiveness of different market designs based on empirical approaches, quantitative modelling, and basic analytical research.

1. Introduction

An unprecedented increase in global renewable energy capacity, especially in photovoltaic (PV) and wind power, was recorded in the last decade. World supply of renewable electricity from PV- and wind increased from 1.3 EJ to 7.6 EJ, driven by an average annual growth rate of about 250% for PV. Yet, this contributed to only 1% of primary energy supply and together with other renewable electricity sources, mainly hydropower, 5% in 2019 [1]. Thus, even this rapid development will need to significantly accelerate to meet the Paris goals [2]. However, PV and wind electricity generation are coined by their supply variability. Also, hydropower and smaller run-of-river plants exhibit flow regime variability [3]. To solve the dynamic puzzle between an increasingly intermittent supply and varying demand, flexibility will become a key feature on the producer and consumer sides.

The current understanding of flexibilization in the energy system only seems to focus on the electricity sector. Flexibility is defined, for example, as the power system's ability to cope with changes in PV and wind supply [4–6]. Flexibility services can be categorized into services for ancillary power markets, which 'manage transactions […] in short to very short term' [7]. Their aim is to balance network frequency and voltage fluctuations [7], provide backup in the event of generation and transmission disruptions or black-start support based on automated load adjustment [8]. Over a longer time frame, flexibility services provide power grids with system balancing, network congestion management, spot market trading, and dispatch on generation capacity markets [7]. Energy storage in different forms (for example, batteries, energy carriers or heat energy storage) can also provide crucial long-term flexibility service, as discussed in Ref. [9]. It is also worth considering how

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* Corresponding author.
E-mail address: schipfer@eeg.tuwien.ac.at (F. Schipfer).

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Nomenclature

BECCS	Bioenergy with Carbon Capture and Storage
Bio-SNG	biobased Synthetic Natural Gas
°C	degrees Celsius
CAES	Compressed air energy storage
CCGT	Combined cycle gas turbine
CHP	Combined Heat and Power
CNG	Compressed natural gas
CO_2	Carbon dioxide
DR	Demand response
DSM	Demand-side management
DSO	Distribution System Operator
EU	European Union
EJ	Exa-Joule (10^{18} J)
FiT	Feed-in-tariff
GHG	Greenhouse gases
IEA	International Energy Agency
LBG	Liquefied biomethane
MW_{el}	Megawatt electrical power
MW_{th}	Megawatt thermal energy
OECD	Organization economic cooperation and development
ORC	Organic Rankine cycle
PHES	Pumped hydro energy storage
PtG	Power-to-Gas
PV	Photovoltaic
RPS	Renewable Portfolio Standards
SNSP	System Non-Synchronous Penetration
TC	Transactive control
TCP	Technology Collaboration Programme
TSO	Transmission System Operator
TRL	Technology readiness level
UK	United Kingdom
U·S.	United States of America
UVA	Mixed Qualified Virtual Units ('Unità Virtuali Abilitate')
VQU	Virtual Qualified Units

flexibility services provide 'negative vectors' to the power grid to valorize surplus renewable electricity on different time scales or provide 'negative vectors' to the atmospheric carbon dioxide budget in terms of negative emissions. Technologies and measures often discussed in relation to flexibility services include, for example, peaker power plants, short and mid-term energy storage such as battery systems, pumped hydro energy storage (PHES), compressed air energy storage (CAES), demand-side management (DSM), virtual power plants and, in general, sector coupling of the electricity system to provide residential heating or energy for transportation. Discussions on long-term energy storage tend to focus on hydrogen and synthetic fuels produced from PV and wind electricity via power-to-gas (PtG). More traditional options include the extension of the power grid or the curtailment of PV and wind surplus generation, although this is resource inefficient and seen as a last-resort solution [8,10,11].

Different bioenergy options providing flexibility services, especially to the electricity system, have also been presented in literature [12]; discuss the potential for bioenergy, and especially biogas and combined heat and power (CHP), to enhance energy security in the German 'Energiewende' [9]. include in their energy storage review PtG based on biogenic CO_2 streams [8]. present CHP in general as a measure for energy system flexibility in their review for approaches, technologies, and strategies to manage variable renewable electricity [4]. notes the potential of CHP combined with thermal energy storage and multi-energy systems able to optimize different energy vectors such as gas, electricity and heat simultaneously [13]. review various options to provide flexibility from bioenergy, including electricity from biogas, electricity from liquid fuels, electricity and heat from solid biomass, and power-to-X [14]. recognize the need for a multi-carrier system including bioenergy to ensure the five properties of energy security - stability, flexibility, resilience, adequacy, and robustness. The scientific literature contains highly relevant and excellent reviews on biomass pre-treatment [15] and conversion technologies [16], how to model their respective supply chains [17] and their impact on competing end-use of biomass [18].

The novelty of the presented paper lies in extending the current energy system flexibility discussion (1) from short-term balancing services to long-term and seasonal flexibility and (2) beyond the power grid to the broader energy system and economic metabolism. While sustainable bioenergy can, for example, provide varying loads of power or heat to match demand patterns, bioenergy carriers can also be stored over longer periods. Furthermore, 'Feedstock flexibility' includes technologies utilizing biomass feedstocks of varying types and qualities, and 'Product flexibility' indicates switching between outputs, for example, to match seasonal demand patterns between power and heat. Still, a review focusing on or comprehensively describing flexible bioenergy options to support the energy system is currently unavailable to the best of the authors' knowledge.

The objective of this present review is to outline the current status and future expectations for sustainable bioenergy flexibility as a means to support **resource efficiency and accelerate the energy transition**. It should serve as a map to guide the scientific community and relevant policymakers, stakeholders, and shareholders in effectively advancing sustainable, modern and flexible bioenergy. Since the views on this topic vary between disciplines and world regions, it is necessary to perform not only a technological review but also a country and implementation status review, as well as a review on market instruments for valorizing flexible bioenergy. The sections of this paper are structured accordingly.

2. Material and methods

The International Energy Agency Bioenergy Technology Collaboration Program (IEA Bioenergy TCP) brings together leading scientists from over 25 countries in the fields of biomass gasification, combustion, biogas, biofuels, sustainability, energy technology system, supply chain, biorefinery, and flexibility. Over a dedicated three-year project on flexible bioenergy, the broader IEA Bioenergy TCP network was used to exchange perceptions and knowledge on the potential contribution of bioenergy practices to the flexibilization of the energy system. Smaller working groups were formed from discussions within the project consortium to collect technology and country-specific views. It has to be stated that the working groups' questionnaires and their evaluations and reporting did not follow scientific methods. In contrast, survey research would have to provide rigorously designed and pretested surveys, following quality control measures and using state-of-the-art statistical, analytical and reporting techniques [19]. We furthermore acknowledge 'that surveying can only be fully effective if there is a common understanding of terminology and a clear framing of survey questions.' [20].

Despite these severe limitations of the underlying work for the present paper, the gathered perceptions and information represent the currently best available dataset on the examined topic. Especially the lack of a clearly defined and commonly agreed-upon terminology was an important starting point for many discussions and out-of-the-box thinking. Synthesizing the findings for this review article proved to be challenging, but the results turned out to include an exceptionally high diversity of valuable viewpoints. The underlying processes of the working groups are shortly described in the following paragraphs. To transparently outline the missing quality criteria for survey research, the term ‘questionnaire’ was used instead.

As a basis for the technology review, a collection and clustering of flexibilization options for different conversion technology types were drafted, and respective experts within the IEA Bioenergy TCP network were asked to provide feedback on issues such as the Technology Readiness Level (TRL), Research and Development needs, expectations, technical performance and flexibility characteristics. An extensive technology report [21] was compiled, the key findings of which are summarized and discussed in this paper.

For the country and implementation status review, a questionnaire was designed to capture country-specific information, including statistical data on renewables and bioenergy implementation status, flexible bioenergy best practices, incentives, barriers, subsidy systems and policy frameworks, and this was distributed to dedicated country experts within the IEA Bioenergy network. Responses included in the present paper are limited to Australia, Austria, Denmark, Finland, Germany, Ireland, Italy, the Netherlands, Sweden, Switzerland and the United States. The results were compared and discussed, resulting in an extensive country overview [22], used as the basis of the present paper. The country review is limited, focusing on European countries, but should serve well as starting point for this discussion.

Finally, we follow up on one of the barriers for implementation – the missing market mechanisms to valorize flexible bioenergy – with a literature review, completing the scope of this paper. Here, we analyze energy economic literature on flexibilization of power supply and demand and supplement it with non-electricity flexibility dimensions identified in the technology and country reviews. Due to the novelty of this work, the literature review is limited to providing an overview only. However, we can outline the main barriers for flexibility valorization and respective research opportunities.

3. Results and discussion

This chapter starts with a review of bioenergy technologies (section 3.1) that can provide flexibility services to the energy system. Section 3.2 is a country and implementation status review outlining the current and expected pressure resulting in flexibility demand, existing policy measures, demonstration projects and limitations for further expansion. Section 3.3 reviews market instruments for valorizing flexible bioenergy since missing economic feasibility was the prevailing barrier mentioned in the questionnaire responses.

3.1. Bioenergy technologies providing flexible services

An immediate conclusion of this research points to the large variety of bioenergy solutions potentially providing flexibility services. To deliver a comprehensive overview for this paper, we group these technologies according to different flexibility service types, discussing each type in terms of its respective biomass types, energy products, intermediary bioenergy carriers, and implementation phase. A detailed review of the variety within each presented major technology family is out of the scope of this paper. Still, it can be found in the underlying report [21] or in critical review publications on biomass conversion technologies [16], biomass pre-treatment [15], how to model their respective supply chains [17] and their impact on competing end-use of biomass [18].

Flexibility is predominantly discussed in the literature regarding short and medium-term services to the power grid [7,8]. Bioenergy contributes short and medium-term flexibility to the energy system based on combustion in combined heat and power plants, anaerobic digestion and biomass gasification (see section 3.1.1). On the other hand, long term energy storage for balancing especially seasonal fluctuations is dealt with to a lesser extent. Biomass pre-treatment and bioenergy upgrading technologies could contribute to closing this gap. Thus, it appears essential to highlight the respective major technologies families, namely mechanical pre-treatment, pyrolysis and liquification, hydrothermal processes and upgrading biogas to biomethane or gas from gasification to biobased synthetic natural gas (section 3.1.2). ‘Negative vectors’ to the power grid and the atmospheric carbon dioxide budget furthermore summarize options to remove renewable electricity in times of surpluses and carbon dioxide from the atmosphere (section 3.1.3). Finally, we present the interconnection between the bioenergy technologies that can provide flexibility services identified by the experts in the IEA Bioenergy TCP (section 3.1.4).

3.1.1. Bioenergy conversion technologies for short and medium-term flexibility services

Biomass combustion for power-only or combined heat and power (CHP):

Dry forestry residues either in wood chips or dried wood pellets of uniform size are combusted for electricity production employing steam turbines or organic Rankine cycles (ORC). These technologies are state-of-the-art up to the scale of several 10–100 MW [21] and can be ramped up and down within minutes for ancillary services. Combustion can be modulated between 1/3 or half to full capacity, while the turbines allow 0–100% flexibility [13,16,23]. The process is dependent on feedstock, which can be stored, resulting in a typical combustion start-up time of anything between several hours and several days.

3.1.1.1. Anaerobic digestion and the deployment of biogas. Wet biomass such as sewage sludge, manure, food (processing) residues, green wastes and energy crops (for example, maize) cannot generally be converted efficiently by combustion due to high water content, although anaerobic digestion (AD) results in the production of methane-rich biogas [24]. report that agricultural residues, industrial- and bio-waste are the main deployed feedstocks. Sewage sludge plays a significant role in the fleets in Switzerland and Sweden, while the UK and Australia still exhibit high shares of biogas from landfills. After removing humidity and impurities (for example, sulfur species), biogas can be used in internal combustion engines to produce heat and power with an electrical efficiency of around 30% and a thermal efficiency of up to 60% [8]. Depending on the set-up, shares of the produced electricity and heat are used for electronic equipment of the digester, sludge dewatering and for reactor heating [25]. The microbes in the digesters favor continuous living- and process conditions rendering the digestion process rather inflexible. Still, inflatable storage tanks are regularly used to store the product gas for flexible combustion [26]. The gas engines can be operated between 0% and 100% with a start-up time of under 5 min. Their ramp-rate capacity and duration depend on the gas storage capacities [27].

3.1.1.2. Biomass gasification. Small scale gasification and gas engine systems for heat and CHP production are already commercially available and, in some countries, subsidized by government schemes [13,28]. They usually run on wood pellets, a relatively easy-to-handle dry fuel with very low ash content. Comparable to steam turbines and gas engines running on biogas or biomethane, wood pellet power output can be changed relatively quickly, and it can reach the necessary high temperatures within up to 24 h. This should enable continuous operation with moderate load change, while the gas engine itself can be ramped up and down between 0% and 100% within the space of 5 min. Like biogas-based CHPs, the capacity depends on the stored product gas [13,29]. Furthermore, the share between heat and power output can be adjusted flexibly via the amount of steam directed through the engine [28].

Standardized small scale gasification-based CHPs running on wood pellets already enjoy a significant market share [30]. For less expensive feedstock such as wood chips from forest residues or straw from agricultural residues, several gasification processes have been demonstrated successfully at scales of up to several 10 MW thermal input over several years [30,31]. 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. In contrast, economies of scale and efficiency gains provide potential business cases.

Typical demonstration 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), and the Pyroforce gasifier in Stans in Switzerland [31].

3.1.2. Biomass pre-treatment and bioenergy upgrading technologies for long term flexibility services

3.1.2.1. Mechanical pre-treatment processes. Classical, mechanical pre-treatment processes include chipping, pelletization, briquetting and bailing of biomass, which reduces transport and handling costs and better facilitates the storage and trade of densified bioenergy carriers [32]. Torrefaction, a mild form of pyrolysis, can further enhance relevant properties of the bioenergy carriers such as energy density, grindability and hydrophobicity [33]. A large number of publications focused on the impact of densification technologies on decreasing supply chain costs [15] to promote biomass commodification and trade [34,35] and to improve conversion efficiency, for example, through gasification [36]. However, the value of energy and carbon being reliably stored over a long time becomes particularly relevant in light of the flexibility discussion. We must also consider that existing infrastructure and markets, as well as the versatility of carriers such as pellets, given their varied energy and material purposes, contribute to long-term flexibility services provided by bioenergy.

3.1.2.2. Fast pyrolysis of wood. For fast pyrolysis of biomass, the raw material (wood or straw) is heated in the absence of air at 450–600 °C. This yields a biobased liquid of up to 75% of the dry input mass [37]. The flammable non-condensable gases (10–20% of dry input mass) with an average of 15 MJ/m^3 and/or the carbon-rich solids (10–25% of dry input mass) with 35 MJ/kg left over after the pyrolysis are used to provide the heat for the pyrolysis, improving energy efficiency [38]. The liquid fraction often referred to as bio-oil, has a high energy density and can be deposited in oil storages, transported via existing fossil fuel infrastructures and burned in standard oil boilers or further upgraded in refineries transport fuels [39]. Many oxygen-containing functional groups in the hydrocarbons lead to permanent chemical reactions within the oil, changing properties such as viscosity and stability [39,40]. By catalytic hydro-treating, that is, the saturation of reactive double bonds and removal of oxygen from the molecules, it is possible to stabilize the oil [40]. The first commercial pyrolysis plants are already in operation, for example, in Hengelo/NL with TRL 8 [41].

3.1.2.3. Hydrothermal processes. Biological processes usually convert wet feedstocks into aqueous phases. The full conversion is often not possible, and the left-over ('digested') residue still contains carbon and nutrients [42]. Therefore, hydrothermal processes have been developed that operate at relatively high pressures and temperatures, allowing for nearly complete conversion without causing the water to evaporate [43]. For different operation conditions, the products range from solid via liquid to gaseous state (carbon monoxide and hydrogen, if no catalyst is applied; methane and CO_2 with suited catalyst) [44] and contribute to the flexibilization of the energy system by providing storable bioenergy carriers as outlined in the discussion of pre-treatment technologies above.

3.1.2.4. Upgrading biogas to biomethane. While biogas can only be used on the spot, upgrading it by scrubbing the non-methane content to biomethane of higher purity allows bioenergy to be stored and transported using existing natural gas infrastructure [45,46]. It can then be used in existing, well-developed and efficient applications as a substitute for natural gas at room temperature, compressed natural gas (CNG), or liquefied biomethane (LBG). Liquified biomethane is largely considered a promising option for the decarbonization of heavy and long-distance transport [47].

Biogas upgrading primarily requires separating the CO_2 content from methane-rich natural gas. This is achieved using pressurized water scrubbers, chemical scrubbers, pressure swing adsorption or membrane separation, accompanied by desulfurization, drying and the addition of odorants for user safety [48–50]. Several biogas upgrading installations are already operational, particularly in Germany and Austria, where economic conditions are favorable.

[14] estimate that only 10% of existing gas storage facilities (in energy content) are necessary to meet the flexibility demand of a fossil-free energy system for power, heat and mobility. Stored biomethane can technically substitute natural gas and thus deliver long-term flexibility over several months through storage and distribution via the existing natural gas infrastructure [51]. discuss the concept of biomethane based CHP swarms connected via the storage infrastructure of natural gas grids, operated to serve as a virtual, flexible power capacity with a load range between 0% and 100% and a start-up time of under 5 min. Heat storage tanks can also provide thermic flexibility, for example, in the supply of hot water and heating in a building.

3.1.2.5. Upgrading product gas from gasification to biobased synthetic natural gas. Product gas from gasification of, for example, woody biomass contains large amounts of hydrogen and carbon monoxide. These components convert methane and other valuable energy carriers and chemicals such as Fischer-Tropsch Diesel, kerosene, gasoline, methanol, di-methyl-ether, and other substances with similar molecular structures. After appropriate gas cleaning, different catalysts and operation conditions (pressure, temperature) can result in different synthesis reactions [52].

The most developed process is the production of biobased Synthetic Natural Gas (Bio-SNG). In Güssung/Austria, a 1 MW$_{th}$ gasifier with Bio-SNG (TRL 7) was developed within the framework of the EU project BioSNG and, in Gothenburg/Sweden, a 20 MW$_{th}$ gasifier (TRL 8) was developed as part of the GoBiGas project [53,54]. Efficiencies higher than 60% were achieved for converting wood to synthetic natural gas [53].

Gasification with Bio-SNG provides a high degree of product flexibility. While gasifiers are used today to provide heat and power depending on seasonal demand, this product portfolio could be extended to synthetic natural gas [55], enabling the operators to react flexibly to even longer-term changing demand trends, such as improved residential heating efficiencies.

Processing to larger molecules than methane usually needs significantly higher pressures than methanation (5–16 bar) and even better process control due to inherent selectivity challenges [52]. As a result, the costs are higher, and efficiencies are usually lower. However, it is not entirely unfeasible, with processes established at the BioTFuel plant in Northern France to produce Fischer-Tropsch-Diesel at TRL 8–9 [21].

3.1.3. 'Negative vectors' to the atmospheric carbon dioxide budget and the power grid

The so far introduced bioenergy technology families have already extended the scope from short to medium-term power grid flexibility services in times of renewable electricity scarcity with long-term flexibility. Storage and trade of energy carriers that can be directly used for residential heating, industrial process heat or transport will play an essential role in providing seasonal flexibility and flexibility for longer-term demand trends.

However, flexibility is not only helpful to deal with resource scarcity but also with resource abundance. We thus coin the term 'negative vectors' to cover the efficient use of abundant resources. Based on the discussion in the IEA Bioenergy TCP on 'negative vectors', we find that the removal of surplus renewable electricity needs to be addressed together with removals of CO_2 from the atmosphere, providing flexibility services to the energy system but also to the environment.

Bioenergy with Carbon Capture and Storage (BECCS) aims to collect the biogenic CO_2 released in bioenergy applications and store it underground. This results in net-negative CO_2 emissions, improving the remaining CO_2 budget. For regular combustion processes, carbon capture and storage can be expensive [56]. However, in the processes of upgrading biogas to biomethane and in the production of hydrocarbons from gasification product gas, a relatively pure biogenic CO_2 stream is produced with no or little additional cost and energy effort [57].

In contrast to BECCS, bioenergy with carbon capture and utilization (BECCU) aims to collect the biogenic CO_2 and to (re)use it [58], for example, within the processor for generating other products such as e-fuels. Even though this does not result in net-negative CO_2 emissions, its application can mitigate emissions from fossil fuels. Furthermore, and in combination with power-to-gas processes, BECCU can provide flexibility services in times of abundance of PV- and wind electricity [57]. This has been shown for upgrading biogas via direct methanation of the CO_2 content [59,60]. There are several process options currently under development. Micro-organisms at around 35–65 °C and chemical catalysts, usually nickel catalysts at 300–550 °C, can catalyze the methanation reaction. To bring catalysts and gaseous reactants into contact, different reactor types are developed. Technologies such as the stirred-bubble-column for biological methanation and fixed-bed and fluidized-bed for catalytic methanation have meanwhile reached demonstration-scale [59,61].

3.1.4. *A network of bioenergy technologies providing flexibility services*

As illustrated in Fig. 1, a network of bioenergy technologies providing flexibility services was identified [21]. The discussed technologies encompass different feedstock types (for example., wet vs dry biomass residues), intermediate bioenergy carriers (liquid, gaseous, solid) and energy applications (electricity, heat, transport fuels). These technologies can provide flexibility services in the short to medium term, as well as in the long term for monthly or seasonal variability or even on sustainable demand trends such as decreasing residential heating but increasing biochemical demand, for example, for biobased insulation materials. Two leading energy and climate system services can be provided by capturing CO_2, especially from biogas or gasification product gas upgrading processes. Negative CO_2 emissions can be achieved if the captured CO_2 is used for sequestration. Alternatively, negative power services can be provided if the CO_2 is converted with renewable hydrogen from electrolysis to use PV and wind electricity in times of abundance.

We want to stress that a broad range of commercially available bioenergy technologies was outlined by the questioned group of international and interdisciplinary experts in the field of flexibility services [21]. These technologies, including gasification for heat, power and Bio-SNG, are flexibly deployed mainly in niche applications today and do not necessarily focus on flexibility for the power sector. Technologies in the pilot and demonstration phase include pre-treatment to bio-oil to improve storage and thus long-term flexibility, but also technologies to extend the feedstock base with more challenging to process residues. Finally, further development and upscaling will be required to bring bioenergy flexibility services to the market to efficiently handle abundant PV and wind power and provide CO_2 removal services.

3.2. *Country and implementation status review on flexible bioenergy*

In transformation research, readily deployable niche innovations may transform socio-technical regimes only if ‘socio-technical landscape pressure’ on the incumbent regime is sufficient. This includes the ‘landscape pressure’ from macro-economics, deep cultural patterns, macro-political developments and, in our case, technological constraints, that is, increasing intermittent power production that will change the means of energy provision and consumption [62]. Section 3.1 outlines various bioenergy technologies that are readily deployable to provide flexibility services to the energy system today. However, the demand for these flexibility services will ultimately decide if they will be part of tomorrow’s socio-technical regime. Therefore, we analyze the landscape pressure in the examined countries in section 3.2.1, discuss first policy frameworks incentivizing flexibility (section 3.2.2) and the implementation of demonstration projects (section 3.2.3) to finally highlight perceived barriers for scaling and multiplication of flexible bioenergy.

A questionnaire on the implementation status of flexible bioenergy (see supplementary material) was filled out by experts from Australia, Austria, Denmark, Finland, Germany, Ireland, Italy, the Netherlands, Sweden, Switzerland and the United States. The latitude spread of the analyzed countries is illustrated in Fig. 2, limited to the European continent. The country selection is based on member countries to the IEA Bioenergy and respective representatives to the IEA Bioenergy TCP Task 44 with expertise in flexible bioenergy. These countries represent a cross-section of OECD countries, ranging from island states to whole continents, with independent states, associations of states and individual states embedded in an economic and political union. Most of the surveyed countries are Member States of the EU. EU regulations set unified standards, which the Member States seldomly outperform due to the risk of jeopardizing the ‘functioning of the Single Market’. In contrast, the United States represent the view of a federal government and its associated states, districts and territories. For example, U.S. states regularly

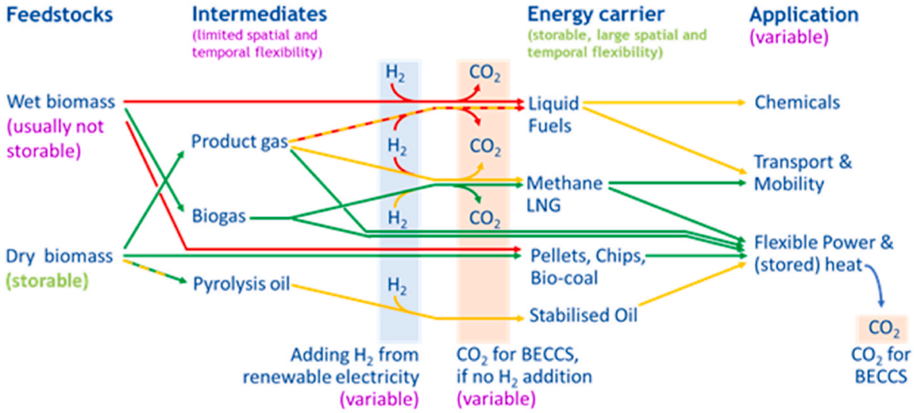

Fig. 1. The network of bioenergy technologies providing flexibility services. Green arrows indicate technologies that are already applied; yellow arrows indicate technologies that have been demonstrated technically but do not yet have a working business case; red arrows indicate technologies under development (from (Schildhauer et al., 2021) with permission).

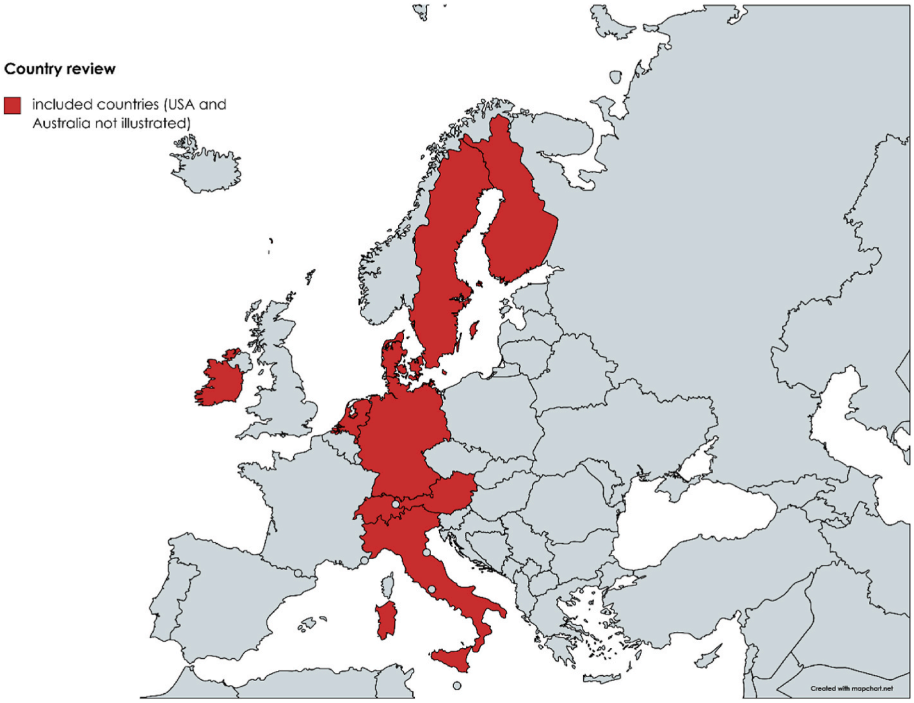

Fig. 2. Illustration of the latitude spread of the reviewed countries in the present paper. The United States of America and Australia are included in the country review but are not illustrated on this map. Source: created in https://mapchart.net/europe.html, (license CC BY-SA 4.0).

apply stricter rules on environmental issues than stipulated by federal laws and regulations, which serve as a minimum standard [63]. Questionnaire responses, therefore, must be interpreted in light of different governance structures. The full report with a complete set of answers is published and can be freely downloaded [22].

3.2.1. Current and emerging flexibilization pressure

Within the EU, wind power shares progressed significantly from 5% in 2010 to 12% in 2020 [64]. At this point, grid congestion can be primarily managed in Germany, Denmark and Sweden through cross-border electricity exchange. While several countries report that negative prices and curtailment are not significant so far, experts from Ireland and the Netherlands specifically mention pressure for investing in additional flexibility measures. System Non-Synchronous Penetration (SNSP) for the island of Ireland is to be increased to 70% by 2030 [65]. The Netherlands are well connected to the international grid, to Germany and Belgium on land, and with three direct current sea cables to the UK (BridNet), Norway (NorNEd) and Denmark (COBRA), although planned PV and wind power plants within the North-East part of the country (South Groningen and East and South Drenthe) face an estimated waiting time of up to ten years for grid connection [66]. In contrast, other countries, including Austria, Sweden, Switzerland and Italy, can utilize already existing renewable flexibility options in pumped hydro- and reservoir storage. Expansion plans of hydropower capacity between 2021 and 2030 are only reported for Austria (by 12%), aiming to achieve (net) 100% renewable power by 2030.

Bioenergy does not contribute to significant renewable electricity shares in most countries but in Denmark [67] and in Finland based on its relevance in the pulp and paper industry [68]. However, residential heating based on biomass is the prevailing renewable application in Sweden, Austria, Denmark, and Finland, while sector-coupling of the power grid for residential heating based on heat pumps is still a niche application in all countries. Bioenergy remains furthermore the only renewable energy source in the transport sector with a relevant share in the energy mix, either based on biodiesel and bioethanol or in the case of Sweden, also on biogas and biomethane.

Within the EU and to jointly achieve climate neutrality in 2050 ‘in a manner that contributes to the European economy, growth and jobs’, the revised Renewables Energy Directive (RED) imposes a reduction of greenhouse gas (GHG) emissions by at least 55% by 2030. It suggests increasing renewable energy supply targets from 32% to 40% in 2030 in all energy sectors, not only limited to the power grid [69].

In the United States, there are no renewable energy targets on a federal level, although some states have Renewable Portfolio Standards (RPS) of 100% for the power system between 2030 and 2050 [70], which impose a particular share of renewable electricity demand on local utilities. In Finland, national climate and energy strategies are currently under revision and expected to be launched in late 2021, with current plans to ban coal in power and heat by 2029 [71] and to become carbon neutral by 2035 [72]. In Switzerland, carbon-net neutrality is to be achieved by 2050 [73]. Australia has adopted a climate strategy in line with the general commitments under the Kyoto Protocol and the Paris agreements [74], although it currently has no official binding targets on activities such as coal-based power generation.

The current ‘landscape pressure’ to introduce flexibilization measures is reportedly low in most countries but Ireland due to limited cross-border trade and the Netherlands due to grid expansion barriers. To date, and to the best of the authors’ knowledge, it is unclear how the surveyed countries will meet the Paris goal commitments. Planning for a complete phasing out of fossil fuels in the power sector takes on concrete forms in some countries, followed at a slower pace by planning for the heating and transport sector. Growing PV and wind power shares for reaching these targets will increase the demand for flexibility services. At the same time, sector coupling, that is, the electrification of residential heating, transportation and industrial process heat, have ‘promising prospects to provide flexibility and improve the efficiency of the energy system’ based on DSM as highlighted by Darby SJ, 2020 in Ref. [20]. On the one hand, this dichotomy and missing plans on holistic energy system transformations make estimating the demand potentials for bioenergy flexibility a challenge. On the other hand, the principle of sector coupling reducing flexibilization pressure can also be applied to the multi-sectoral aspect of bioenergy, thus providing another compelling argument to consider all energy sectors in the bioenergy flexibility debate.

3.2.2. *Policy framework examples supporting flexible bioenergy*

[75] models scenarios for the German heat and power markets with up to 80% renewable energy penetration. He finds that an optimal expansion and use of bioenergy plants as complementary flexibility and CHP-option reduces total system costs by approximately €300 m per year, contributing to the decarbonization and energy security in both electricity and heat markets. In addition, the results from Ref. [76] show positive effects on a business level when adopting a flexible operation of the existing German biogas plants. The Era-Net funded Bioenergy VaBiSys project (Value-optimized use of biomass in flexible energy infrastructure) outlined and quantified the PV and wind expansion facilitator role of bioenergy regarding overall system costs [77], and identified challenges in translating the systemic benefits into monetary terms on either the city and energy company level [78].

Still, market mechanisms directly supporting flexible bioenergy measures are reported only for Germany and Italy. A boom in biogas plant installations in 2009–2011 in Germany and a reform of the electricity act to integrate renewable electricity into the electricity market via direct marketing in 2012 led to the far-sighted decision to allow for added-value generation via a '*flexibility premium*' [79]. The premium incentivizes additional intermediate storage for biogas plants. Eligible beneficiaries include biogas plants that partly produce or feed-in electricity depending on the flexibility demands of the grid. Several requirements are imposed, including proven flexible power generation, gas storage facilities, or direct electricity marketing, and these are monitored regularly. The flexibility premium is granted by the grid operator based on additional capacities [80]. Still [81], discuss that low economic benefits outweigh the efforts for flexible operation, mainly leading back to insignificant electricity price-spreads resulting in a considerable unused flexibilization potential of biogas plants in Germany.

Approaching the subject from a different angle, 'the Italian Ancillary Service Market (ASM) is opening up to new subjects different from traditional producers, defined by the Italian grid code as "significant units"' to include the increasing number of smaller and decentralized players of the power system. The aim is to enable the participation of an eventually distributed set of small-scale electrical loads, plants and storages aggregated by a Balancing Service Provider jointly participating on the ASM. Pilot initiatives for Mixed Qualified Virtual Units ('Unità Virtuali Abilitate', UVA) have been in place since 2019. Virtual Qualified Units (VQU) can contribute to flexibility by reducing consumption (R-VQU), reducing production (P-VQU) or managing their power level in both directions (M-VQU) [82]. Besides bioenergy plants, this mechanism mainly covers small hydroelectric plants and battery storage systems.

[83] provide an electricity market comparison between the United States and Europe. Both world regions show local tendencies either to improve price formation in short-term markets or to place explicit capacity remuneration mechanisms to address long-run resource adequacy challenges. In Italy in particular, the national transmission system operator obtains long-term supply contracts for auctions capacities and calls them to produce when needed [84]. In contrast to the VQU, this market design presents opportunities for larger biopower plants or converted coal or natural gas-fired power plants to become 'peaker plants', contributing to energy system stability.

3.2.3. *Country expert review on flexible bioenergy cases*

Next to the overall 'landscape pressure' for flexible bioenergy services (section 3.2.1) and the policy examples (section 3.2.2), the IEA Bioenergy TCP country experts were questioned about innovative, flexible bioenergy applications in their countries. We acknowledge the country experts' wish to broaden the understanding of flexible bioenergy beyond services to the power grid, and we, therefore, present a selection of cases divided into four categories: *'Feedstock flexibility',* which includes technologies utilizing biomass feedstocks of varying types and qualities; '*Bioenergy carrier flexibility',* which addresses the possibility to store energy in the form of biomass over longer periods; '*Operational flexibility*', which is achieved when varying loads of power or heat are provided on purpose to match demand patterns, and; '*Product flexibility*', which indicates switching between outputs, for example, to match seasonal demand patterns between power and heat or continuous changes in output shares of heat for residential heating and biochemicals for the production of insulation materials.

Cases exhibiting feedstock flexibility:

- In Australia, the Goulburn Bioenergy Project uses biogas for peak load production from effluent, and organic waste from a meat processing industry specialized in digesting fluctuating feedstock quality. The project can displace 75% of peak load, drawing natural gas from the grid to further meet peak loads [85].
- Biomass gasification offers feedstock flexible thermo-chemical conversion for dry biomass [86]. For example, the Järvenpää multi-fuel CHP plant converts forest chips, other woody biomass and 'recycled energy wastes including paper, cardboard, waste wood, recycled wood, horse farmyard manure' into heat and power [87].

Bioenergy carrier (storage) flexibility:

- In Europe and the US, bioenergy carriers in solid form (wood pellets, wood chips, and partly also straw pellets), in the gaseous form (biogas and biomethane), and the liquid form (biodiesel and ethanol) are traded internationally. Significant trading and storage infrastructure for these bioenergy carriers exist and can be used to improve energy system flexibility [35,88,89].
- In Ireland, animal manure is enriched with sawdust through a high-pressure filtration process in the SLURRES project. This novel bioenergy carrier can be transported and stored for flexible conversion in an anaerobic digestion plant [90].
- In the Netherlands, the European ARBAHEAT research project steam-exploded biomass pellets, developed by the Norwegian company Arbaflame AS, are used in a coal-fired power plant in Rotterdam. These novel pellets are water-repellent, more compact and cheaper to transport and store than fresh biomass. The project furthermore aims at switching from providing flexibility power services based on fossil fuels to biobased feedstocks, delivering heat to the surrounding industry in the Rotterdam/Europort area [91].
- Seemingly the most substantial research focus reported by the country experts lies on power-to-gas (PtG) projects. In Germany, the Audi e-gas and BioPower2Gas projects demonstrated the coupling of biogenic CO_2 from biogas upgrading plants. Similar projects can also be identified in Denmark. In Denmark, the BioCat project at Avedøre deploys biocatalysis to convert hydrogen produced with excess wind power to synthetic natural gas. A nearby sewage treatment plant provides CO_2. The bio-SNG can be used on-site for CHP or fed into the natural gas grid [92].

Operational flexibility:

- Operational flexibility is provided by thermal energy storage in residential heating systems [93], in larger scale seasonal storage [94] and even in hybrid systems [95] such as solar-thermal enhanced bioenergy heating cases [96].
- Flexible power provision based on bioenergy has been operational in the Netherlands in the Bioflex-initiative since 2017. Dozens of biogas producers, primarily farmers, allow the grid (TenneT) to regulate the fermentation process to indirectly control the frequency of the power grid [97].
- In Germany, the municipal utility of Ludwigsburg-Kornwestheim deploys a hybrid heating system combining large-scale solar heat and biomass with heat storage. The aim is to buffer intermittent heat quantities served by the solar collector field and compensate for the daily fluctuations in the solar heat yield [98].

Product flexibility:

- Bioenergy CHP plants of small scales [4] and larger cases [99] regularly switch between providing heat and power services or even biochemicals [100]. In addition, operational flexibility concerning power services can be provided [101].
- The ability to flexibly switch between energy and material products is discussed in the Swedish Bioflex case [102] and the Finish Joensuu case producing heat, power and bio-oil [103].
- The now-abandoned 'City Refinery' concept, also in Finland, aimed at producing transportation biofuels by gasification in an urban environment, recovering the process heat for residential space heating [104].
- In Falun in Sweden, a bioenergy CHP plant flexibly produces bioenergy carriers in the form of wood pellets in times when the demand for district heating is low [105].

We want to highlight that various bioenergy technologies are readily available (section 3.1), and can we observe their flexible application in the selected countries, albeit so far only in pilot and demonstration plants. To conclude the country review, we synthesize the barriers for further expansion and multiplication of bioenergy flexibility services as perceived by the questioned IEA Bioenergy TCP community.

3.2.4. *Perceived barriers for bioenergy to provide flexibility services*

As shown in section 3.2.1, the pressure to deploy flexibility services is generally low in most countries. Most of the selected countries reveal limited 'landscape pressure' due to low PV and wind power shares or significant potential from traditional flexibility services, including internationally connected grid infrastructure or hydropower. Ireland, for example, reported the highest 'landscape pressure' for the power system but specifically in this case also a low country-specific readiness for flexible bioenergy due to little experience with and low shares of biopower. Low 'landscape pressure' and missing definitions and terminologies can be highlighted as a possible explanation for the issue of low data availability on bioenergy flexibility as collectively pointed out by the IEA Bioenergy TCP country experts.

Additional short-term flexibility requirements beyond traditional flexibility services such as power-grid expansion and curtailment are expected to increase with the phasing out of coal and gas and, in some countries, with the phasing out of nuclear power. However, the focus in the queried countries lies, on the one hand, on DSM and short to medium energy storage based on large-scale battery farms, such as in Australia, or on compressed air storage, such as in the Netherlands. On the other hand, sector coupling to deploy intermittent renewables to provide residential heating services, electric-vehicle transport and process energy for industrial applications are regularly discussed as a remedy to solve the flexibilization challenge. If the implementation rates of these options can match the growing flexibilization pressure exerted by expanding intermittent renewables is not clear to date [106]. However, we do not expect contributions of these short-term flexibility services to balance seasonal fluctuations.

Seasonal variations in the power supply are mostly expected to be balanced with PtG solutions in the selected countries. Hydrogen strategies, therefore, are in the spotlight in many countries. Current challenges in storing, transporting and handling pure hydrogen can be managed by synthesizing less energy-dense derivates, for example, by adding biogenic CO_2 [107,108]. On the one hand, this represents an opportunity for bioenergy, as highlighted in section 3.1.3. On the other hand, 'fragile climate effectiveness, high costs and uncertain availability' of PtG processes could also turn out to be a barrier [109]. Furthermore, reliance on PtG holds the risk of lock-in fossil-fuel dependency. The lock-in risk demands climate policy responses, such as bans on oil and gas boilers for residential heating and gas-grid disconnections of remote areas [109].

Most country experts stress missing market mechanisms as the main barrier for flexible deployment of bioenergy technologies. Biopower is often only a by-product of heat-driven processes and not subject to balancing markets. While price volatility is reported to be relatively small most times of the year, constant feed-in-tariffs (FiT) or electricity certification schemes obliterate the respective price signals. Feed-in premium schemes, a payment in addition to the wholesale price, are discussed as ways to allow price signals to permeate partly; auction-based premium schemes, for example, are in place in Germany [110] and are currently being introduced in Austria, after two decades of FiT scheme based support [111].

3.3. *Market instruments valorizing bioenergy flexibility*

For a broader implementation and thus to realize the potential of flexible bioenergy to support resource efficiency and to accelerate the energy transition, the benefit of flexible scheduling will have to become attractive enough for a critical mass of market actors to adopt this niche application. We thus provide a brief overview of how the added value of flexibility has been determined so far (section 3.3.1). Based on this, we discuss what would be necessary for bioenergy flexibility options, also beyond the power system, to give this service of flexibility an economic value on the component level and thus to unfold its potential and benefits to the energy system.

3.3.1. *State-of-the-art valorizing flexibility services*

Literature provides an account for the historical development of demand trends for flexibility services and extension of fossil-based and renewable flexibility capacities. Retrospectively, the integration of pumped hydro-storage (PHES) is an important renewable flexibility trend to discuss.

Traditionally, flexibility was provided for the electricity grid via the supply side, mainly for securing electricity supply and power quality [112,113]. Large-scale and centralized coal plants and combined cycle gas turbine (CCGT) plants have been flexibly dispatched to meet peak demand at all times, at high costs and without taking into consideration the willingness-to-pay of the end-users for their additional marginal demand [112]. Between 1970 and 1990 the importance of PHES expanded, contributing to 99% of European energy storage today [114]. Interestingly, most PHES constructions fall in periods without the respective electricity sector being subject to unbundling, despite vertically integrated companies and no competitive markets [115]. As a possible result, studies and reviews on PHES and energy price arbitrage are rather scarce [114,116–118]. Additionally [114,119,120], point out the difficulties of determining the profitability of electrical energy storage, including the high complexity of trading off low full-load hours with added values from arbitrage, peak capacity and (grid ancillary) balancing services.

Despite the prevailing importance of PHES, the focus of the literature on valorizing flexible services lies in sector coupling of the power sector and its potential to provide short-term flexibility services via DSM or DR either based on household or industrial consumption [106,121]. Current flexibility valorization literature discusses how to enable decentralized consumers and prosumers to indirectly communicate with the Distribution System Operator (DSO) and the Transmission System Operator (TSO) via aggregator agents [122]. Also, energy sharing and energy supply contracting concepts in energy communities gain in relevance [123]. Viewer publications address the valorization of flexibilization options beyond the power sector. Identified papers include reviewing seasonal thermal energy storage [89,90] and managing flexible production of biobased heat, power and biofuels [100].

With the present paper opening up the definition of flexibility due to the results of the bioenergy technology review (section 3.1) and the country review (section 3.2), we have to consider the valorization options of the various flexibility types that can potentially be provided based on biomass.

3.3.2. *Biomass supply chain perspective for bioenergy flexibility services*

Analytically approaching the flexibility types identified in discussion with the IEA Bioenergy TCP technology and country experts, we spot the underlying supply chain character of the flexible bioenergy topic. 'Feedstock flexibility', 'Bioenergy carrier flexibility', 'Operational flexibility' and 'Product flexibility' can be traits of the individual supply chain steps of an interconnected biomass supply chain (see Fig. 3).

[124] stresses that bioenergy deployment for heat, electricity and mobility always requires a complete system and supply chain perspective. A plethora of publications [88,125–127] deals with the simulation and discussion of biomass-to-end-use chains, examining, for example, the chain from forest to primary storage, to densification to wood pellets via trading infrastructure, and to individual consumers for space heating. Similarly, the previous sections' collection of flexible bioenergy options goes beyond short- and mid-term flexibility provision and flexibility services for the power grid. Likewise, and supported by the results presented in the previous sections, we propose to extend the concept of flexible bioenergy to the entire supply chain and its integration into the broader energy system. The supply-chain view facilitates to link the flexible bioenergy valorization discussion back to existing scientific domains:

On the one end, feedstock flexibility provides the option to valorize either feedstock of varying quality or different types of biomass, for example, depending on seasonal availability or prices, or to cater to suddenly emerging needs due to severe weather or pests [128]. managed to combine geospatial data of biomass residues in California, US, with information on their seasonal availability. Cost-supply curves based on biomass potentials are used to simulate the marginal costs for biomass demand in economic and Integrated Assessment Models such as the IMAGE or MESSAGE-GLOBIOM as reviewed in Ref. [129]. However, seasonal cost-supply curves are at best used in specialized models such as the BeWhere [130] or the Vito OPTIMASS model [131]. In practice, real price information on biomass residues or intermediary bioenergy carriers such as wood pellets and chips is strongly limited in terms of the quality and availability of data, which impacts negatively on market efficiency [35]. Market organization models for these residues and commodities lack diversity and experience, with some trials, such as straw auctioning in Denmark [132] and financing instruments such as pellets futures [133]. Furthermore, intermediary bioenergy carriers, either solid, liquid or gaseous, have been considered mainly to improve mass-energy density and homogeneity of provided biomass to reduce costs for transportation and trading. However, in Ref. [32] we also highlighted that the highest relevance of biomass densification technologies lies in improving volumetric energy density to reduce costs for storage and for delaying biological degradation, thus improving storability.

At the other end of the supply chain, product flexibility extends beyond providing positive and negative residual loads or supply and power quality security to the power grid. The combination of bioenergy carriers is inevitably linked to excess heat production, which can and should be utilized for space heating or for lower or higher temperature industrial processes. Furthermore, the product gas from gasification can be refined to produce transport fuels or other chemical feedstocks for material applications [134]. To account for different energy qualities of electricity and heat, the irreversibility of energy transformation processes, for example, in the cogeneration of heat and power, is calculated in exergy-economic evaluations [135–137]. Exergy cost analysis and related concepts, primarily formulated to optimize overall system efficiencies [138], can furthermore be adopted not only to cover the 'usefulness' of different energy forms under varying environmental conditions (for example, ambient temperature) but also of (biogenic) carbon-containing materials concerning the carbon content in the atmosphere [139]. In practice, however, even energy content-focused competitive heating (and cooling) markets allowing for flexible CHP business cases are rather the exception. Some cases can be observed for the provision of district heating in Denmark, Sweden and Finland, although these are mostly with heat prices fixed or regulated by monopolies or municipalities [101,140]. Day-ahead multi-carrier markets [141] for integrating gas, electricity and heat markets distinguishing between conversion and storage orders have been proposed as one solution to address the flexibility potentials between those energy carriers and services. Exergy efficiency and thus different grades of 'usefulness' of the energy carriers have not yet been anticipated in this theoretical market organization.

The power system can gain flexibility due to simply broadening its scope with sector coupling. Similarly, it might be relevant to consider how a broader bioeconomy integrating the sustainable deployment of biogenic residues for energy, materials and nutrient services could contribute to the flexibilization of the overall economic metabolism. The scientific challenge would be to model the added value of the flexibility services provided by bioeconomy supply networks. These networks would include energy and material flows and resource cascades and stocks, which are currently underrepresented in energy system models [142]. Also, competition and synergies in highly branched biomass supply networks, simultaneously meeting the demand for different energy, material and nutrient services, are not discussed in recent bioeconomy modelling reviews [129,143].

3.3.3. *Organizing markets to account for a broader definition of flexibility*

Finally, we want to bring theoretical considerations to valorize different types of flexibility in system models back to discussing their potential integration into a market design based on actionable market mechanisms.

[112] discuss how proper price signals of short time intervals and reasonable price spreads are necessary to be able to trigger flexibility measures in wholesale and retail power markets. Transactive control (TC) schemes represent an extreme case in establishing adequate price signals. These include "real-time" merit-order based bidding and market clearing, as currently demonstrated in some smart-metered home pilots [144], and for residential thermal energy storage as a flexibility source [93]. Implementation of these reactive control mechanisms in the aluminium, steel, cement and food industry is considered more straightforward with, for example, higher potential financial gains and well-defined cost functions. At the same time, the residential consumer would want to optimize the comfort level without spending any or too much time 'tracking their electricity usage' or being 'remotely controlled' [144]. Still, critical information and market barriers and a lack of evaluation of DR benefits limit the integration of DR in the

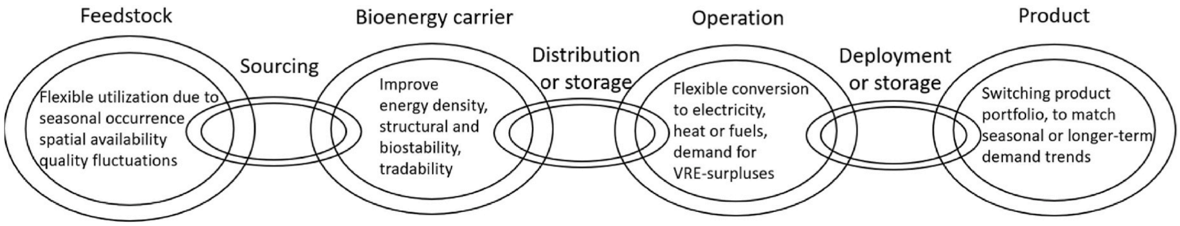

Fig. 3. Illustration of the supply chain character of the bioenergy-based flexibility types. Intermittent renewable energy surpluses are abbreviated as VRE-surpluses (variable renewable energy). Source. Own illustration.

industry globally [145,146].

Considering the 'diverse performance criteria and constraints' of flexibility services, the market organization would have to 'sufficiently differentiate and qualify the commodities or services traded' [93]. Even more so, the design of multi-carrier markets with responsive and coupled sectors for electricity, heat, mobility and biobased materials would have to account for the different qualities of carriers, processes and services, possibly based on a set of criteria including the discussed second law efficiencies (exergy evaluation). We can also point to the primarily non-existent price signals of bioenergy feedstocks and their storable intermediaries [35]. At this end of the supply chain, even established potential assessments vary quite significantly [147], leaving simulated marginal costs on, for example, a yearly or non-seasonal basis, fraught with significant uncertainties.

Finally, significant progress in control theory calls for more robust integration of predictive scheduling, which could even turn out to be 'incompatible and exclusive' to TC [93]. Modern planned control mechanisms are inherently different to concepts such as centralized capacity payments, which are, according to Ref. [112], the 'death of competition' and the last-ditch efforts of 'old centralized fossil and nuclear-based generation planned economies'. In light of the discussion on broadening the flexibility definition, we would like not to exclude decentralized, transparent and cooperative planning pre-maturely. Rolling horizon approaches [93,148] but also theoretical frameworks from other disciplines such as financial risk management and ecosystem resilience modelling [149] hold vast potential to extend forecasting horizons and to improve accuracy, minimizing costs and risks and maximizing welfare.

The presented review clearly illustrates the lack of means by which to valorize flexibility provided by bioenergy and biobased supply chains as a complex and versatile niche in the flexibility toolbox. Irrespective of the final grade of market liberalization, considerable progress in various discussed areas is first needed in order to model systemic added value before flexible bioenergy businesses can be reimbursed for their system stabilizing contributions.

4. Conclusions and suggestions for policymakers

We have reviewed the current status and expectations for bioenergy-based flexibility services, including the diverse perspectives of experts from the international IEA Bioenergy TCP network. The scientific literature on flexibilization of the energy system is, so far, mainly associated with balancing production and consumption of renewable electricity only. However, within the bioenergy and bioeconomy discussion, perceptions and expectations extend far beyond just electricity.

To accelerate further advancements in this field, and in particular, to facilitate discussion within and between the scientific community, policymakers and other stakeholders, we propose a definition of sustainable, flexible bioenergy as *deploying sustainable biomass to provide multiple services and benefits to the energy system under varying operating conditions and/or loads contributing to energy security.* We conclude that a broad range of bioenergy technologies is commercially available that could already today provide sustainable flexibility services without significant additional technological efforts. The definition of sustainable, flexible bioenergy includes:

- utilizing 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, fuels, and non-energy products 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 biochemicals for the production of insulation materials, and;
- 'negative vectors' for renewable electricity surpluses and the CO_2 budget, for example, on hydrogen from PV or wind surpluses converted to synthetic fuels with biogenic CO_2 from biogas or biomass gasification providing energy or material services.

We find that the 'landscape pressure' for flexibilization of the energy systems is still low in most analyzed countries. Biobased electricity is primarily a by-product in CHP units, with limited national ambitions to expand and low-efficiency of electricity-only conversion in the light of finite biomass resources. Strategies instead focus on internationally integrated electricity grids and high hydropower shares to balance the low to moderate intermittent renewable shares. The island in our country selection, Ireland, sees novel flexibilization options as a priority due to limited energy trade possibilities. However, biobased power is not expected to play a role since the country traditionally lacks experience and expertise on this topic. Only in Germany is there a dedicated policy instrument with the flexibility premium for additional biogas storage capacities, although Italy's technology-agnostic Virtual Qualified Units programs do in some ways meet the definition of policy support for flexible biobased power. When considering broader definitions of flexibility, we have to stress that recognizing enabling factors for bioenergy carrier storage and trade is of particular importance. Policy instruments for biomethane gas grid injection and respective certification schemes support seasonal and long-term flexibility services and should be addressed as such.

Growing PV and wind power shares for reaching emission reduction targets will increase the demand for flexibility services in the future. Further electrification of residential heating, transportation, and industrial process heat holds promising potentials for flexibilization. Thus, the nexus between growing intermittence shares and further electrification makes it challenging to estimate the demand potentials for flexible bioenergy in specific. However, we advise considering how the principle of sector coupling reducing flexibilization pressure applies to the multi-sectoral aspect of sustainable biomass use. We hypothesize that including non-electricity based energy flexibility services and coupling additional bioeconomy sectors alters the stability of the energy system and the broader economic metabolism.

However, we identify the prevailing barrier for multiplying presented flexible bioenergy options lying in missing tools to valorize flexibility services in general. Flexibility can help to tackle resource scarcity but also provides resource efficiency in times of resource abundance. Still, the market mechanism to valorize flexibility to improve resource efficiency dynamically is reportedly scarce. The benefits of flexibility services and sustainable bioenergy can be first and foremost evaluated on an integrated energy system level, for example, based on cost or GHG savings, internalizing security of supply, and overall system stability. However, translating these societal gains into an economic profit on a business or individual prosumer level would require frameworks for the designated market mechanism. The electricity market design debate is characterized by a dichotomy between improving real-time price formation to foster market and price-signal based resource allocation and longer-term investment decisions (often denoted as the 'electricity only market') or designing more regulated markets, for example, based on capacity remuneration mechanism. Considering the large variety of flexibility services discussed in this paper, we must highlight that markets and frameworks would have to be designed to sufficiently reflect the qualities and limitations of the different commodities or services. A detailed elaboration on the feasibility to meet this requirement for the other debated market concepts and their potential implementation beyond the power sector is out of scope for this study. Indeed, limitations on data availability and accessibility, as we see here in the discussion on findings from bioenergy supply chain research, make such discussions challenging. However, we have to strongly advocate for a heterodox energy economic debate to help settle fundamental questions about the effectiveness of different market designs based on empirical approaches, quantitative modelling, and basic analytical research.

Future work will have to consider the broader definition of bioenergy flexibility, for example, in energy systems or economic metabolism models. Such models should be able to simulate resource cascades and stocks to depict competition and synergies in highly branched bioeconomy supply networks, simultaneously meeting demand for different energy, material and nutrient services. Optimization algorithms to account for the resilience in transforming systems should be developed, and where possible, integrated with incumbent Integrated Assessment Models. Research questions should be addressed regarding the quantification of flexibilization potentials and the value of achieving multi-sectoral and societal objectives, including facilitating high intermittent renewables shares. A novel objective function to account for flexibility should be considered; Minimizing adverse and maximizing beneficial consequences of resource uncertainty could result in dynamically mitigating resource scarcity and valorizing abundant resources. Modelling efforts should allow for comparative assessments of fundamental market designs. Self-cannibalization of flexibility services eroding their margins with increasing shares (also ‘saturation effects’) has not been addressed in this study; however, it could present an exciting question for theoretical study or respective modelling.

Finally, we want to outline that the used approach in the present paper stands in contrast to bibliometric, ontological or terminological review, which is required to proceed with this work based on an entirely unambiguous ontology. The keyword ‘flexibility’ joins in with ‘adaptability’, ‘agility’ and ‘versatility’. Furthermore, related terms include ‘robustness’, ‘stability’, ‘elasticity’ and ‘resilience’, and, on a system-level, ‘variety’, ‘redundancy’ or ‘diversity’ of components and connections among each other. Distinct and clear logical and mathematical definitions could explain the energy system and economic metabolism discussion and modelling.

Credit author statement

Fabian Schipfer: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition; Elina Mäki: Conceptualization, Writing – review & editing, Project administration; Uta Schmieder: Conceptualization, Writing – review & editing; Nora Lange: Investigation, Writing – original draft; Tilmann Schildhauer: Conceptualization, Writing – original draft, Writing – review & editing; Daniela Thrän: Conceptualization, Methodology, Writing – original draft, Writing – review & editing; Christiane Hennig: Conceptualization, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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