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REVIEW

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Flexible bioenergy supply for balancing fluctuating renewables in the heat and power sector—a review of technologies and concepts

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Abstract

Today bioenergy plays a major role in the renewable energy provision, for heat and power and for liquid biofuels as well. With an increasing share of renewables on the one hand side and a limited availability of biomass on the other hand, the provision of bioenergy has to consider the demands of the future energy system with high shares of fluctuating wind and solar power. This includes new and improved technologies and concepts for biogas, biomethane, and liquid and solid biofuels, which are discussed in the following, while for the electricity sector, the demand for more flexible provision might take place in the years to come; for more flexible heat provision, the transition is expected in a longer time frame. For their market implementation adopted regulatory framework and price signals from electricity markets are necessary.

Review

Introduction

The transition of the energy system towards greater use of renewable energy is a precondition for the envisaged reduction of greenhouse gas emission [1], for a sustainable use of the finite resources [2] and for macroeconomic benefits as well as for fair access to energy [3]. The total use of renewable energy sources has been increased worldwide over the last decade with biomass as the most important source covering 10 % of the total global primary energy demand [4]. Biomass is a renewable carbon source and can be used for provision of a wide range of bioenergy carriers and substitute fossil fuels in the power, heat, and transport sector. Additionally, biomass and the produced bioenergy carriers are storable and can provide energy on demand in principle. This quality is especially relevant in energy systems with high shares of fluctuating renewables like wind and solar power.

In general, the provision of bioenergy is based on different principles and concepts: There are thermochemical, biochemical, and physicochemical conversion systems available to produce solid, liquid, and gaseous fuels from biomass (Fig. 1). In the following steps, these fuel sources are converted—mainly combusted—to generate heat and power in stationary and mobile applications:

- Thermochemical conversion includes the use of systems to transform solid (and sometimes also liquid) biomass into charcoal, pyrolysis oil, product gas, and thermochemically treated solid biomass (i.e., torrified biomass).
- Physicochemical conversion is used for oilseeds to provide vegetable oil or biodiesel.
- Biochemical conversion includes the anaerobic digestion of organic matter to produce biogas as well as the fermentation of sugar rich and lignocellulosic resources to bioethanol.

All the converted biofuels can be processed further, i.e., product gas to synthetic natural gas ("SNG") or liquid biofuels ("bio-to-liquid"), vegetable oil to hydrogenated biofuels ("HVO"), biogas to biomethane, so in theory pathways are possible from almost every resource to every energy carrier. Established is heat provision

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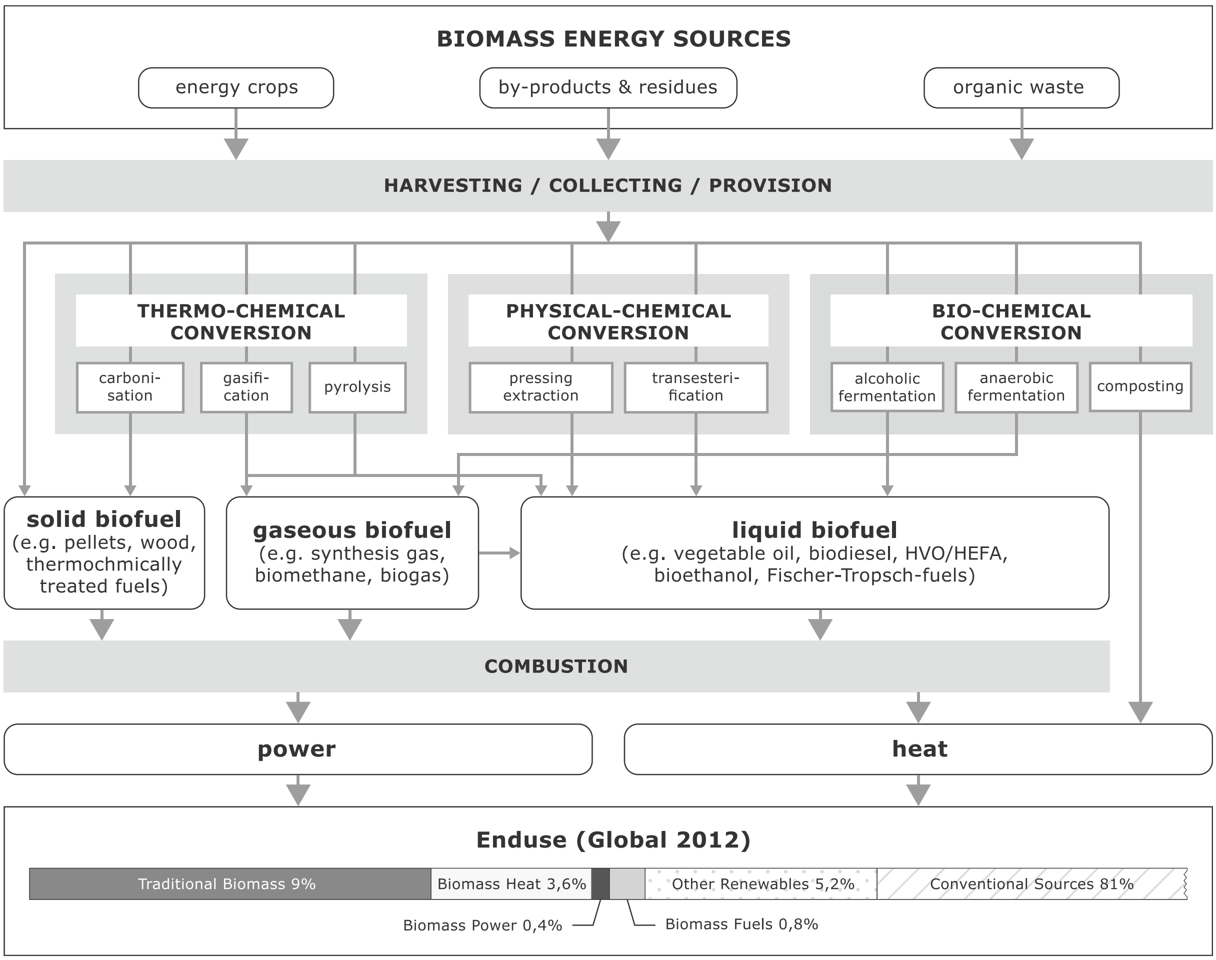

Fig. 1 Biomass conversion pathways and related global bioenergy provision in 2012. Data for final consumption from REN21 [101]

from solid biomass, combined heat and power provision from different bioenergy carriers, such as biogas, solid biofuels, and vegetable oil, and the use as a transport fuel, including biodiesel, bioethanol, and biomethane [4]. With those different conversion concepts, biomass provides 14 % of the overall primary energy, what is—compared to 5 % other renewables—75 % of renewable energy at global scale in 2012 [5] (Fig. 1).

Also in Germany, 61 % of the renewable energy provided is a product of biomass, with the potential to reduce 54 million tons of CO_2-carbon dioxide equivalents, which represent 37.2 % to the total amount of German greenhouse gas reduction by renewable energies in 2013 [6].

This review focuses on the technical options to adapt existing bioenergy provision plants to a flexible energy provision. The method is described in "Method". To consider the specific energy market condition as well, we analyzed for Germany exemplarily the expected demand pattern for flexible bioenergy in systems with higher shares of solar and wind energy ("Demands on bioenergy from the transition of the energy system"). The review includes biogas provision concepts ("Electricity from biogas—a wide range of options for balancing fluctuating power supply"), electricity provision from liquid biofuels ("Electricity from liquid fuels—technically promising but in competition with other utilisation pathways"), electricity from solid biofuels ("Electricity from solid biomass—moderate chances for heat-driven plants"), and flexible heat provision ("Heat from biomass—shrinking but exact controllable installation lead into future"). Also new concepts of cross-sectoral energy provision is included and discussed with the potential role of biomass in power-to-X concepts ("Balancing across energy sectors—the role of biomass in power-to-X concepts"). Finally, we discuss the potential and availability of the different flexible bioenergy provision concepts and conclude the economic frame condition for market implementation.

Method

We conducted a literature review to summarize recent knowledge regarding technical adaptation for flexible bioenergy supply in Germany: flexible electricity from biogas, from liquid and solid biofuels, heat from biomass, and power-to-X concepts as well. We reviewed English and German peer-reviewed journals and publications by using the databases and library services of ScienceDirect, (http://www.sciencedirect.com), Web of Science (www.webofknowledge.com), and Google Scholar (http://scholar.google.com) (time period: 1970 to December 2013). In those fields where adequate literature is not available yet, we conducted some basic demands and options for different kinds of flexible bioenergy provision.

Additionally, we used data available from the DBFZ database to describe the status quo on bioenergy. The data available are based on the evaluation of an annual survey. The survey has been carried out annually since 2007. It is a written survey on the basis of a standardized questionnaire, which has been sent out. Starting with app. 500 in 2007 up to app. 10,000 in 2015, questionnaires have been sent out and usually 10–15 % are returned to us. Selected results of the survey are published as a report "Renewable energy sources act monitoring report." Within the scope of the survey, operators and owners are asked about data concerning the tariffs, produces energy, operational, and technical parameters and substrates. The database covers about 90 % of the total number of bioenergy plants.

Demands on bioenergy from the transition of the energy system

In the past, continuous support instruments have been necessary to introduce renewable power provision. Germany has implemented an active policy for the transition of the energy system towards the use of renewable energy more than a decade ago. The development of the renewable energy sector in Germany actively started to gain momentum in 1991 when the electricity feed-in law came into force, which was renamed as the "EEG"—Renewable Energy Sources Act in 2000 and has since then undergone several amendments [7–10]. The EEG aims to enforce technological development in order to introduce renewable energy into the electricity market and integrate it into the energy system. Since 2001, the European energy policy has promoted electricity production from renewable energy sources on the domestic electricity market [11].

In 2012, 25.3 % of the electricity consumed in Germany is produced from renewable energy that is mainly supported by the EEG, with the fluctuating use of wind and photovoltaic power accounting for 55 %, and electricity from biomass and hydropower accounting for 45 %. Although bioenergy has a relatively small amount of installed capacity (9 %) among the renewable energies compared to wind or solar power, due to its high full load hours (about 7500), it has a relatively high percentage (31 %) of overall renewable power feed in [12]. Due to a drastic incentive cut for bioenergy within the amendment of the renewable energy sources act in 2014, market expansion is expected mainly for wind power and photovoltaic.

The transition of power generation towards more renewables also leads to different supply patterns: With the increasing supply from wind and solar power, the supply pattern changed to variable proportions of wind and solar power and a remaining demand to be covered by flexible and controllable power plants—the so-called residual load. Due to the sunlight dependency of solar power, the residual load is at a minimum during midday (Fig. 2) and could in future also become negative on sunny days, when the demand for power is generally low (i.e., on Sundays or holidays) [13]. Future markets for renewable electricity will therefore have to focus on an efficient supply of system services to balance the fluctuating renewables, including short-time residual load from biomass and other flexible provision options as well as storage technologies. They have to meet the need for compensation of large variation in within short periods for grid stabilization and on the longer term for balancing the given weather condition as well.

In the upcoming transformation of electrical power production in Germany and Europe, wind and solar power have also gained special importance. The main reason for this can be said to be a largely absence of marginal costs of production because wind and solar power have no fuel costs at all. As a consequence, electricity from wind and solar has a priority for the feed in [9]. On the other hand, these two types of renewable energies are produced erratically and not always in line with demand patterns, so system services from the other renewables need to provide grid stabilization and residual load in times of disadvantageous weather condition. For this very reason, a range of flexibility options are required, for example, demand-side management, network expansion, energy storage, and flexible power plants [14, 15]. From a short-term perspective, flexible power could be met from fossil and renewable sources, but from a long-term perspective, this task should be transferred exclusively to renewable power plants and other no-fossil options (demand-side management, storage systems, etc.). The changing role of bioenergy in a transforming energy system integrating larger amounts of fluctuating wind and solar energy has been discussed in a few studies only [16, 17]. It is not a question if biomass can cover the whole gap, rather it will contribute to the missing capacities. Additionally, bioenergy will replace most likely a higher portion of fossil fuels within these remaining capacities plus acting in markets with increased prices for electricity.

Additional targets for the transformation of the heat sector have been defined: In line with the European Renewable Energy Directive, Germany's national renewable

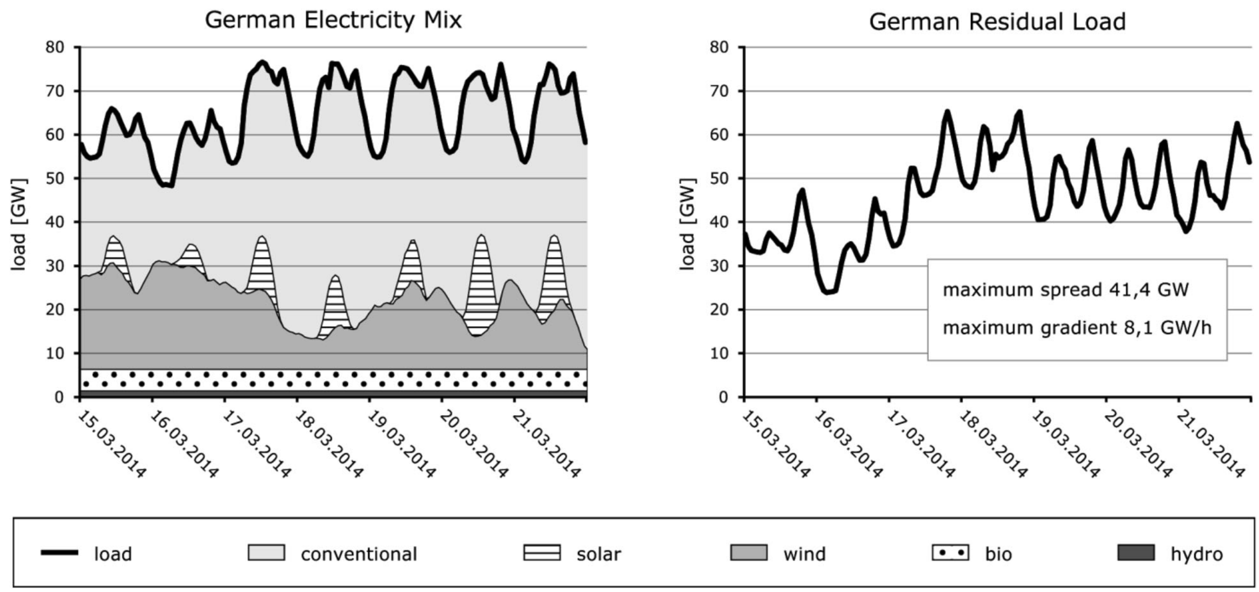

Fig. 2 Recent electricity mix and variation of residual loads (defined as load less wind and solar generation) in Germany, 11th week 2014, own presentation based on [102, 103, 104]

action plan aims to increase the renewable energy share for heating from 9.1 % in 2009 to 15.5 % in 2020 [18]. The development of heat provision from biomass does not depend so much on support schemes but on emission control regulation, especially for the small-scale sector. The framework background tightens the emission protection enactment, which stipulates the lowering of emission limits especially for carbon monoxide and particulate matter [19].

The development of heat provision from biomass is influenced by the improvement in building insulation, emission reduction targets for biomass stoves and boilers, market conditions for combined heat and power installations based on biomass, targets for renewables in the heat sector, and the market development of renewable heat provision from other sources. For the midterm, a strongly shrinking heat demand is presumed (45 % decrease) if ambitious restoration targets can be realized [20]. Under those conditions, also a lower seasonal variety can be expected, with a more constant demand for hot water. Furthermore, mixes with other renewable heat sources such as solar heat, geothermal heat, heat pumps, and the conversion of excess electrical energy from power to heat will all increase [21]. Experiences from the past lead to the expectation that the transition in the heat sector will take place much slower than in the electricity sector.

Electricity from biogas—a wide range of options for balancing fluctuating power supply

Status quo

At the end of 2013 in Germany, the utilization of agricultural substrates as energy crops and manure dominates the biogas sector with app. 7700 plants [22]. Flexibilization of the energy provision and in particular the biogas sector has been identified as an important task for the future—in Germany [23, 24] and also in other European countries [25, 26].

For the flexibilization of biogas, plants have been offered an incentive within the Renewable Energy Sources Act in 2012 and has been continued in 2014. According to the DBFZ Database [27] in March 2015, close to 3000 biogas plants have been registered for the special tariff, which has been established to support flexible plant operation. Technically, the plants have been designed for a constant operation, and consequently, the flexible operation needs adjustment in design and operation. So far, most plants are reluctant to invest in additional infrastructure and use their existing plus simply adding CHP capacity. More sophisticated flexibility concepts, e.g., [24], have not been realized yet due to a drastic incentive cut within the amendment of the Renewable Energy Sources Act in 2014 for new plant constructions.

Biogas plants can have profitable access peak power prices under the conditions of the Renewable Energy Sources Act from 2012 [8], and it can be assumed that this is also the case for the amendment of 2014, since it has very similar conditions. Looking at market conditions, there is financial revenue from flexibilization of the energy output; however, without incentives, the income cost balance is negative [23]. Reasons are the low energy prices and the small price fluctuations at the electricity market [25].

Technology

Biogas can be produced from several organic substances as solid wastes and waste waters from municipalities and industry, energy crops, sewage sludge, etc. There are plenty of technologies adapted to the characteristics of the different substrate stream [28, 29]. The main process technology applied is the continuous stirred tank reactor system. The produced gas is collected in rubber domes (one and two layer systems) on top of the digesters, with an approximate storage capacity of 4 h [30]. After a drying process and H_2S removal, the gas is usually utilized within a combined heat and power unit. At the end of 2013, 154 plants [22] use an upgrading process to produce biomethane for injection into the natural gas grid.

The options for the flexibilization of the energy provision are first of all limited by the available power provision capacity, which is in most cases a combined heat and power unit (CHP). Consequently, the reaction time of the CHP is a limiting factor. Usually, the CHP can shut down and restart or change to part load operation within several minutes. The risk of a failure of the restart process can be avoided by offering only part load operation. Second, the available plant design and infrastructure is limiting the flexibility. Given the situation, a plant has a nominal load which should be achieved in average during annual operation; any downtime needs to be compensated by an equivalent time of correspondent additional energy output. The larger the available overcapacities in comparison to the nominal load, the more flexibility a plant can provide. However, besides the CHP, the upstream equipment has also to be considered—the CHP needs to be fed with gas when needed. Consequently, the "quality" of the plant flexibility is also influenced by the availability and storage stability of the substrates, the feeding management, storage of intermediates of the biological process, and most important, the storage capacity of the biogas [17]. The response characteristics of the overall process chain can be improved by an adequate storage capacity of biogas within the process and a harmonized and controlled operation of gas production, gas storage, and gas utilization. In [25], the positive effect on flexibility options by means of an appropriate feeding strategy is presented.

The consequent utilization of existing gas storage capacity can provide the biogas for flexible power generation [24] and represents the simplest approach and does not require many changes in design and operation. Assuming an 8-h biogas utilization bloc per day, this consequently leads to the lowest additional costs in comparison to other more sophisticated flexibility concepts with substrate pretreatment, fractionation, and separate digestion or plants with upgrading technology [31].

Any concept aiming at more flexibility options within a given plant design by means of variation of the biogas production needs to consider the stability of the biological process. [25] showed that the biological process is stable and controllable. Even the yield is not influenced substantially under rapid changes as [32] shows.

Most options for a demand oriented utilization of the biogas are obtained by means of upgrading a feed in the natural gas grid, thus resulting in almost endless possibilities regarding the location and the point of time of utilization [17]. According to the technical components, a plant has several options to realize flexibility. In any case, the flexibilization concept is most often focused on the electricity output. If the plant has also to supply a heat outlet, the concept needs to take care of the demand on that side too. However, all options on the plant side need to match the demand of the market and the grid side, which is described below.

Market

Depending on the demand of the energy market and marketing, there are different options for this flexibilization from several minutes to seasonal shifts, requiring different adjustments to the concepts of the biogas plant (Table 1). The regulatory conditions for biogas plants resulting from the Renewable Energy Sources Act (Amendment 2012, RESA) are described in [24]. In terms of marketing, it has to be taken into account that biogas plants are usually too small to participate on their own in this marketplace, but specialized marketers have started to pool several biogas plants to contribute to the spot market [17].

An optimized electricity supply from renewables is the business case of some new companies in the electricity market in Germany since 2012. These power traders developed portfolios of mainly renewable capacities (a lot of wind and solar power but also biogas and fossil-based CHP). Since the share of renewables increased significantly in Germany, also the influence of renewable energy sources on power market prices has grown. Consequently, a higher demand for flexibility in the power markets evolved. Today, the renewable energy source pools of these power traders are put on different power markets, especially day-ahead and intraday markets. But also, balancing power particularly secondary control reserve and minute reserve is provided. Newly, even primary control reserve is offered by one company (energy2markets). Thus, these new players also take over functions for grid stability and security of energy supplies, which is today in large part supplied by fossil capacities [33].

Outlook

For the conception of flexible power generation from biogas, different technical options are available and under development:

Besides these rather obvious changes in capacity utilization, the speed of the shift and the duration of the

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

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

downtime (or reduced load) are also of importance for the operation of a biogas plant.

Depending on the situations described, potential flexibility concepts for biogas plants can be distinguished as follows:

- Short-term flexibility (reaction time, 5 to 15 min, duration: up to several hours): This kind of flexibility can be achieved by means of a shutdown or substantial decrease of the operational performance of the CHP for a short period of time, usually up to 1 h, in individual cases several hours. Minimal changes in the overall plant operation are necessary. The implementation only requires control technology for the CHP units; the CHP needs to be outfitted to sustain frequent start stop operation. The time limit for the shutdown period is the available gas storage. In order to compensate for an average nominal load, a slight overcapacity is required.
- Mid-term flexibility (reaction time, >15 min, duration: according to a weekly schedule): The amplitude and the duration of load alternation are greater than within the short-term flexibility. The alteration is triggered within a day or for the following day. In such cases, besides the overcapacity required on the gas utilization side and sufficient gas storage, the flexibility of the plant can be improved by means of a feeding management and a correspondent control system for the biological process. All installations on site have to match the requirements of the load variation, in particular any excess heat utilization might require additional installations.
- Long-term flexibility (reaction time: per season, duration: months): In this case, the provision of energy is adjusted in the long term. Reasons for such an operation could include seasonal adjustments (e.g., production is ruled by the heat demand of municipal housing), the utilization of residues from seasonal production processes, or long-term weather conditions (wind, solar). The limit for the amplitude is the CHP overcapacity required, and the installations on site have to match the long-term changes to operations. Consequently, the plant availability of the biogas production process is more secure through a constant operation, a sudden start-up, or an increase in the load has a certain risk of process failure. Therefore, the overall process is not recommended for critical increases in loads (e.g., quick startups as an emergency backup for other critical industrial processes).

In general, it is possible that the different options are provided at one plant simultaneously.

Within the overall process, the most sensitive and critical part is the biological process of gas production. While the CHP units can be shut down and ramped up within minutes, the biological process requires days to weeks for the same procedure. The rate limitation of the biological system is determined by the type of fermentation technology and the substrate characteristics. The microorganisms require a stable temperature, constant minimum feeding, and the mechanical parts such as pumps and mixers need to be operated frequently in order to avoid malfunctions. Consequently, the flexibility option of a complete shutdown of the biogas production for a longer period of time cannot be recommended. In the following insertion, an example for the interlinkage of flexible gas consumption according to a flexible energy output of the plant and the operation of upstream components as gas storage capacity and gas production rate resulting directly from the biological process is given. In [24], the gas storage utilization is addressed. Assumptions are different compared to the example given here—but all lead to the conclusion that the gas storage capacity is a crucial part of any flexibilization concept.

Example for the relation of biogas production and gas storage capacity utilization

The example given in Fig. 3 presents the effect of flexible biogas production on the necessary gas storage capacity based on different gas consumption (e.g., CHP, boiler, or an fuel cell) capacities and subsequent different gas consumption operation time periods. The average load (gas production and consumption) is equal in all analyzed scenarios.

The flexible gas production (Fig. 3a, solid black line) was taken from laboratory experiments using a feeding management, which proofed the stability of the process even under large gas production amplitudes [24].

The average gas production which is equivalent to the nominal load (Fig. 3a, gray dotted and dashed line) has been displayed as constant gas production and used as reference case (set to 100 %). The available gas storage capacity has been set to 8 h of nominal load gas production rate for all cases.

The consumption of the produced gas has been set for three scenarios at 16, 12, and 8 h of gas utilization (Fig. 3a, gray and black dotted lines). These conversion times result in a demand of respective 16, 12, and 8 h of gas storage capacity.

Figure 3b–d illustrates the effect on the necessary gas storage capacity caused by flexible and continuous gas production for the respective scenarios of gas conversion/gas storage time 16/8, 12/12, and 8/16 h. Since the standard case has a gas storage capacity of 8 h, the 8/16 scenario represents the limit of the operation with

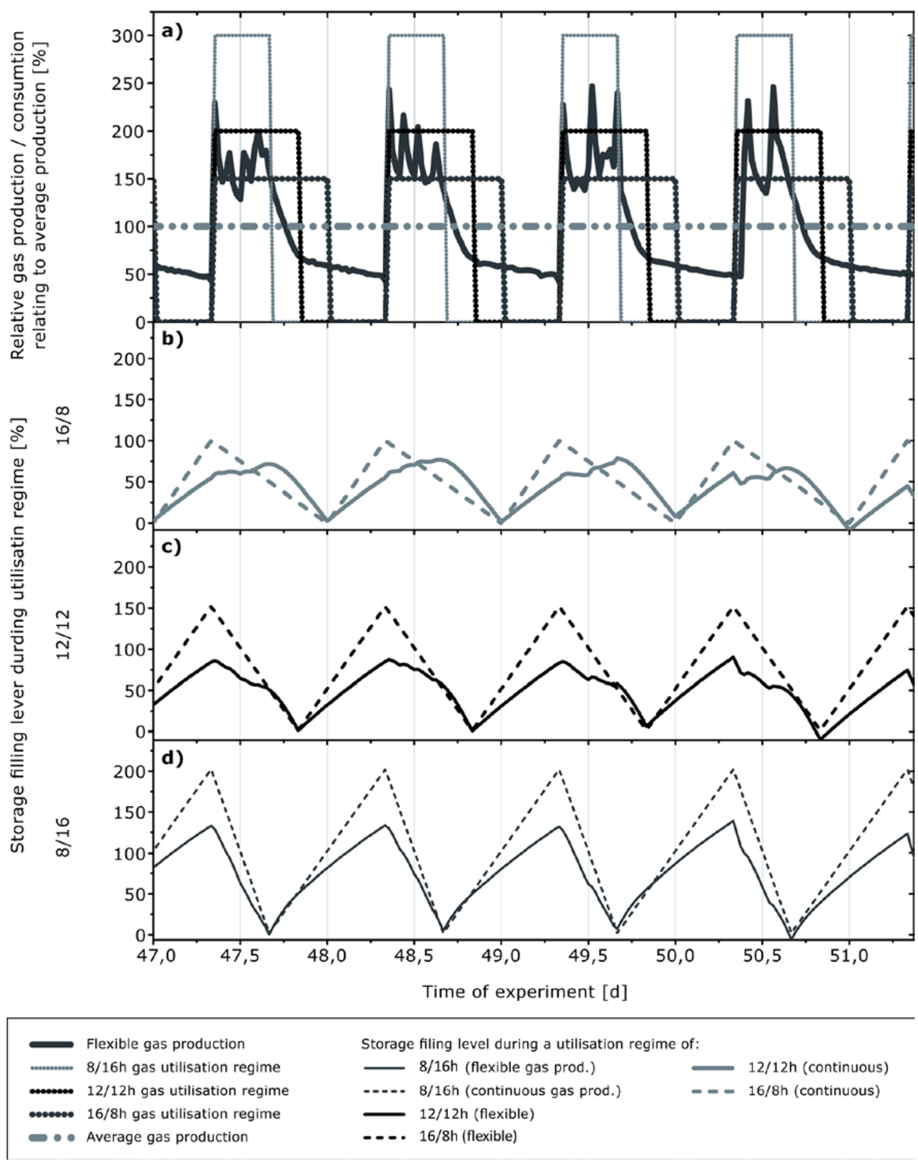

Fig. 3 Gas storage demand comparing continuous feeding and flexible feeding [105]

constant gas production. The available gas storage (100 %) is utilized completely. The flexible gas production requires a substantially reduced gas storage capacity (Fig. 3b solid line). The 12/12 scenario (Fig. 3c) is already not to realize by means of constant gas production, whereas the flexible gas production allows such an operation without exceeding the available gas storage capacity. The scenario with 8 h of gas consumption and 16 h of storage cannot be accomplished by neither constant nor flexible operation (Fig. 3d). The available gas storage and the variation of the gas production rate are not large enough.

Nevertheless, in all cases, the flexible gas production reduces the necessary gas storage capacity substantially. It is obvious that the flexible gas production increases the options of the plant regarding flexible energy output—in this case, the possible downtime of the plant could be enlarged from 8 to 12 h—without any additional invest or alterations within plant construction [34].

Different from other concepts aiming at minor changes of existing technology as the increase of the gas storage or the adjustment of feeding management, in [24], technical concepts for flexible biogas production are introduced. The concepts suggest first a hydrolysis of the substrate and subsequent separation of the easy degradable liquid fraction. This fraction will be treated in a separate fixed bed digester allowing fast ramps in gas production. A second concept includes the feeding of the fixed film digester from a leach bed digester instead of the hydrolysis effluent [24]. The third concept presented includes a hydrothermal pretreatment followed by a liquid/solid separation aiming at fiber rich fraction for material use or combustion and a liquid fraction suitable for digestion in a high rate concept [24].

Electricity from liquid fuels—technically promising but in competition with other utilization pathways

Status quo

Liquid biofuels could also be used in stationary engines, producing heat and power. In Germany, more than 2000 CHPs using vegetable oils were installed in support of Renewable Energy Resource Act until 2012. Currently, approx. half of them are still operating with vegetable oils (mainly rape seed oil and palm oil). The plants are operated heat driven between 1000 and 4000 full load hours per year [34].

Technology

Liquid biofuels are mainly produced for the transport sector. In general, they are transported and stored in tanks. Due to the comparable high energy density of 9.6 kWh per liter, the effort for storage and transportation is significantly lower than for raw biogas, which has a typical energy density of around 6 Wh per liter [35]. Liquid biofuels are converted in retrofitted diesel series engines [36]. Adjustment of the engines to different kind of liquid biofuels is stated [37]. One concept for flexible provision combining a domestic biodiesel CHP system of 2.5 kW_{el} with hybrid electrical energy storage has been practically tested in the UK to improve the efficiency of stand-alone renewable power supply systems [38]. So, in principle, conversion units for liquid biofuels can provide flexible power for a comparatively high number of applications as biogas can.

Market

Due to increasing prices for vegetable oil, a large number of plants are not operating anymore or have been converted to alternative renewables like biomethane, wood gas, or fossil fuels [22]. On the other hand, the relevance of other liquid bioenergy carriers such as used cooking oil, animal fat, pyrolysis oil, biodiesel, and bioethanol is increasing globally [39]. Also, for the currently operated plants in Germany, the additional income potentials from flexible power provision are not of major interest: most of the plant operators in Germany do not actively use the market options so far [34].

Outlook

Liquid biofuels however are regarded as one of the options for the transition of the transport sector, and because of this possible feedstock competition, the provision of electricity might not play a major role in the near future.

Electricity from solid biomass—moderate chances for heat-driven plants

Status quo

The thermochemical conversion of solid biomass plants could also contribute to flexible power generation. Today's combined heat and power plants for the production of energy from solid biomass are designed to provide either electrical power on a fixed level or to meet heat demand. In Germany, the main existing types are working with water steam cycle (with typical electrical power of more than 1 up to 20 MW_{el}), Organic Rankine cycle (ORC) with 0.1 to 5 MW_{el}, or a combination of gasification and gas engines with usually less than 500 kW_{el} [40]. Depending on size and technology, different degrees of flexibility can be reached. Together, these systems provide an installed electrical capacity of more than 1.5 GW [22].

A systematic questionnaire-based survey conducted by DGAW (Deutsche Gesellschaft für Abfallwirtschaft e.V.) showed that 29.5 % of steam and ORC based power plants for solid biomass in Germany are already offering flexibility, while 10.5 % are currently in the preparation to do so [41]. All of these plants offer negative control power, with a few additionally offering positive control power. Nominal power of these plants was between 1.6

and 20 MW_{el}, of which 20–88.5 % are offered as control power. Most of those plants (71.4 %) offer only tertiary control, 17.9 % are offering secondary control, while the remaining 10.7 % offer both types of control power. About 50 % of the plants required additional investments, typically in the range of 10,000 to 50,000 €, which were spent for additional control and automation. According to the questionnaires, about half of the remaining 60 % are technically capable to adapt for offering control power.

Technology

Increasing flexibility can mainly be achieved in two different ways. On the one hand, existing equipment within the operation units can be exchanged or improved to increase their flexibility. This includes not only hardware but also the control system. On the other hand, introducing additional storage options for intermediate energy carriers may provide higher flexibility.

- In steam-cycle-based power plants, solid biomass is completely burnt within a furnace to produce superheated steam which drives a steam turbine. There are different furnace technologies, including a variety of grate firings and fluidized bed combustion. Within a number of heat exchangers (boilers), water is heated and converted to steam, which is superheated. The parameters for this steam, especially temperature and pressure, are an important design feature and have influence on investment and operation costs as well as on electrical efficiency. A common way for negative control power is the bypassing of steam around the turbine, providing additional heat to heat grids or storages. Additionally, some technologies (e.g., furnaces with stoker spreader) are capable to easily reduce combustion load [41].
- In power plants based on the Organic Rankine Cycle (ORC) [42], combustion heat is transferred to silicon oil with special thermodynamic properties. The transfer often takes place via a thermal oil cycle to prevent overheating of the silicon oil. ORC requires less manpower in operation but has higher investment costs. ORC power plants already offer a relatively high flexibility and can be operated at 10 to 100 % of nominal load with good load change rates [43, 44].
- In gasification-based CHP systems, the thermochemical conversion of solid biomass is separated into two different process steps. At first, gasification takes place in an explicit reactor. The product is a gas with high hydrogen and carbon monoxide content. With high-quality fuels, a high load flexibility of the gasifier is already proven [45]. The second step is final oxidation, which takes place in more or less conventional combustion engines or turbines or in electrochemical systems like fuel cells. A common existing approach for flexibilization of power generation from biomass gasification is the combination of several small systems.

The main advantage of gasification-based systems in terms of flexibility is the possibility to use existing flexible CHP technology known from gas conversion. It should be noted that for comparable installed power solid fuel CHPs usually have higher start-up and shutdown times compared to liquid- and gas-fuelled systems [46].

The installed power plants for the use of solid biomass and the existing methods for flexibilization give an indication towards the general approaches: (a) increasing flexibility of larger CHP units with methods in analogy to large-scale fossil fueled power plants and (b) using small and decentralized units that allow for grid support from the bottom.

Besides existing methods to increase flexibility, there are also ongoing research activities using both approaches. One example for the first one is a research project on flexible power production in biomass CHP plants. The project is conducted by a consortium of a research institute, a German virtual power plant operator, a power plant engineering company, and an operator of a biomass CHP plant based on ORC technology [47]. Within the project, several options for flexibilization of a solid biomass CHP will be researched and tested in an existing power plant. Within another study, the optimal operation of a biomass CHP within a spot market has been investigated [48]. The steam-based CHP with extraction turbine had a nominal power of 2.05 MW_{el}, with an electrical efficiency of 14 %. The study showed that higher flexibility in such biomass CHP, including flexible operating point (part load behavior) and thermal storages, improves the feasibility of including it to district heating networks. Other research is dealing with the flexibilization of decentralized CHP systems [45, 49], concentrating on the second approach.

Increased flexibility of power production from solid biomass is also a topic in hybrid energy research. Especially, the combination of concentrating solar power (CSP) with bioenergy (usually from grate firing or fluidized bed combustion of solid biomass) has been a focus [50–58]. A CSP-biomass hybrid power plant with 22.5 MW of electrical power has gone in operation in Spain, combining parabolic trough technology with thermal oil [59]. Although CSP is no common approach for Germany's power market due to climatic conditions, research in the CSP-biomass hybrid field has some common topics with development of flexible stand-alone solid biomass CHP.

Market
By increasing the flexibility of such existing plants, these plants could help to stabilize the power grid and reduce residual load demands. The application of different technical adaptations allows for power provision in different time frames of flexibility (see Table 2).

Currently, there are several developments in the sector of small and micro scale CHP units, which could provide decentralized heat and power in a flexible way [60, 61]. Introducing such plants to buildings' heating, ventilation, and air conditioning (HVAC) systems, they can provide electrical power based on the demand of either the local power grid or the object power supply. Control systems, which should be linked to building automation, are considered to be an important factor for successful technical integration.

Outlook
At the moment, support schemes are not envisaged for thermochemical conversion for greater flexibility among Germany's renewable energy resources [9]. Still, about 30 % of solid biomass-based power plants in Germany already offer flexibility in terms of secondary and/or tertiary control, with about 10 % more currently preparing to do so and 30 % more having the technical potential. Thus, the technical potential of current installations for flexibility is in the range of 500 MW_{el} (up to 70 % of plants, around 50 % of nominal power). Together with ongoing research activities, the potential contribution might increase in the mid- or long term, provided that a general economic perspective of solid biomass electric power generation is granted.

Heat from biomass—shrinking but exact controllable installation lead into future
Status quo
In Germany, about 12 to 14 million biomass room heaters and 0.7 to 0.9 million wood boilers are installed in buildings. In sum, they provide 40 % of the renewable heat. While room heaters are typically used as additional heat source, boilers are either used as a baseload heat source in combination with a gas or oil boiler or as single heat provision unit.

New installations of single room heaters are at a level of 0.4 to 0.5 million per year, while new installations of biomass heating boilers are at a level of 50.000 to 70.000 per year. Small-scale CHP systems with less than 10 kW of thermal output and significant electricity production (at least 20 % of fuel input) for solid biomass are not market ready at the time [62].

For wood boilers, combination with a solar-thermal-heating devices is stated. Additionally, since some years, the combination of heat pumps and single room heaters with a connection to the hot water cycle of the housing is considered to be ecologically and also economically feasible [63]. Efficiencies and emission levels are within regulatory frames as long as the systems do not perform too many load changes or too much time in low part load.

In the literature, flexible energy from biomass is mainly a topic of power generation (see other chapters in this article) and not of flexible heat provision. For Inland Norway, there is a study about the influence of using more bioheat boilers and heat pumps instead of heating with electricity [64], but the main concern also was about the electricity system.

Technology
The heat demand in the residential sector is characterized by seasonal, weekly, and daily shifts due to season, weather conditions, and behavior of the inhabitants, for example. Typically, three main concepts of heat supply from solid biomass are state of the art [65, 66]:

Small scale additional heat from furnaces using log wood or wood pellets. The furnaces run on full load, and adjustment to the heat demand is realized by operation time and the control system of the central heating system (e.g., oil boiler with heat sensors in the housing).

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

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

Small scale boilers (pellets, wood logs, and sometimes wood chips) as central heating system of buildings, sometimes, in combination with solar thermal energy. Changing load demand is handled by load adjustment of the boiler and by switching the boiler on and off. Often a thermal buffer tank is installed to reduce the number of start and stop-phases of the boiler.

Wood chip boilers of medium size are mainly operated as baseload heat provision in combination with an oil or gas boiler. Quick adjustments to the heat demand are operated by the oil or gas boiler, whereas the biomass boiler is run on a more or less stable load level.

Different papers analyze the hybrid use of heat from biomass and other renewables and try to calculate an optimal distribution [67–69]. Within the expected changes in future heat supply with more fluctuating sources like solar thermal heat, environmental heat by heat pumps, waste heat, and heat from surplus electricity biomass heat systems are faced with the following challenges: (i) the need for adaptation to a fall in the load demand for heat through improved building insulation and (ii) the need for much higher flexibility to adjust not only to changes in load demand but also to often rapid changes in the provision by other heat sources [70, 71]. Even as heating or cooling of water cycles is not possible in short times, the total efficiency of heating systems with different sources very much depend on an adequate integration of heat from biomass. For example, even the common combinations of solar thermal and biomass heat generation often have quite low annual efficiencies due to too long operation times of biomass boilers [72]. Also, it is well known that emissions from wood chip boilers increase during load changes and also for part load quite below 50 % of the nominal load [73]. Therefore, to achieve even higher flexibility as now without increasing the air emissions and without significant losses in efficiency, further developments are needed.

According to the above mentioned basic heat from biomass concepts, listed in Table 3 are some exemplary options for future more smart heating concepts.

Market

Changes to more flexibility of single room heaters and small scale boilers are still quite random. For small room heaters, there is a small but growing market of heat pumps combined with single room heaters with an integrated water cycle to the central heating system in very well-insulated buildings [63]. The advantage is the cheap thermal heat from the single room heater especially on the very cold days when the efficiency of the heat pump decreases quite significantly. So the total annual efficiency can increase.

At the moment, no quick changes towards more flexible biomass-fed heating technologies are to be expected as the use of renewable heat is increasing only at a very low level, and the further insulation of buildings is also stagnating in Germany. Additionally, at the moment, there are no economic incentives to combine bioenergy with other renewable heat sources (renewable hybrid systems).

Outlook

With the need for a full renewable energy supply in the future due to climate conservation also in the heating section biomass will become a gap filler as it is stored easily.

Table 3 Exemplary options for future smart heating concepts, data based on Smart Bioenergy, Ch. 6 [107]

State of the art concept	Changes in concept	Needed research and developments	Timeframe
Small scale log wood and wood pellet furnaces	By integration of water pockets, the furnaces will be linked to the central house heating system. A central control unit will give advice to the user for additional heat demand and will optimize automatically the heat release to the room and to the central heating system which has a heat storage.	Automatization of the heat release; furnaces with active air control; system controllers to integrate the biomass heat into the heating system of the building	First combinations of heat pumps with wood log stoves or wood pellet stoves are already installed; optimized systems could be market available in up to 5 years; fully integrated and intelligent controlled smart systems will be available in about 10 years
Small scale wood pellet, wood log, and wood chip central heating boilers	Either fully integrated biomass boilers or micro-CHP-units will be installed to fill all the remaining heat gaps by stabilizing the electricity grid as much as possible.	Small size high flexible combustion as well as gasification units; improved high-quality fuels; micro-CHP-units with high electrical efficiency and very quick reaction times; intelligent system controllers	Highly flexible and almost emission-free wood pellet boilers with less than 4 kW thermal output market ready in up to 5 years; improved fuels also from non-woody sources stepwise in the next 5 to 15 years; small-scale gasifiers depending on fuel 5 to 10 years; micro-CHP-units depending on the fuel, technology and level of electrical efficiency 5 to 20 years
Medium-sized bi-fuel wood chip heating systems with additional oil or gas boiler	Highly flexible small scale CHP units with high electrical efficiency will be integrated into local heat distribution grids stabilizing the electrical grid as much as possible at the same time.	Small-scale gasifiers especially for non-woody biomass; highly flexible motor engines and fuel cells; highly efficient heat distribution systems; intelligent system controllers	Depending on the scale of efficiency the systems will be available in 5 to 15 years; market integration will very much depend on economical conditions

The realization of the shown future concepts depend very much on energy prices, change of heating systems towards a high share of renewables, research success in the field of small scale gasification, and also on the development of power storage units.

With regard to the shifting demands of heat and power small- and medium-scale CHP systems will be key, so that the heat from solid biofuels will become more and more a co-product of electricity provision for very local grid stabilization in integrated energy systems.

Balancing across energy sectors—the role of biomass in power-to-X concepts

Status quo

With the ongoing increase of the transformation of the power system from fossil to renewable energies, fluctuating solar- and wind generation could lead to period where the power generation exceeds the need [74]. If this happens, the surplus energy has to be transmitted, stored, or become curtailed [75–77]. If in the future the frequency and duration of these periods increase [78], another approach is to transfer the surplus energy into other sectors.

Currently, different concepts are discussed and tested: (i) power to gas, (ii) power to liquid, (iii) power to chemicals, and (iv) power to heat. They are in different stages of realization. Combination with biomass is seen especially in the power-to-gas systems. Today, in Germany, 16 power-to-gas systems are installed [79].

Technology

Power-to-gas concepts are based on electrochemical conversion units which primary produce hydrogen by electrolysis using surplus electricity. It is also possible to convert hydrogen plus carbon dioxide into synthetic methane which is available for long-term energy storage in the existing gas grid [80–82]. In power-to-gas concepts, the integration of biomass is mainly discussed for biogas plants: one approach of integration is use of excess power to increase the methane output, without additional feedstock necessity by converting the CO_2-fraction of biogas with the addition of electrolysis-hydrogen [83]. These so-called "power to gas" concepts are based on the assumption that fluctuating renewable energy sources such as wind and photovoltaics produce excess electricity which is available for long-term energy storage [84].

The hydrogen could be converted to methane by adding carbon dioxide—a major by-product within the biogas production process [85, 86]. The conversion process can be realized from a thermochemical process in the presence of catalysts or from a biological process [87, 88]. Concepts for the latter include the injection of hydrogen into the process through membranes or the direct injection of the gas [89]; another option could also be a separate fermentation tower for gas conversion [90].

The produced methane can be fed into the gas grid and further be processed to liquid fuels (power to liquid) [91] or to chemicals (power to chemicals) [92]. For electricity supply, power-to-gas concepts provide an additional opportunity to use the natural gas grid as a storage system to compensate fluctuating wind and solar power for some days or even weeks.

A very cheap option to get along with surplus power in the grid might be the heating of water buffers in heating systems by this surplus energy (power to heat) [93]. Today, 14 multi-megawatt installations in Germany are stated [94]. As long as the grid capacities are given, this is more efficient than stopping renewable generators. As in typical heating systems, only temperatures of less than 100 °C are created and transferring back to electricity later on is not valuable.

Market

Most of today's power-to-gas plants can be operated as pilot installation for research and development; a minor proportion is used for commercial purposes [95]. For example, some power-to-gas plants feed their gas into public gas grid and sell it virtually to private and customers as a renewable alternative for or an addition to natural gas [96].

The Market for power-to-heat applications is an early stage and still under construction. Typically, power to heat is used in combination with CHP, to serve negative control power by maintaining the thermal output [97].

Outlook

As surplus electrical power is at the time especially not a winter problem, the heat from this source is not reliable for secure heating and even cannot reduce the needed heating power installed in a building. Even it is only an option for very quick reaction times and should not be used for longer times without an intelligent system controller, power to heat is one easy option to preserve renewable exes energy to get lost [98].

The potential role of power to gas is more important in a long-term perspective, when the share of renewable energies exceed about two-thirds of energy demand [99, 100]. Nevertheless, it is necessary to develop this technology also at pilot scale to achieve gradually improvements of this technology and to collect practical experience under real conditions.

Conclusions

In the future, energy system flexible bioenergy can cover some of the residual load especially in the power sector. For Germany, the expectation is to contribute to the missing capacities and to replace a higher portion of fossil fuels within these remaining capacities and acting in markets with increased prices for electricity. Therefore, the individual technologies and plants need to be adopted towards an optimized contribution of bioenergy technologies to the overall energy system. This requires conversion plants with units that can be controlled with precision and well adapted to short reaction times, with a partial load function of the conversion process and additional storage facilities. The conceptual approaches and the technical potential for developing different biomass provision routes towards more flexibility are manifold.

Power provision from biomass is one application, where increasing flexibility can be expected in the years to come when electricity from wind and photovoltaic will become even more important. Due to the specific frame conditions of power provision, the demand for flexibility in this sector is expected to be very challenging, requiring reaction times of only a few minutes to provide positive or even negative energy to balance grid stability.

Highly flexible heat provision in small scale combustion units is not so much an issue at the moment but is expected prospectively to be due to an increasing supply of heat from solar systems and/or heat from excess energy from wind and photovoltaic (power to heat).

Furthermore, the increased availability of fluctuating wind and solar power will provide excess energy during certain periods. Basically speaking, this excess electrical energy can be converted into thermal or chemical energy and meet some of the demand for heat or fuel consumption. As a result, some of the flexibility needs can be shifted between the different sectors.

Challenges on the road to becoming more flexible do not only occur from the technical options and limitations but also from the elements of the supply chain, including sustainable feedstock provision, the implementation of flexible conversion concepts, and the demand from the renewable energy market. The new technology options might also support the introduction of bioenergy plants in regions of instable grid conditions or locally fluctuating energy supply. Flexible provision of bioenergy is always connected to higher specific provision costs because additional conversion units are needed and/or the plant is providing energy in part load. Especially in the electricity market, price signals are necessary to shift existing bioenergy plants towards flexible provision.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
JL carried out the options for power from flexible biogas. AO carried out the options for flexible power from solid biofuels. VL carried out the options for flexible heat from biomass. MD carried out biomass options for power-to-X concepts and participated in the market analysis. DT conceived of the study and participated in its design and coordination and helped to draft the manuscript; she carried out introduction and conclusion and the demand from energy markets and the options for flexible power provision from liquid biofuels. All authors read and approved the final manuscript.

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