Pfau et al. Energy, Sustainability and Society (2017) 7:17
DOI 10.1186/s13705-017-0120-5

Energy, Sustainability and Society

ORIGINAL ARTICLE

Open Access

Biogas between renewable energy and bio-economy policies—opportunities and constraints resulting from a dual role

Swinda F. Pfau[1*], Janneke E. Hagens[1] and Ben Dankbaar[1,2]

Abstract

Background: Biogas plays a major role in two policy domains: the renewable energy domain and the bio-economy domain. The purpose of this paper is to examine the relationship of current biogas practices with the two policy domains and to identify how biogas can contribute to both.

Methods: The paper is based on an analysis of views and ideas gained in a large European project addressing different aspects of biogas production and application, gathered through interviews with a variety of stakeholders involved in the project.

Results: Current practice shows opportunities for biogas to contribute to both domains. Biogas production is an efficient way of using especially residual biomass and can provide multiple products for both policy domains. Biogas can function as a system service provider in the renewable energy domain, and various products of the biogas production chain can serve as input for bio-based products. However, the diverging goals of the two policy domains and associated instruments currently hinder the development of innovative connections between them.

Conclusions: The focus on biogas for energy as single main product should be diversified towards creating multiple products and using biogas optimally through innovative solutions. To maximize the contribution to both policy goals, policy makers should jointly aim at optimal use of biomass for multiple goals. Policies should aim at improving the competitive position of biomass-based products over fossil-based products and optimizing the use of biomass resources, rather than inciting competition between the different biomass applications.

Keywords: Biogas, Bio-economy, Renewable energy, Policy coherence

Background

Biogas plays a major role in relation to two different, but interconnected, policy goals currently pursued by the European Union and its member states: increasing the share of renewable energy and achieving a transition towards a bio-economy. These two policy domains partly overlap where they are concerned with the same resource, biomass, but different applications. This overlap results in a competition between policies over scarce biomass resources. The purpose of this paper is to examine the relationship of current biogas practices with the two policy domains and identify how biogas can contribute to both policy goals, maximizing the efficiency and sustainability of biomass use. Empirically, it is based on data collected through interviews with project partners in the Dutch-German INTERREG project 'Green Gas'. The project partners, addressing a great variety of topics related to biogas production in this project, can all be considered stakeholders involved in current practice in the biogas sector.

We first review the goals and drivers of the two policy domains in the EU, Germany and the Netherlands, and elaborate on the position of biogas within them ('Dual role of biogas in policy goals' section). We then analyse the scientific debate regarding the position of biogas in the two policy domains ('Between renewable energy and bio-economy' section). In the 'Research approach' and 'Results and discussion' sections, we present our research and explore current biogas practices with regard to both policy domains. We discuss the opportunities identified by

* Correspondence: s.pfau@fnwi.ru.nl
[1]Institute for Science, Innovation and Society, Faculty of Science, Radboud University Nijmegen, P.O. Box 9010, Nijmegen 6500 GL, The Netherlands
Full list of author information is available at the end of the article

practitioners to contribute to the different goals as well as the constraints they encountered. In a concluding section ('Conclusion, policy implications and future research'), we discuss the most promising ways for biogas to contribute to both policy goals in the future and give recommendations for aligning policies in the two domains.

Dual role of biogas in policy goals

Following the Renewable Energy Directive (RED), the European Union aims at a 20% share of renewable energy in the total energy consumption in 2020 [1]. Important drivers for renewable energy policies in Europe are security of energy supply, related to dependence on oil and gas-exporting countries, concerns regarding nuclear energy, and the impact of greenhouse gas (GHG) emissions on the global climate [2–7]. Electricity and heat production from biogas are important building blocks to achieve the European 20% goal. In 2014, biogas accounted for 6.4% of all renewable electricity production in the EU 28 [8]. In Germany and the Netherlands, biogas contributed to renewable electricity production for 16.8 and 10.6%, respectively, in 2015 [9, 10]. Germany is the European leader in biogas production with around 8900 installations in 2015 [11], mainly due to the introduction of performance subsidies[1] that were relatively high in comparison with other countries until 2012 [12, 13]. The high contribution of 16.8% to overall renewable electricity production shows the important position of biogas in the German renewable energy strategy. Biogas is considered a versatile form of energy, since it can provide electricity and heat and can be stored and distributed via gas pipelines. Storage offers the potential to buffer fluctuations in the provision of photovoltaic and wind energy [7, 14, 15]. Figure 1 schematically shows a biogas production chain with typical routes for energy production. Especially, heat production from biogas has a high potential to reduce CO_2 emissions [7]. In the Netherlands, support for biogas production has been described as a 'roller coaster' [5]. It was initially aimed at treating waste streams such as manure and organic waste and not seen as a promising technology for energy production. The sector suffered from political and financial uncertainties until regulations and subsidy regimes were altered in 2003–2004 [5, 16]. This is reflected in the relatively low contribution of biogas to Dutch renewable electricity production (10.6%). Later, the introduction of a fixed premium subsidy enabled the development of biogas and green gas projects, but a finite budget for this subsidy and a first come, first served granting system made it less reliable for both businesses and investors than the German subsidy system [17]. In the last few years, renewable energy policies focused mainly on heat production from biomass and the combination with carbon capture and storage (bio-CCS) [18, 19].

The EU, Germany and the Netherlands have published strategies for a so-called 'bio-economy', where biomass replaces fossil resources for a great variety of applications, including not just bioenergy but also bio-based materials [20–22]. Important drivers in the bio-economy policy domain are the need to reduce dependence on fossil fuels, reduction of GHG emissions, secure supply of energy and commodities, and an expected boost for economies in general and rural areas in particular [20, 22–25]. These drivers not only partly overlap with the drivers for renewable energy policies (security of supply and reduction of GHG emissions) but also feature some additional aspects. Bio-economy policies do not exclusively focus only on bioenergy but also on other biomass-based products, for example replacing fossil resources in material production and securing commodity supply. In Western Europe, hopes are high that high-tech, bio-based products will create economic revenues [26]. There are no subsidy schemes aimed directly at biogas production in the bio-economy domain; biogas production is only stimulated from a renewable energy perspective. In Germany, in reaction to sustainability issues and the food vs. fuel debate, research and development policy specifically focuses on the use of residual biomass for biogas production and the integration of biogas in the bio-economy through cascading and biorefineries [27]. In the Netherlands, an academic and societal debate around different biomass applications has evolved in the last years. On the one hand, it is argued that bioenergy is extremely important to reach renewable energy goals and mitigate climate change [4]. On the other hand, bioenergy is heavily criticized as being inefficient in actually reducing carbon emissions and competing with other land uses [28]. It is argued that while there are other sources of renewable energy,

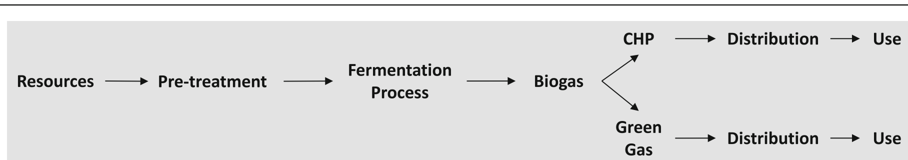

Fig. 1 Schematic representation of typical biogas production chains

fossil resources as raw material for the production of various materials can currently only be replaced by biomass (ibid.). In current bio-economy policies, bioenergy is included as one of the products, but it is viewed as the least valuable utilization of biomass [21, 25, 29]. Different concepts, such as cascading principles, biorefineries or prioritization according to the value of the end product, are discussed. Generally, these concepts aim at using biomass resources efficiently for multiple products and favour higher-value applications. Biogas for electricity and heat production is often ranked particularly low in this context (ibid.).

While the different applications compete for the same resource, they may also face similar problems regarding, for example resource availability, and may thus be able to profit from joined undertaking. This may offer various synergies between policy domains.

Between renewable energy and bio-economy

In the scientific literature, several issues regarding biogas are discussed that relate to this position between different policy domains. We summarize the debate under the following headings: resources, technology, products and financing and regulations.

Resources

Various biomass resources can be used as a feedstock to produce biogas. The majority of biogas installations in the EU currently use energy crops, such as corn, as a co-substrate together with manure [30]. But due to high corn prices, competition for land and ethical considerations, some argue that residual biomass resources should be preferred for energy production, while cultivated biomass, which is generally of a higher quality, should be used for other purposes (cf., [31]). Other proposed routes are focusing on the production of multi-purpose biomass, aiming to overcome the food vs. fuel debate through the provision of multiple products from agricultural biomass [32], and the adoption of multi-feedstock technologies that allow for the use of both waste and agricultural biomass, depending on local resource availability [33].

Products

Biogas can be used to produce energy in different ways. As an alternative to the production of electricity and heat in combined heat and power (CHP) units, biogas can be upgraded to 'green gas' (or biomethane), which is gas with a higher methane to carbon dioxide ratio. For example, carbon dioxide in biogas can be converted into methane through methanation reactions adding hydrogen. The hydrogen needed for these reactions can be produced with power-to-gas technology [34–36]. Through the conversion, the methane content in the gas is increased, which makes green gas compatible with natural gas. It can be fed into the natural gas grid and thus replace natural gas [34]. The sustainability of green gas, (partly) replacing natural gas, has been shown to be perceived as positive by the Dutch public [37]. Not only does green gas enable energy applications in other locations and at other times, it also provides an interesting link to other sectors, where natural gas is currently used as a source of methane for the production of chemicals. Using biogas or green gas based on residual biomass for the production of chemicals could increase the societal acceptance of bio-economy products [38].

Technology

Most biogas installations produce biogas with a methane to carbon dioxide ratio of 60 to 40 as main valuable output, which is subsequently converted into energy in CHP units [30, 39]. The technology of biogas production is still under development, aiming at higher biogas yields. However, it is argued that rather than focussing on increasing biogas yield, innovative technologies should be applied to produce multiple products. An example is the treatment and use of digestate, the residue remaining after processing in the biogas reactor, as synthetic fertilizer substitute. This way, biogas installations could be integrated in small biorefineries, a concept which is increasingly appreciated in the development of a bio-economy [40, 41]. Moreover, the decentralized production of biogas becomes more economically viable through integrated production systems [33].

Financing and regulations

Currently, subsidies for biogas production are provided in the renewable energy domain. Other applications of biogas do not enjoy the same financial advantage. Production of green gas as transportation fuel has to comply with sustainability regulations defined in the European RED,[2] while bio-based products are not yet subject to comparable regulations. Some biomaterial applications can be realized despite the unfavourable financial situation, but this is expected to result in a competition over resources that increase feedstock prices, which in turn strongly influence the economic viability of applications [42]. Both energy and material applications furthermore face different types of regulations, e.g. regarding feedstock requirements or waste treatment regulations [12, 43].

Methods

To analyse the current practice of biogas production and its position between policy domains, we analysed the results and experiences gained in the Dutch-German INTERREG IV A project 'Green Gas.' This European trans-boundary project started in 2012 and was finalized in June 2015. It consisted of 16 subprojects with a great variety of project partners including research institutes, governmental organizations and private sector organizations from both Germany and the Netherlands. The Green Gas subprojects addressed different aspects of biogas production and application in Germany and the Netherlands, aiming to advance the biogas sector. Most subprojects focussed on the possibilities of green gas applications and the use of residual biomass resources. The diversity of subproject aims provided the possibility to gain a comprehensive overview of current biogas practice.

We conducted semi-structured interviews with project partners from the different subprojects. A total of 15 interviews with partners from 14 subprojects were carried out in 2014. We interviewed the project leaders of these subprojects, as shown in Table 1. They were chosen as interview partners because they had comprehensive knowledge of their own subproject and worked in close interaction with project partners from research institutes, private sector and governmental organizations. Furthermore, they were also able to reflect on the experiences gained in other subprojects in which they were involved as project partners. The interviews were concerned with the views and ideas of the interviewees regarding the relationships of current biogas practices with the renewable energy and bio-economy policy domains. The interviewees were regarded as stakeholders involved in current practice in the biogas sector, not necessarily as policy experts but knowledgeable on the impact of current policies.

The interviews were analysed in line with a thematic analysis approach. We used the qualitative data analysis (QDA) software package ATLAS.ti (version 7) to identify common themes in the interviews, coding the transcripts in several steps. The interview questions were based on the topics derived from the literature as discussed in the 'Between renewable energy and bio-economy' section (resources, products, technology, financing and regulations) and addressed context, goals and results of the individual subprojects, the experience of project partners regarding current practices, their views on the potential of biogas production, and the relationship between biogas and the policy goals of renewable energy production and the bio-economy. In the 'Resources' to 'Financing and regulations' sections, we present the common themes identified in relation to each topic.

Figure 2 shows the various topics addressed in the Green Gas subprojects and their relationship to a schematic biogas supply chain, incorporating various options of feedstock choices, processing steps and distribution pathways. The fact that this project addressed so many different aspects of biogas is of particular value regarding the goal of this paper, since opportunities and constraints may be found along the whole biogas supply chain. All subprojects considered biogas production in co-production facilities, using animal manure in combination with a co-product as feedstock. Only the feedstock choice for the co-product is depicted separately in this figure. Mono-digestion of manure receives a lot of attention in the Netherlands, but since manure is currently not considered as feedstock for bio-based products, there is no competition between bioenergy and bio-economy applications. Therefore, we do not consider biogas production from mono-digestion of manure in this paper but rather focus on the competition over biomass that serves as co-products in biogas production. The subprojects are briefly introduced in Table 1. More information can be found on the project website.[3]

Results and discussion

In this section, we present the results of our analysis, organized according to the four headings described in the 'Between renewable energy and bio-economy' section. Under each heading, we will first describe the views and expectations of the interviewees and subsequently interpret and discuss them in relation to the position of biogas between the renewable energy and bio-economy policy domains. We will refer to one (1), some (2–7), or most (>7) interviewees expressing a certain view or experience. Most issues were raised by only a couple of the 15 interviewees, which can be explained by the differences in project focus and background. Finally, in the 'Overview of results and general discussion' section, we will provide an overview of our results.

Resources

Some interviewees point out that there are currently biomass resources available that are underused. While processing routes and markets for bio-based products are still under development, biogas production is currently feasible and could make use of such resources, for example manure, landscaping residues, agricultural residues, catch crops and biomass from field borders. Some interviewees suggest that resources should not be wasted while waiting for innovative technologies but used now for applications that are already developed, such as biogas production. Furthermore, they expect that the demand for biomass created when the biogas production is increased will also help to mobilize the provision of more biomass resources. The supply of biomass is still underdeveloped and increased demand could be an incentive for more and better harvesting and logistic structures, increasing the availability of resources not only for energy production but all for biomass applications. According to the interviewees, improved logistics may also include new types of contracts to enable cost effective biomass management, for example parties that maintain landscapes for free in exchange for the right to harvest, use or sell the biomass growing there.

Table 1 Goals and results of the Green Gas subprojects and information on the interviewees

Subproject name and short description	Background interviewees
New generation biogas digesters: optimizing all process parameters in biogas digestion for more biogas production, higher economic returns and reduced environmental impact. Comparing different thermal and chemical pre-treatment options for residual biomass streams. Modelling fluid dynamics in digester	[a]Project developer; HoSt (industry, NL) Researcher; Saxion University of Applied Sciences (NL) Researcher; Münster University of Applied Sciences (GER)
Mechanical and enzymatic pre-treatment of organic residues: testing different mechanical and enzymatic pre-treatment options on various ligno-cellulosic substrates, focusing on biogas return, energy use and cost reduction	[a]Researcher; Münster University of Applied Sciences (GER) Director; DNL contact (industry, GER)
More divers resource use focussing on sugar beet: assessing possibilities to use sugar beets instead of maize in biogas installations	[a]Project coordinator; Centre of Competence 3N (industry, GER)
Biogas collection as connection between green gas producers: analysing possibilities to connect biogas producers via a biogas net and centralized green gas production	[a]Consultant; Ekwadraat (industry, NL)
Natural grass chain: improving biogas technology from pre-treatment to post-treatment to enable utilization of natural grass and roadside vegetation. Technological and economic analysis	[a]Managing director; Byosis group (industry, NL)
Information exchange via potential map: plotting information relevant for biogas development (e.g. existing biogas installations, biomass potentials, energy demand) on an interactive, web-based map to enable more biogas projects in the future	[a]Public servant; Province of Groningen (governmental organization; NL) Researcher; Münster University of Applied Sciences (GER)
Green Gas InNet: comparing different applications of biogas regarding, e.g. GHG emission reduction potential and technical and juridical conditions. Analysing possibilities to feed green gas into the natural gas net	[a]Researcher; Münster University of Applied Sciences (GER)
Green Gas in spatial energy concepts: analysing possibilities for biogas in joint energy management in industrial areas	[a]Researcher; University of Oldenburg (GER)
Assessment and management of Green Gas supply chains: technical benchmarking of biogas installations, identifying key levers for efficiency and environmental performance	[a]Researcher; University of Oldenburg (GER)
Waste water treatment plants as part of Green Gas hubs: optimizing sludge digestion in combination with waste water treatment, looking e.g. at processing, energy use, pre-treatment options. Analysing alternative options of using existing sludge digesters, e.g. using other feedstock.	[a]Researcher; Saxion University of Applied Sciences (NL) Researcher; Saxion University of Applied Sciences (NL)
Cheap resources and Sabatier process: analysing possibilities to improve the overall business case for biogas and looking for better technologies to upgrade biogas to green gas.	[a]Director; Hanze Welands (industry, NL)
Biogenic methane production from hydrogen and German–Dutch database biogas research: analysing technical possibilities to realize biogenic methanization to create CH_4 from CO_2 and H_2 as alternative for catalytic methanization. Developing an open source database for biogas literature in three languages	[a]Researcher; Münster University of Applied Sciences (GER)
Decentralized energy landscapes Germany–the Netherlands: integrated assessment of the use of residual biomass for biogas production. Focusing on sustainability and feasibility assessment of complete biogas supply chains, integration in regional context and landscapes. Analysing potential of using various residual biomass streams in biogas digesters. Investigating the potential of applying public-private partnerships for the use of residual biomass for biogas production	[a]Personal participation, Radboud University Nijmegen (NL) Researcher; University of Oldenburg (GER)
International trade of Green Gas via certificates: comparing policies for biogas and green gas in GER and NL and modelling possibilities of harmonizing international policies. Analysing possibilities of improving international trade of green gas via certificates, comparing existing certification schemes	[a]Project coordinator; JIN (industry, NL)

[a]Subproject leaders

Some interviewees suggest that biogas production can become an added value for waste processing. It can be used to process organic waste streams, creating added value through the production of energy and, in the future, extraction of valuable components. Interviewees expect that even if the focus may shift towards other

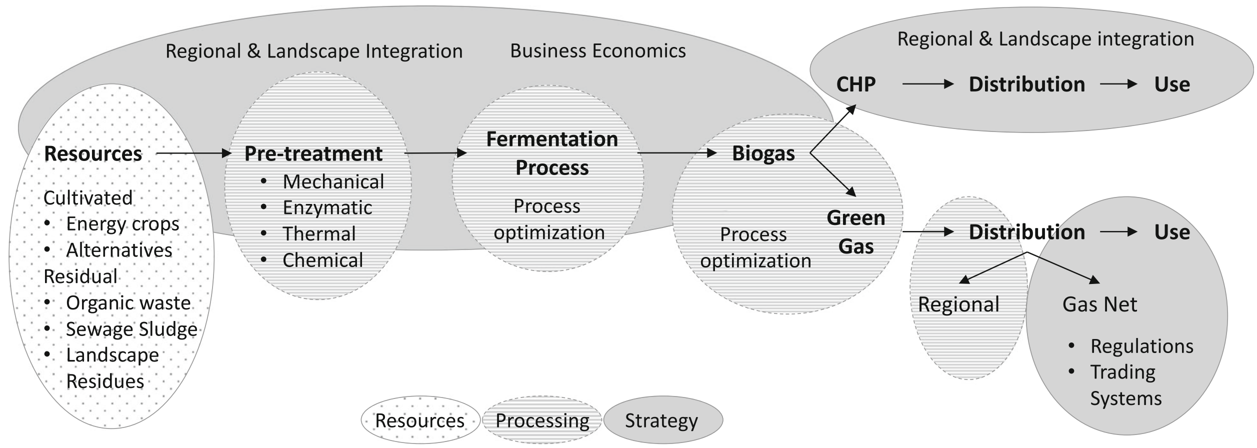

Fig. 2 Topics addressed in the Green Gas subprojects

products in the future, unusable waste streams will always remain that can be used for energy production.

Discussion: towards low-value biomass

These suggestions show the rise of a new perspective on resources in current biogas practice, focusing on biomass that is less attractive, less readily available and more difficult to process. Until now, the choice of resources was mainly focused on high energy food crops, enabling a high return of biogas per tonne. Rising prices for traditional biogas co-substrates, such as corn, and the food vs. fuel debate appear to force the sector to look for alternatives. Moreover, the upcoming bioeconomy, where higher-value products from biomass are expected to be developed, forces the biogas sector to look for different resources such as residual biomass. The switch from high energy food crops to residual biomass is not a new idea; it reflects a movement in the biofuel sector from first generation biofuels (produced from food crops) to second generation biofuels (produced from energy crops and residues) and a preference for residual biomass that has also been discussed for the broader bio-economy [31, 44]. However, while this switch has been approached from a sustainability perspective in the scientific debate, in biogas practice, economic incentives appear to be at least as influential. From a renewable energy perspective, optimal biogas production would be achieved with high-value biomass, but in practice it is expected that these resources will become the main feedstock for bio-based products. Thus, the perspective of the bioenergy sector moves away from choosing the best feedstock towards trying to find appropriate processing for otherwise unusable resources. This may reduce the energy output but could increase the overall benefit gained by using all resources efficiently, either for energy or for bio-based products.

Products

All interviewees were asked to reflect on the choice between using biogas to produce electricity in CHP units and upgrading biogas to green gas. Their comments showed that biogas is generally applied locally, whereas green gas is sold nationally or even internationally. The markets for biogas and green gas differ, and the choice should be made based on local conditions. One of the most important considerations is the vicinity of consumers: in CHP units, both heat and electricity are produced. While electricity can be fed into the grid and thus distributed easily, heat has to be used locally in a considerable proportion. Next to the heat used in the installation itself, the ability to sell heat in the vicinity is of great importance for the business case of biogas installations. An alternative that has been considered in one of the subprojects is to set up a regional network specifically for biogas, enabling the transport of biogas to locations where a CHP unit can serve both electricity and heat consumers. However, this appeared to be expensive and difficult to realize. Green gas offers the advantage of wider application; it can be fed in where it is produced and used where it is needed (provided access to the gas grid is in reasonable proximity, e.g. by choosing the location for upgrading installations strategically). Furthermore, the gas is storable (in the grid or otherwise) and can be used when needed, while CHP units always produce heat as well as electricity, even when the heat cannot be used (e.g. when there is little demand at night or in the summer). The biggest disadvantage of green gas is that, according to interviewees, it is very expensive to upgrade, requiring high investment costs up front. Furthermore, for feed-in, strict quality standards apply for green gas, and sometimes, conditions are unclear or changing. Some interviewees describe that some network operators in the Netherlands are not keen on accepting green gas, setting up conditions that are difficult to meet. Some interviewees emphasized that biogas can best be applied regionally, but the application has to be adapted to the geographical, demographical and political landscape. Biogas is considered useful to create and keep value in a certain region, but if regional use is not possible, green gas becomes more attractive and useful.

All interviewees emphasized advantages biogas can offer for the energy system. First of all, they described the potential for biogas to be a 'system service provider' for the electricity system. Electricity from biogas could be used complementary to other renewable energies, providing power when the sun does not shine and the wind does not blow, buffering oscillations in electricity production. However, it does not fulfil this function at the moment. Subsidies for renewable energy production are always paid when electricity is produced and fed into the grid. It is therefore most convenient to have the system running continuously. Biogas could be stored for at least some hours (e.g. in the digesters, as green gas in the grid, or in storage units) and thus be regulated much more easily than other renewable electricity. According to the interviewees, current regulations and subsidy systems do not promote this system service provider function in the Netherlands, while there is an attempt to change this with a flexibility premium in Germany. However, this requires specific technological adaptations, and the normal route of running a CHP unit continuously is currently more attractive for most biogas producers.[4]

Interviewees also argued that another role for biogas in the energy mix could be to replace fossil energy that is difficult to replace with other renewable energies. Most often mentioned are energy sources for sectors that cannot switch easily to electric energy, such as fuels for shipping, road transport and air transport, and the production of industrial heat. Next to the use of green gas, upgrading biogas to bio-LNG could provide an opportunity to replace fossil fuels in these sectors. One interviewee observed that green gas, just like natural gas, is often used for heat production, while it could substitute transportation fuels that are far more difficult to make and more valuable.

Most interviewees expected that in the future, biogas production will diversify into producing multiple products. Technology development is focussing on using by-products and creating additional products (see the following section). The whole production chain is considered, from pre-treatment of biomass to post-treatment of digestate. Potential products named are proteins, fibres, lignin, nitrate, phosphate, potassium, rare earth elements, carbon dioxide and water. These additional products could make the business model around biogas more stable by adding new customers, while energy remains as one of the products or even becomes a by-product.

According to some interviewees, additional advantages are win-win situations, where the products mitigate currently existing problems, for example replacing artificial nitrate production requiring high energy inputs, or recirculating phosphate, which is less and less readily available in concentrated form and as a consequence turning into a scarce resource worldwide. They also propose that biogas installations can form a processing step, separating biomass into its components. While some parts could be separated up front, others remain in a more concentrated form in the residues after organic components have been removed during the digestion, making them a good input for further processing. However, some interviewees say that it is still unclear how a good balance between products can be achieved. Biogas energy yields could decrease if the focus shifts to multiple products, but the traditional focus on one product could also inhibit the optimization of the process towards multiple products.

Discussion: biogas as by-product for specific energy applications

The choice between biogas or green gas production described by the interviewees is mainly related to renewable energy production and the integration of bioenergy in the current energy system. Generally, this choice should aim at using biogas or green gas as efficiently as possible, taking into consideration aspects, such as the regional situation, the efficiency of CHP vs. green gas in household heating installations and the potential for short-term storage of heat. Both biogas and green gas producers are adapting to the current possibilities of the energy market. In December 2015, the Dutch Ministry of Finance published a vision paper on biomass in the Netherlands by the year 2030, in which it confirms the opinion of some interviewees that bioenergy is especially interesting for transportation fuels and industrial applications [29]. Specific energy applications, such as transportation fuels, industrial applications and functioning as a system service provider, could be the most interesting future routes for biogas production according to the ministry. The broader option of producing multiple (energy and non-energy) products and viewing biogas for energy as only one of the products or even a by-product is closely related to the bio-economy development, where different concepts such as bio-refinery and cascading strive for the creation of multiple products from biomass resources. This could offer new possibilities for the biogas sector. Expanding biomass use from energy production to other products has been described as not only promising for the enhancement of energetic and economic efficiency but also challenging regarding the definition of efficient biomass use [45]. Combinations of biogas for energy with other bio-economy applications, though technically interesting, may be difficult at this stage because they further complicate both the production process and the business case, thereby increasing risks.

Technology

Technology for biogas production is perceived by most interviewees as still under development but getting more and more robust and efficient. The development now often focuses on using more difficult, heterogeneous feedstock, making use of by-products such as CO_2, and extracting components from digestate, such as nitrogen and phosphate compounds. Interviewees identified the dependence of the business case around biogas production on subsidies as one of the reasons for this development. Traditionally, biogas producers have to pay for both the input (the co-substrate) and the output (treatment of digestate). The price for the produced biogas is determined by current subsidies, so it is the input and output side where the business case can be influenced, creating higher incomes by reducing the costs for resources and residues. This stimulates the search for cheaper resources and better use of by-products and digestate. The more traditional biogas digester may then transform into a wider processing route, where biogas itself is only one of the products. Interviewees expect the most promising processing route to be a useful application of biogenic waste streams, i.e. where biogas provides the energy for the process and some extra, and components in the effluent are extracted, concentrated or purified. They expect that biogas can serve as a basis for further development of technology for the bio-economy, increasing the efficiency of energy production and developing methods to extract different components, making different or multiple products. In the estimation of some interviewees, the biogas sector can still learn from other sectors, especially regarding processing technologies and equipment. Examples named are the food and feed industry (processing of straw to make it better digestible, drying techniques), the chemical industry and biotechnology.

An issue that requires further consideration according to some interviewees is the logistic organization of biogas technology. Decisions not only regarding location for the biogas installation itself (transport distance biomass) but also nutrient recovery or upgrading installations (decentralized or centralized), as well as energy production (location CHP or feed-in into the gas grid), influence the overall business case.

Discussion: from energy production to broader biomass processing

Focus in biogas technology appears to be moving away from mainly increasing yields within the digester itself to tweaking the front and rear end of the production chain. This also widens the focus from one product, biogas, to multiple potential products and a more diverse business case. With regard to the renewable energy and bio-economy policy domains, this development could represent a shift away from pure energy production towards broader biomass processing routes with multiple outputs, similar to the technologies envisioned in a bio-economy. The bio-economy may offer chances to increase knowledge transfer between sectors, since it is envisioned that fossil-based products in various sectors are replaced by biomass, and concepts such as cascading use of biomass and bio-refineries not only enable but also require collaboration across sectors. Logistic decisions could be influenced by the development of both the renewable energy sector and the bio-economy. Especially, the development of bio-refineries could determine the level of centralization of processing steps. Biogas production may become an integral part of a bio-refinery.

Financing and regulations

Interviewees described financing (both through subsidies and investors) and regulations as main barriers for the further development of biogas production both as renewable energy and in the context of a bio-economy. Some criticize the fact that subsidies are mainly stimulating the use of biogas for electricity production. They claim that this focus on specific technologies leads to very uniform biogas installations with little room for experimentation and innovation. Developments towards more diverse products or other energy products are scarcely stimulated and thus unattractive. Furthermore, the financial push of using biomass for energy indirectly hampers other applications or cascading, since only energy applications can receive a subsidy. For example, methane based on green gas could serve as an input in the chemical industry but is rarely applied. In Germany, subsidy is not granted for methane production itself but only for the electricity output at the CHP unit.

A crucial difficulty in the realization of biogas production for many interviewees is the financing of projects. Financing from banks or public funds is connected to strict requirements, especially in the Netherlands. For example, it is required that biogas producers show that they will receive subsidy for renewable energy production and have established long-term user agreements for the produced energy and long-term biomass supply contracts. Especially, the latter is very hard to acquire for biogas producers that do not produce their own co-substrate. Intermediaries, trading biomass from various sources can offer security of supply but orient their prices on the subsidies to be received, increasing their own profit margin while reducing that of the biogas producers and thus increasing the risk of investments. When residual biomass resources are used, an additional difficulty is that the amount of residues depends on the original product stream, not the demand of the biogas installation.

Financing of innovative projects is perceived to be especially difficult. Technically, higher yields of biogas may be achievable, but new technologies require higher investments, which constitute a risk few investors are willing to take. If anything else but energy is produced, subsidies are not granted and often that rules out financing. The security of demand is difficult to prove for additional products next to energy, since they rely upon new or developing markets.

Interviewees identified several bureaucratic obstacles that in their perception hamper biogas development. First of all, when setting up a biogas project, companies have to hand in a variety of permit applications, including environmental reporting and public consultation procedures. The process is perceived to be overly complicated, time-consuming and difficult for small companies. Decisions on applications regularly took half a year or even a year in the Netherlands.

Regulations regarding input and output streams further complicate matters. At the moment, it is not allowed to use digestate as a replacement for artificial fertilizers in the Netherlands. This is described as a big constraint for biogas production in the Netherlands, because the treatment or export of digestate has to be paid for. Furthermore, regulations regarding resources that are allowed to be used as co-substrates in biogas installations differ across the EU. In some countries, a certain biomass resource may be allowed, while it is not in another and the other way around. As a consequence, biomass distributers profit from transporting biomass across the EU, selling it where it is allowed. Interviewees argue that this decreases the efficiency of biogas production and makes it more complicated to use biomass locally or regionally.

Different EU countries use different systems of pricing, subsidies and certifications. Additionally, they have different gas quality regulations. This can be difficult for international trade, e.g. in green gas. Opinions regarding trade in green gas differed among the interviewees. One interviewee argued that systems dealing with the 'green value' of gas could provide a good opportunity for national and international trade. However, the prices of certificates are not high enough and an offer by a third party to buy a certificate is insufficient to get financing from a bank. Other interviewees argued that certificate schemes can carry the risk of quickly losing value, as has been experienced with CO_2 certificates in the past. Certification schemes are often not compatible internationally and according to some would have to be based on a measureable, technical value, not only on guarantees of origin or similar paper trails.

Two main differences between Germany and the Netherlands became apparent in the interviews. First of all, in the Netherlands, many data are more freely available than in Germany, for example geographical data, information about gas networks and locations of users or companies. Secondly, the main focus and the level of consistency in policies regarding biogas production differed in both countries. In Germany, the focus is very much on renewable energy production as part of the 'Energiewende' (energy transition). To promote this, subsidies were granted to specific technological solutions, mainly the application of biogas in CHP units, and specific groups of people, mainly farmers. This has increased the number of biogas installations but has also resulted in a very uniform landscape of biogas production. In the Netherlands, less subsidies were granted and they were a lot less stable, leading to more experimentation and more diverse solutions but also a lower implementation of biogas technology.

Discussion: subsidies vs. innovative solutions

The experiences shared by the interviewees suggest that a subsidy focus on renewable electricity has hampered not only the development and production of other forms of renewable energy by means of biogas but also the production of alternative or additional products and technologies. This is neither favourable for bio-economy policy goals nor does it promote the position of bioenergy in the renewable energy mix. With financing being strictly linked to renewable energy subsidies, which in turn are largely based on electricity production, innovative solutions in the production of biogas and other products, which may be technically feasible and attractive to improve the overall business case, become difficult to realize. While developments in the sector are focusing on integration in the bio-economy, subsidies for biogas production are currently only granted in the renewable energy policy domain. Chemical production from biogas or green gas is not subsidized, which currently makes it less attractive than energy production. Current energy policies aim for an increased production of renewable energy and especially electricity. The focus of subsidy schemes on electricity production from biogas or green gas is therefore logical, but does not necessarily promote an efficient use of resources or optimal business cases. Instead of efficient resource use and creation of multiple products, the focus of subsidies lies on optimal energy production only, because it is motivated solely by energy considerations. This focus does not go well with the vision in the bio-economy domain, where different and more drivers are at play and energy is only a sideshow. Innovations in the sectors towards a better contribution to both policy goals are thus hampered by the diverging focus of the two policy domains and a lack of incentives in the bio-economy domain. To increase overall benefit, policies in the two domains would have to be aligned better and aimed at optimal use of biomass resources for multiple goals.

Overview of results and general discussion

The results of our empirical analysis of the current practices of biogas production and its position between policy domains are summarized in Fig. 3 and Table 2. Figure 3 shows the most important technical links between biogas and the two policy domains. Important opportunities and constraints to contribute to the two policy goals resulting from the in-between position of biogas are summarized in Table 2.

In the renewable energy domain, biogas is mainly appreciated as a versatile energy source that can be used to produce electricity, (industrial) heat or transportation fuels, and that can be stored, transported and used when and where needed. In the bio-economy domain, it is included as a way to use low-value biomass, at the end of cascades, and as a by-product. In current practice opportunities are explored to link biogas production to the bio-economy through extraction of components and production of by-products (Fig. 3).

One of the biggest challenges in the transition to a bio-economy is to prioritize between different applications. Concepts such as cascading and biorefineries aim at producing multiple products and using resources efficiently, as discussed by Bruins and Sanders and Vaneeckhaute et al. [41]. Our study shows, however, that current practice is still dominated by a competition for resources used for energy production only. Furthermore, many technologies still rely on cultivated (first generation), high-quality and homogenous biomass while policies aim at more diverse feedstock [27, 29]. Our study revealed that in the biogas sector, it is expected that higher-value applications in the bio-economy will increasingly compete for biomass and will be able to pay higher prices. As a consequence, biomass owners tend to be cautious with long-term commitments of biomass supply for fixed prices, because they expect to profit from the higher purchasing power of bio-based producers in the future. However, bio-based products not only compete with bioenergy over resources, they also compete with fossil-based products via product prices. While they try to close in on the cost price of their fossil benchmarks, their business case is not necessarily stronger than that of biogas, especially because they do not receive subsidies. The expectation that in the future biomass will increase in value because different players are able to pay more for it is thus not necessarily accurate. This is especially true for low-value, heterogeneous biomass, such as many residual biomass streams, that require

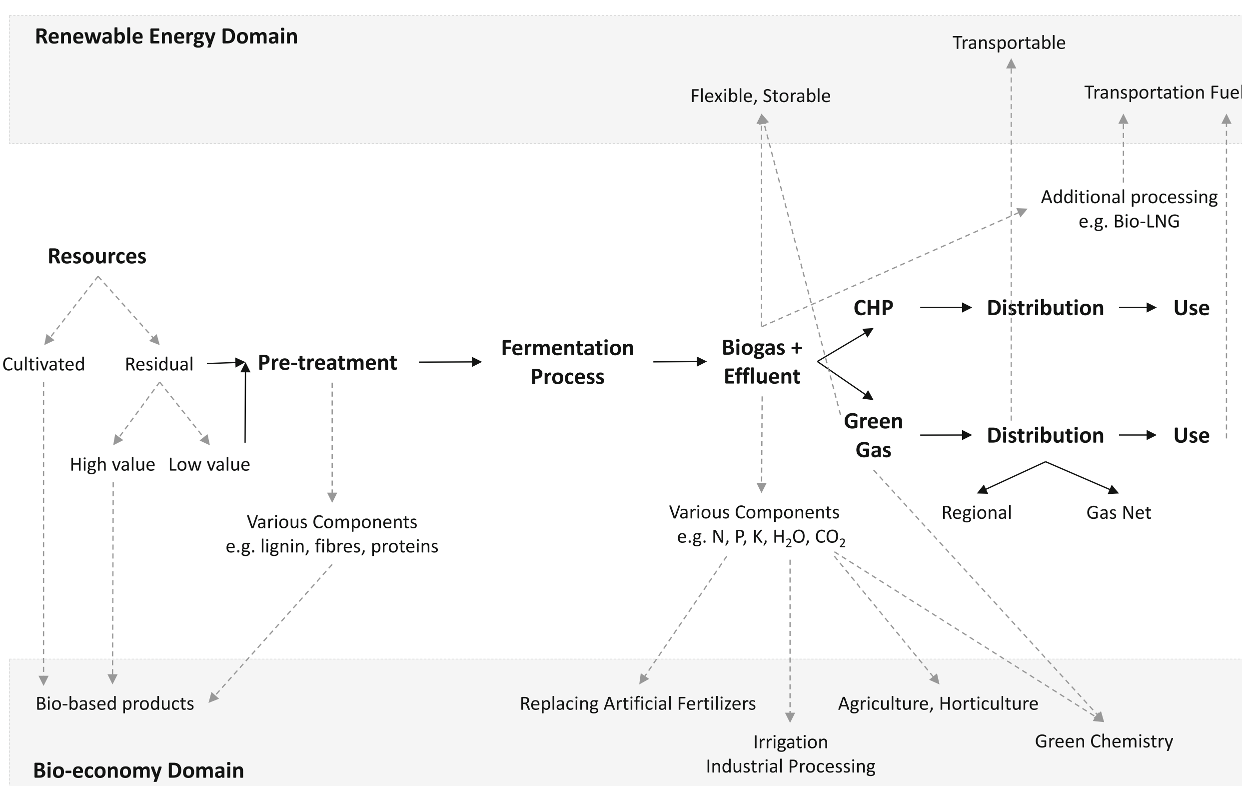

Fig. 3 Schematic representation of potential technical links of biogas with the renewable energy and bio-economy policy domains

Table 2 Opportunities and constraints of biogas between policy domains

Topic	Discussion point
Resources	Change of perspective: from using the best feedstock for energy production to using all biomass resources optimally
	Better use of residual biomass: combining efficient processing of organic waste streams with creating added value through extraction of valuable components and production of renewable energy
	Starting today: using all available biomass for currently feasible processes, thereby mobilizing biomass and creating stepping stones towards a more integrated use of biomass resources
Products	Context: adapting choice between biogas and green gas to the local and regional landscape
	Function in energy system: from inflexible renewable energy source to system service provider, using biogas where it offers advantages over other renewables, e.g. profiting from flexibility and application for difficult energy carriers
	Multiple products: no longer just energy but multiple products, integrating in bio-economy concepts like bio-refinery
Technology	Shifting focus: away from only increasing biogas yields towards tweaking the front and rear of the production chain
	More diversity: more products and more diverse business cases. Fermentation as processing step, creating enabling technologies for a bio-economy
	Unclear logistics: appropriate scales, logistics and integration in landscapes require more attention
Financing and regulations	Financing related to subsidies: aiming at specific technologies or products leaves little room for experimentation and innovation
	Level playing field: subsidies favour energy production over new or additional products and inflexible financing possibilities hamper innovative business cases
	Complications: bureaucratic obstacles and international differences counteract expansion and innovation

intensive pre-treatment. The feasibility of all business cases is furthermore dependent on the development of oil prices.

The subsidies currently granted in the energy domain are instruments designed to bridge the gap between the market price for energy and the cost of renewable energy production. Arguably, this gap exists only because the external (societal) costs of non-renewable energy production are not reflected in the price of energy. The costs of these externalities (like the production of GHG and radioactive waste) are borne by society. As long as these costs are not reflected in the price of energy, renewable energy production will probably require subsidies. However, these subsidies make other uses of biomass, which are not subsidized, less attractive. In the light of multiple goals for biomass use in both the renewable energy and the bio-economy domain, the competitive position of biomass-based products in comparison with fossil-based products is an important aspect limiting the potential to achieve the goals in both policy domains.

The idea to move away from high-value crops to residual biomass is regularly discussed as a possibility to address controversies and land use issues [31, 44]. However, a narrow focus on the sustainability challenges of high-value crops, such as the 'food vs. fuel' debate, and a focus on biomass supply hamper a holistic view on residual biomass as alternative biomass source [44]. Our study revealed that in current practice, there is a focus on using all biomass resources optimally and combining processing of organic waste with energy production (Table 2). But it has to be taken into account that residual biomass is seldom without function, which is lost when it is re-directed to biogas production [31]. The impacts of using residual biomass should be addressed from a broad and more inclusive sustainability perspective, including ecological and economic impacts. More generally, in the future, it will be important to ensure a sustainable supply of biomass under increasing demand for biomass from different sectors, which may be less strictly regulated than the energy sector.

Logistic aspects of biogas production, such as an appropriate scale of installations, the level of (de)centralization and integration in landscapes pose uncertainties in current biogas practice and require more attention (Table 2). Regarding the spatial context of biogas installations issues of importance are, for example, local availability of resources (manure and co-substrate, e.g. on farms), vicinity of users of the produced heat and connectivity to infrastructure (transport networks, gas and electricity grid access). On the one hand, decentralized biogas production offers the advantage of being adaptable to local circumstances and using locally available biomass to avoid transport [46]. Vicinity of potential users of by-products of biogas production may, for example, increase chances to realize multi-purpose applications of biomass [47]. On the other hand, upgrading biogas to green gas is very expensive and far more feasible on a centralized scale than for individual installations. In between these extremes, regional networks of local initiatives can help biogas producers to profit from e.g. multiple biomass suppliers or multiple heat users, making both supply and demand more robust [47]. Embedding biogas production in a local situation does, however, rely heavily on social capital [48].

It should be noted that this paper was based on interviews with project leaders of a large European project focused on green gas, which imposes some limitations on our findings but allowed us to receive practical and personal information. Interviews provide indirect information filtered through the views of the interviewee [49], which is further influenced by the type of questions in this study, relating not only to objective project outcomes but also to experiences and perceptions on the potential of biogas in the realm of current and future policy domains. The answers of our interviewees were influenced by their background and the subprojects they participated in. This may have triggered them to address certain opportunities and constraints while neglecting others. In this sense, the interviews are not necessarily representative for the experience of all relevant stakeholders in the biogas sector. However, any effects of subjectivity were minimized through the thematic analysis of the interviews, in which we collated themes expressed by the interviewees and discussed them in the context of the policy domains to provide generalized insights. We think that the practical and personal nature of data in this study provided valuable in-depth information on the actual challenges in current biogas practice, partly confirming but also extending and highlighting the information from policy and research ('Dual role of biogas in policy goals' and 'Between renewable energy and bio-economy' sections).

Conclusions

The purpose of this paper was to examine the relationship of current biogas practices with the renewable energy and bio-economy policy domains and identify how biogas can contribute to both policy goals. The exploration of the position of biogas within the policy domains showed that biogas can play an interesting, dual role in both of them. Our empirical study revealed some developments in current biogas practice that offer opportunities for an improved contribution of biogas to both policy domains. Innovation efforts appear to be focused mainly on a better integration in the bio-economy. In the renewable energy domain, upgrading to green gas has the potential to make biogas the envisioned system service provider but faces technical, financial and logistical difficulties. Technical developments mostly focus on using lower value and more difficult resources and adapting the processing technology towards producing multiple products. These developments fit well with bio-economy policies.

Our study also revealed several constraints for a contribution of biogas to both policy goals. The advantage of biogas as versatile system service provider in the renewable energy domain is underused in current practice and not stimulated effectively. Innovations towards multiple products for a bio-economy are hampered by subsidy schemes, regulations and bureaucracy. And the use of alternative, residual biomass resources is impeded by limited financing possibilities.

Biogas can provide a valuable contribution to both policy domains but only if the current focus on energy is diversified. In the long run, it is probable that biogas will no longer be a solitary main product but rather one of the many products created in intricate biomass processing. It can, however, remain a useful processing step and a way to make use of otherwise unusable biogenic residues and create added value during necessary waste treatment. Future research should focus on defining the most efficient use of all biomass resources and developing technologies to extract as many valuable components as possible. In the meantime, biogas production is a technology that is already available and can be applied to use biomass efficiently right now. There are various links to new and existing technologies in both the renewable energy and the bio-economy sector that can be used and developed further. The use of biomass to produce biogas right now can furthermore provide an incentive for biomass owners to harvest and use or sell their biomass, thus increasing the availability of biomass. Biogas can thus serve as a stepping stone in the transition towards a bio-economy: biomass can be used for feasible applications now while also enabling the development of new technologies for improved efficiency in the future.

Energy transitions have been described to be changing in character, with different drivers than in the past and the potential to accelerate, drawing on synergies between multiple domains [50]. Biogas has the potential to contribute to such synergies and as a system service provider can also serve as a stepping stone in the transition towards a renewable energy future (cf., [51]). This underlines the dual but also time-dependent role of biogas in two transitions.

The diverging goals of both domains currently hinder the development of innovative connections between them, even though current practice already offers many opportunities for smart combinations. Hurdles such as overly complicated bureaucracy and rigid financing schemes should be lowered, and subsidy schemes should allow for alternative business cases, including different products. Political insecurity and ups and downs in policy schemes have been a major hurdle for development in the past. In the future, joint goals, clear priorities and fair policy schemes should be designed to overcome inefficiency in the sector. Policy makers should jointly aim at optimal use of biomass resources for multiple goals to increase the overall benefit. To maximize the contribution to both policy goals, policies must be more balanced to enable all valuable functions of biogas. Policies should aim at improving the competitive position of biomass-based products over fossil-based products and optimizing the use of biomass resources, rather than inciting competition between the different biomass applications. This aligns with the conclusion of Silveira and Johnson [52], stressing the importance of coordinating bioenergy policies across sectors and considering biomass not only in the energy domain, but taking advantage of complementary uses of biomass in different sectors.

The project under investigation in this paper involved two European countries, but similar developments might also be observed in other countries with policies for both renewable energy and a bio-economy. Future policy development could benefit from research about the policy coherence in other countries and comparison of opportunities and constraints experienced there. Lessons can be learned both from countries where the policy coherence might be greater and countries where bio-economy policies are more fragmented, such as Canada, where competing visions were detected even within one domain [53]. This paper, based on interviews with a selection of stakeholders, provides insights into opportunities and constraints for biogas to contribute to both domains. Further research to understand visions of various stakeholders can be a valuable instrument to establish aligned goals for the renewable energy and bio-economy policy domains.

Biogas is not the only issue that falls under two policy domains. The concept of coherence between policy domains has been addressed in general by May et al. [54], concluding that increased policy coherence can improve implementation success and policy acceptance. They found that focussed attention for specific issues, supportive institutional structures and involvement of interest groups can foster greater policy coherence. Examples of other issues falling under two policy domains are the consideration of forestry in climate change policies [55] and the changing perspective on water management, where the technical water management and spatial planning policies meet [56]. Future policy development in the bio-economy and renewable energy domains could benefit from research into lessons learned from other sectors where policy domains intersect.

Endnotes

[1]The term 'subsidy' is commonly used for any kind of financial support by government, whether it involves a transfer of funds from government to the receiving party or a (partial) waiver of taxes or a lower than normal rate payable for government services by the subsidized party. In this paper, we use the term 'subsidy' to refer to instruments installed to bridge the gap between the market price for energy and the (higher) cost of energy production from biogas. The financial support to bridge this gap can be realized with different instruments (e.g. performance subsidies or market premiums). Currently, these instruments differ in Germany and the Netherlands.

[2]The RED specifies legal sustainability criteria for biofuels and liquid biomass (Article 17). Biogas thus does not fall under these regulations. However, the sustainability criteria do apply for all transportation fuels, including green gas (Article 2.i). Green gas to be inserted into the gas grid as a replacement of natural gas thus has to be certified, for example by NTA8080 or ISCC.

[3]http://groengasproject.eu/

[4]The flexibility premium has been introduced in the 2012 update of the German subsidy scheme Erneuerbare-Energien-Gesetz (EEG). In 2014, about 20% (ca. 800 MW of 3905 MW) of installed capacity of biogas production was able to provide electricity flexibly [14]. In the 2014 update of the EEG, the stimulation of flexible provision was increased further for new installations: only half of the installed capacity is subsidized, and this is combined with an additional supplement for flexible provision through use of gas storage [57].

Abbreviations

Bio-CCS: Bioenergy production with carbon capture and storage; CHP: Combined heat and power; EU: European Union; GHG: Greenhouse gas; QDA: Qualitative data analysis; RED: Renewable Energy Directive

Acknowledgements

We are thankful to the interviewees who agreed to participate in this study.

Funding

The research leading to this paper has received funding from the INTERREG IV A program (Deutschland-Nederland 2007–2013) as part of the project 'Groen Gas-Grünes Gas'. It was partly conducted in the subproject 'Decentralized Energy Landscapes Netherlands Germany' (DELaND). This research is also part of the research program RiverCare, supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs under grant number P12-14 (Perspective Programme). The funding agencies were not involved in the design, execution and reporting of this study.

Availability of data and materials

All data supporting our findings are presented in this paper. The original transcripts of the interviews are not published to protect the privacy of the interviewees.

Authors' contributions

All authors were involved in the design of the study. SP performed the interviews, analysed the data and drafted the paper. All authors participated in the interpretation of the results, revised the manuscript critically and approved the final content.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Author details

[1]Institute for Science, Innovation and Society, Faculty of Science, Radboud University Nijmegen, P.O. Box 9010, Nijmegen 6500 GL, The Netherlands. [2]Institute for Management Research, Radboud University Nijmegen, P.O. Box 9108, Nijmegen 6500 HK, The Netherlands.

Received: 27 January 2017 Accepted: 19 May 2017
Published online: 08 June 2017

References

1. European Parliament (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. Off J Eur Union 140:16–62. doi:10.3000/17252555.L_2009.140.eng
2. Wüstenhagen R, Bilharz M (2006) Green energy market development in Germany: effective public policy and emerging customer demand. Energy Policy 34:1681–1696. doi:10.1016/j.enpol.2004.07.013
3. Hoefnagels R, Banse M, Dornburg V, Faaij A (2013) Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level—a combined approach for the Netherlands. Energy Policy 59:727–744. doi:10.1016/j.enpol.2013.04.026
4. Faaij APC (2006) Bio-energy in Europe: changing technology choices. Energy Policy 34:322–342. doi:10.1016/j.enpol.2004.03.026
5. Negro SO, Hekkert MP, Smits RE (2007) Explaining the failure of the Dutch innovation system for biomass digestion—a functional analysis. Energy Policy 35:925–938. doi:10.1016/j.enpol.2006.01.027
6. Jacobsson S, Lauber V (2006) The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. Energy Policy 34:256–276. doi:10.1016/j.enpol.2004.08.029
7. Bundesministerium BMU, Bundesministerium BMELV (2010) Nationaler Biomasseaktionsplan für Deutschland—Beitrag der Biomasse für eine nachhaltige Energieversorgung. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) and Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV). Berlin
8. EurObserv'ER (2015) The state of renewable energies in europe
9. Bundesministerium BMWE (2015) Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2014. http://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Entwicklung_der_erneuerbaren_Energien_in_Deutschland/entwicklung_der_erneuerbaren_energien_in_deutschland_im_jahr_2014.html. Accessed 16 Oct 2015
10. Centraal Bureau voor de Statistiek (2016) Hernieuwbare elektriciteit; productie en vermogen., http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82610NED&D1=3&D2=0-2,5-10&D3=23-25&VW=T. Accessed 27 Oct 2016
11. German Biogas Association (2015) Branchenzahlen 2014 und Prognose der Branchenentwicklung 2015
12. Edwards J, Othman M, Burn S (2015) A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia. Renew Sustain Energy Rev 52:815–828. doi:10.1016/j.rser.2015.07.112
13. Poeschl M, Ward S, Owende P (2010) Prospects for expanded utilization of biogas in Germany. Renew Sustain Energy Rev 14:1782–1797. doi:10.1016/j.rser.2010.04.010
14. Hahn H, Holzhammer U, Gerhardt N et al (2014) Kurzstudie zum Thema Effekte des Ausgleichs von Stromdefiziten durch Biogasanlagen—Zusammenfassung aktueller Forschungsergebnisse
15. Brudermann T, Mitterhuber C, Posch A (2015) Agricultural biogas plants—a systematic analysis of strengths, weaknesses, opportunities and threats. Energy Policy 76:107–111. doi:10.1016/j.enpol.2014.11.022
16. Raven RPJM, Geels FW (2010) Socio-cognitive evolution in niche development: comparative analysis of biogas development in Denmark and the Netherlands (1973–2004). Technovation 30:87–99. doi:10.1016/j.technovation.2009.08.006
17. Dóci G, Gotchev B (2016) When energy policy meets community: rethinking risk perceptions of renewable energy in Germany and the Netherlands. Energy Res Soc Sci 22:26–35. doi:10.1016/j.erss.2016.08.019
18. Ministerie EZ (2016) Energierapport—Transitie naar duurzaam. Ministerie van Economische Zaken (EZ). The Hague
19. SER (2013) Energieakkoord voor duurzame groei
20. Bundesministerium BMELV (2013) Politikstrategie Bioökonomie—Nachwachsende Ressourcen und biotechnologische Verfahren als Basis für Ernährung, Industrie und Energie. Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV) Referat 531 – Strategie und Koordinierung der Abteilung „Biobasierte Wirtschaft, Nachhaltige Land- und Forstwirtschaft". Berlin
21. Ministerie MLNV (2007) Government vision on the Biobased economy for energy transition—"Closing the chain." Ministerie van Landbouw, Natuur en Voedselkwaliteit (LNV). The Hague
22. European Commission (2012). Innovating for sustainable growth: a bioeconomy for Europe. COM(2012) 60 final. Brussels
23. Pfau S, Hagens J, Dankbaar B, Smits A (2014) Visions of sustainability in bioeconomy research. Sustainability 6:1222–1249. doi:10.3390/su6031222
24. Asveld L, van Est R, Stemerding D (2011) Getting to the core of the bio-economy: a perspective on the sustainable promise of biomass. Rathenau Instituut, The Hague
25. Commissie Duurzaamheidsvraagstukken Biomassa (2015) Duurzame biomassa voor betere materialen, energie en brandstoffen
26. Staffas L, Gustavsson M, McCormick K (2013) Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches. Sustainability 5:2751–2769. doi:10.3390/su5062751
27. Bundesministerium BMBF (2010) Nationale Forschungsstrategie BioÖkonomie 2030—Unser Weg zu einer bio-basierten Wirtschaft. Bundesministerium für Bildung und Forschung (BMBF), Referat Bioökonomie. Berlin
28. Katan MB, Vet LEM, Rabbinge R (2015) Visiedocument Biobrandstof en Hout als Energiebronnen. Effect op uitstoot van broeikasgassen.
29. Ministerie EZ (2015) Biomassa 2030—Strategische visie voor de inzet van biomassa op weg naar 2030. Ministerie van Economische Zaken (EZ) Directie Groene Groei & BioBased Economy Directoraat-Generaal Bedrijfsleven en Innovatie. The Hague
30. Weiland P (2010) Biogas production: current state and perspectives. Appl Microbiol Biotechnol 85:849–860. doi:10.1007/s00253-009-2246-7
31. Pfau SF (2015) Residual biomass: a silver bullet to ensure a sustainable bioeconomy? In: Eur. Conf. Sustain. Energy Environ. 2015 Off. Conf. Proc. pp 295–312
32. Shortall OK, Raman S, Millar K (2015) Are plants the new oil? Responsible innovation, biorefining and multipurpose agriculture. Energy Policy 86:360–368. doi:10.1016/j.enpol.2015.07.011
33. Mangoyana RB, Smith TF (2011) Decentralised bioenergy systems: a review of opportunities and threats. Energy Policy 39:1286–1295. doi:10.1016/j.enpol.2010.11.057
34. Eker S, van Daalen E (2015) A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty. Energy Policy 82:178–196. doi:10.1016/j.enpol.2015.03.019
35. Götz M, Lefebvre J, Mörs F et al (2016) Renewable power-to-gas: a technological and economic review. Renew Energy 85:1371–1390. doi:10.1016/j.renene.2015.07.066
36. Schaaf T, Grünig J, Schuster MR et al (2014) Methanation of CO_2—storage of renewable energy in a gas distribution system. Energy Sustain Soc 4:1–14. doi:10.1186/s13705-014-0029-1
37. Perlaviciute G, Steg L, Hoekstra EJ (2016) Is gas perceived as sustainable? Insights from value-driven evaluations in the Netherlands. Energy Res Soc Sci 20:55–62. doi:10.1016/j.erss.2016.06.002
38. Zeng AP, Kaltschmitt M (2016) Green electricity and biowastes via biogas to bulk-chemicals and fuels: the next move toward a sustainable bioeconomy. Eng Life Sci 16:211–221. doi:10.1002/elsc.201400262
39. Vanholme B, Desmet T, Ronsse F et al (2013) Towards a carbon-negative sustainable bio-based economy. Front Plant Sci 4:1–17. doi:10.3389/fpls.2013.00174
40. Bruins ME, Sanders JPM (2012) Small-scale processing of biomass for biorefinery. Biofuels, Bioprod Biorefining 6:135–145. doi:10.1002/bbb
41. Vaneeckhaute C, Meers E, Michels E et al (2013) Closing the nutrient cycle by using bio-digestion waste derivatives as synthetic fertilizer substitutes: a field experiment. Biomass Bioenergy 55:175–189. doi:10.1016/j.biombioe.2013.01.032
42. Höltinger S, Schmidt J, Schönhart M, Schmid E (2014) A spatially explicit techno-economic assessment of green biorefinery concepts. Biofuels, Bioprod Biorefining 8:325–341. doi:10.1002/bbb.1461
43. Wittmann N, Yildiz Ö (2013) A microeconomic analysis of decentralized small scale biomass based CHP plants—the case of Germany. Energy Policy 63:123–129. doi:10.1016/j.enpol.2013.05.069
44. Mohr A, Raman S (2013) Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Energy Policy 63:114–122. doi:10.1016/j.enpol.2013.08.033
45. Ganzevles J, Asveld L, Osseweijer P (2015) Extending bioenergy towards smart biomass use issues of social acceptance at Park Cuijk, The Netherlands. Energy Sustain Soc 5:22. doi:10.1186/s13705-015-0053-9

46. Oteman M, Wiering M, Helderman J-K (2014) The institutional space of community initiatives for renewable energy: a comparative case study of the Netherlands, Germany and Denmark. Energy Sustain Soc 4:1–17. doi:10.1186/2192-0567-4-11
47. de Boer J, Zuidema C (2013) Towards an integrated energy landscape. AESOP-ACSP Jt. Congr. Dublin 2013 Proc.
48. von Bock und Polach C, Kunze C, Maaß O, Grundmann P (2015) Bioenergy as a socio-technical system: the nexus of rules, social capital and cooperation in the development of bioenergy villages in Germany. Energy Res Soc Sci 6:128–135. doi:10.1016/j.erss.2015.02.003
49. Creswell JW (2003) Research design—qualitative, quantitative, and mixed methods approaches, 2nd ed. Sage Publications, Inc. Thousand Oaks
50. Sovacool BK (2016) How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Res Soc Sci 13:202–215. doi:10.1016/j.erss.2015.12.020
51. Hauser E, Wern B (2016) The role of bioenergy in the German "Energiewende"—whose demands can be satisfied by bioenergy? Energy Sustain Soc 6:35. doi:10.1186/s13705-016-0101-0
52. Silveira S, Johnson FX (2016) Navigating the transition to sustainable bioenergy in Sweden and Brazil: lessons learned in a European and International context. Energy Res Soc Sci 13:180–193. doi:10.1016/j.erss.2015.12.021
53. Birch K (2016) Emergent imaginaries and fragmented policy frameworks in the Canadian bio-economy. Sustainability 8:1007. doi:10.3390/su8101007
54. May PJ, Sapotichne J, Workman S (2006) Policy coherence and policy domains. Policy Stud J 34:381–403. doi:10.1111/j.1541-0072.2006.00178.x
55. Buizer M, Humphreys D, De Jong W (2014) Climate change and deforestation: the evolution of an intersecting policy domain. Environ Sci Policy 35:1–11. doi:10.1016/j.envsci.2013.06.001
56. Wiering M, Immink I (2006) When water management meets spatial planning: a policy-arrangements perspective. Environ Plan C Gov Policy 24:423–438. doi:10.1068/c0417j
57. Bundesministerium BMEL (2015) Das Erneuerbare-Energien-Gesetz. Daten und Fakten zur Biomasse—Die Novelle 2014. Bundesministerium für Ernährung und Landwirtschaft (BMEL). Berlin