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Governance of sustainability in the German biogas sector—adaptive management of the Renewable Energy Act between agriculture and the energy sector

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Abstract

Biomass is an integral part of the energy system being not only used in the chemical industry, but also as a basic raw material for the bio-economy sector, which is promoted worldwide. However, its potential can only be exploited sustainably if biomass is cultivated and governed appropriately. Consequently, governance systems are needed to ensure sustainability throughout the bioenergy value chain to maximise the benefits and minimise possible negative impacts. This study investigates how sustainability is put into effect in the German biogas market, the largest biogas market worldwide. The development of Germany's biogas market is described according to the structure of a four-phase market model of Heuss: the introduction, expansion, maturing, and stagnation phase. Within each of these market phases, the most important German legislation for development of the biogas market was analysed, namely the Renewable Energy Act and legislation addressing associated sustainability issues. The development of the biogas market was controlled and steered by the adaptive Renewable Energy Act, particularly by incentivising cultivation of energy crops. Efforts to promote sustainability started during the transition from market expansion to market consolidation. The effects of these efforts on greenhouse gas emission reductions have been monitored and reported for more than 15 years, but assessment of other aspects of sustainability has varied. In general, legislation regulating the agriculture sector was changed to address new sustainability concerns with some delay. Sustainable development of the agricultural biogas market requires elements of governance, including adaptive legislation within the energy sector as well as monitoring and regular reporting of environmental impacts and related developments in areas of the agriculture sector, such as meat production. Rapid growth of capacity in the biogas sector combined with a significant increase in meat production, dependent on increased fodder production, created risks to sustainability. It can be concluded that the sustainable development of biogas requires additional instruments, possibly national regulation, in addition to legislation applied to the broader agricultural sector.

Keywords: Sustainability governance, Biogas value chain, Renewable Energy Act, Biogas market

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Introduction

For many decades, biomass has been a very important and versatile renewable energy (RE) source worldwide and it is expected to play a leading role in the transformation of the energy supply to renewable energy [1]. Beyond the traditional use of charcoal and wood as energy sources, modern societies are increasingly relying on biomass-derived energy carriers, such as biofuels, biogas, biodiesel, and bioethanol. Biomass is also used in the chemical and pharmaceutical industry and is promoted as a basic raw material for industrial development in the global bio-economy. Although the possible applications of biomass are manifold, its full potential can only be exploited sustainably if its production and use are regulated appropriately [2]. Without regulation, the production of biomass for energy and industrial purposes might induce unwarranted land use changes [2], have negative impacts on access to land [3], or stimulate conversion of land use in areas less suitable for sustainable agriculture, such as forests, wetlands, or grasslands [4]. Likewise, biomass production might affect other aspects of sustainability, such as water quality and availability, and the global carbon and nitrogen cycles.

Governance of sustainability in brief

A variety of governance systems have been established to ensure sustainability of biomass and bioenergy throughout the value chains while maximising the benefits and minimising any possible negative impacts [5]. The term "governance" is used in numerous ways and with a multitude of different meanings [6–9]. In this paper, we regard governance to be a process "undertaken by governments, market actors, voluntary organisations or networks that aim at steering formal or informal organisations, or territories, through laws, private certification, standards, or norms to achieve specified outcomes" [9]. This concept recognises the interdependencies of different processes (governmental and market) and the possible relationships amongst them.

The concept of sustainability and sustainable development commands wide support, and therefore demand has increased for governance systems to ensure an orderly progress towards a more sustainable development [9]. Processes for governing sustainability have emerged in the European Union and its member countries. In 2009, the European Union adopted the Renewable Energy Directive (EU-RED I), which is one of the most important regulations for sustainability in relation to biofuels [10]. The EU-RED I combines subsidies to achieve binding renewable energy targets with sustainability criteria compliance, i.e. de-incentivise processing of biomass from land with high biodiversity or high carbon stocks, or from formerly undrained peatlands [11].

The revised Renewable Energy Directive, adopted in 2018 (EU-RED II), sets a framework for increasing the overall consumption of renewable energy sources to 32% of the total consumption by 2030 in EU as a whole [12]. Likewise, it sets a minimum target of 14% for renewable energy in road and rail transportation by 2030. These goals come along with newly added sustainability criteria for forestry feedstocks, revised sustainability criteria for agricultural feedstocks, and greenhouse gas (GHG) emission reduction thresholds for solid biomass and gaseous biofuels, such as biogas and biomethane used in electricity, heating, and cooling.

Sustainability governance of the biogas sector in Germany

Today, more than 9000 biogas plants in Germany process residues, such as manure and bio-waste, as well as energy crops. The increased use of biogas and biomethane raises questions on sustainability of biomass supply, including intensification of agricultural practices, which may be addressed through governance systems [13–16]. According to Adger [9], governance is closely associated with the term of "sustainability", which in turn raises the questions how sustainability is defined and how sustainable practices might continuously improve and be implemented. In this study, we do not focus on defining "sustainability" but on how existing sustainability requirements might be put into effect in the German biogas market, the largest biogas market worldwide. The production of biogas from energy crops and manure via anaerobic digestion holds great GHG emission-saving potentials when biogas replaces fossil fuels. The use of bioenergy thus supports the decarbonisation of the energy and agricultural sector [17]. However, in addition to these desirable effects, biogas production and utilisation are often associated with risks to other aspects of sustainability, such as increasing competition with other land uses, or effects on ecosystems as well as local noise and odour. Hence, during energy system transformation, it is not only crucial to ensure sustainability by using governance mechanisms to ensure successful market introduction, but also precautionary management to avoid undesirable environmental, economic, and social side effects. Currently, a number of laws address various sustainability issues, while there is limited use of other types of governance.

The development of the German biogas sector has mainly been triggered and driven by consecutive versions of the Renewable Energy Act (REA) as well as accompanying regulations, especially since 2004. These acts have created advantageous conditions for the access of biogas to electricity markets and grids, as well as measures to a secure investment and financing of biogas plants through remuneration. Past research on energy legislation fostering market development and guiding sustainable development of the German biogas market has mainly been focused on the national REA. Different studies addressing the impact of the REA mostly focus on effects related to economics, such as capacity build-up, energy efficiency, and flexible power provision [18], as well as impacts on structural change in agriculture [19] and investment decisions [20]. The REA has generally been found to be very successful in promoting market development of renewable energy technologies, e.g. for biogas as well as wind and photovoltaics. The objectives of the REA are being achieved through the implementation of a number of regulations and rules are adjusted periodically. While the literature addressing the REA is dominated by a focus on the economic point of view, no literature currently address the broader implications for sustainability of the development of the biogas market in Germany, and how sustainability issues are regulated and governed.

Aims of the study

This study aims to answer the question of how sustainability has been governed during development of the biogas market in Germany. Our focus is on environmental aspects, such as GHG emission savings, impacts on soil quality and fertility, and emissions of pollutants to water and air. We differentiate between four different market phases and analyse how relevant laws have been adapted in response to the development. Due to the importance of energy crops and agricultural residues as feedstock, we focus on governance in the energy and agricultural sector, especially on national legislation, as the governance of biogas has been dominated by legalisation at the national level. It should also be noted that participation of stakeholders in decision-making is of great importance and required by the national REA. This aspect has been further analysed in an associated study by Sutor et al. [21].

Market phase model and considered legislation

The market phase model

According to Heuss [22], four market phases can be distinguished: (1) Introduction, (2) Expansion, (3) Maturing, and (4) Stagnation. During the introduction phase, a significant level of investment is usually required without any guarantee of future financial success. Typically, this phase is characterised by no or small markets, high costs, and small profits, on the one hand, and high prices and limited competition, on the other. The expansion phase is generally the most important phase for establishing a product on a market. It is characterised by increasing competition, lower prices, changing marketing strategies, reduced costs, and increased profits. The expansion phase is typically preceded by a maturing (or saturation) phase characterised by a peak in sales, a decreasing market share, and an ongoing reduction in production costs. The final stagnation (or devolution) phase is defined by a drop in sales and profits, and a need for innovation and cheaper production.

In this study, the market phase model of Heuss is used to describe the different phases of development of the German biogas sector. The characteristics of the identified biogas market phases are somewhat different from those of the model, as they are policy-driven in most cases [23]. Nevertheless, we have found them useful for the purpose of this study. We primarily defined the market phases based on the numbers of new biogas plants built per year, leading to identification of (1) the introduction and (2) the expansion phase. Currently, the German biogas market has reached (3) the consolidation (maturing) phase, possibly moving into a future (4) stagnation phase, even if this last development is highly uncertain and requires future follow-up and research.

The development of governance can be linked to the different phases of market development. We structured the different governance initiatives aimed at biogas market development and the associated sustainability impacts according to a set of parallel phases ("The development of the biogas market and the enabling legislation" section): build-up of expectations (biogas capacity scenarios), political aims (GHG reduction, renewable energy share, and common agriculture policy), and implementation (capacity building). These phases correspond to the first three main phases of market development, but for governance, we were further able to identify sub-phases in the early and late stage of each of the main phases.

Legislation considered in this review

The most important German national legislation for the development of biogas markets is the REA and legislation addressing associated sustainability issues (Fig. 1). The legislative instruments included in this study were selected on the basis of their direct or indirect influence on the development of the biogas market and their effect on the associated risks to sustainability. The EU-RED (I and II) and the Common Agricultural Policy (CAP) are also relevant as frameworks for the German legislation but are not considered specifically in the present study, as they are implemented through national legislation.

In summary, governance of sustainability in the German biogas sector is implemented by both agriculture and energy sector legislation, with different ministries or agencies responsible for the different pieces of sustainability legislation (Table 1). While the production of biogas falls mainly within the agriculture sector, its utilisation is regulated by laws and acts from different sectors without a harmonised interplay for the adoption of the agricultural legislation. In this way, sector development and sustainability are governed by separate entities that independently create sectorial legislation.

Sustainability

For the several phases in the development of the German biogas market and associated legislation, governing sustainable production and utilisation within that market, a closer examination of the risks to sustainability caused by biogas value chains is required. This study screened the scientific literature and provides information encompassing the risks to the three pillars of sustainability, i.e. the

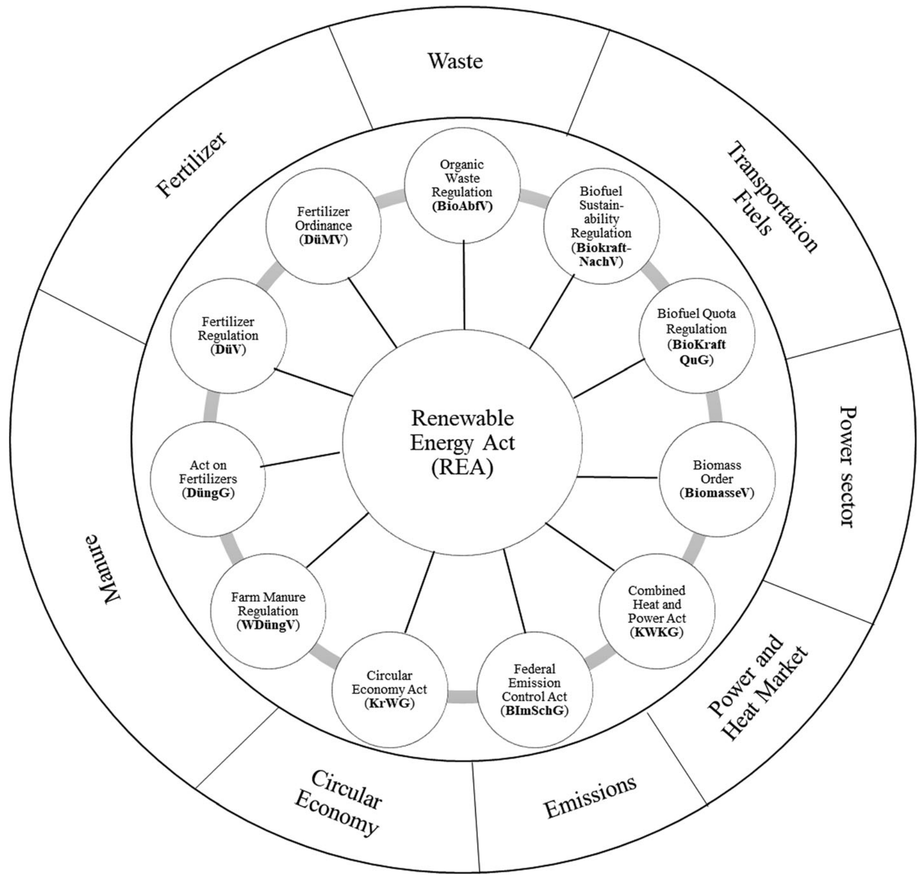

Fig. 1 Thematic presentation of national legislation relevant to the German biogas sector (see Table 1 for details)

environmental, economic, and social aspects [24]. We evaluated in detail the significant trade-offs between economic profitability and environmental sustainability of the agricultural biogas production systems, and reviewed the extent to which existing legislation in Germany covers each of the identified sustainability risks ("Sustainability and its coverage by legislation" section).

The development of the biogas market and the enabling legislation

Legislation that directly affects the development of the biogas sector has been regularly revised to meet the goals of higher-level legislation and to respond to impacts caused by the developing sector (Fig. 2). This is illustrated by the vertical dashed lines in Fig. 2, where the stages of sector development are linked to the respective REA version. Since about 2000, the higher-level goal of greenhouse gas (GHG) emission reduction has been adapted according to national and international developments, such as the different climate change agreements [24]. The goal for RE share was introduced in the REA in 2000 and has been adjusted since then (Fig. 2). The higher-level goals of the Common Agricultural Policy (CAP) also play an important role in sector development, because the main legislation framing the biogas sector development is part of the agricultural sector. In more detail, schemes such as the crop specific premium, the set-aside premium, the energy plant premium, and greening had a significant influence on the agricultural sector, and hence the biogas production. All of the above-mentioned higher-level strategies had to be considered during market development of biogas and also in the design of market-incentivising instruments under the REA. Likewise, one issue influencing parts of this system is meat production, which is particularly important since intensive livestock production creates manure that can be used in biogas plants (Fig. 2). The next sections describe the development in the relevant legislation and its interaction with the different phases of market development.

Introduction phase

With the oil price crisis in the 1970s and an increasing supply of liquid manure, more biogas plants utilising this manure were built [27]. Between 1990 and 1999, there was almost no market for the produced biogas. It forced the government to introduce a feed-in tariff

Table 1 German legislation influencing the biogas sector or addressing associated risks to sustainability. Year denotes the time when the act or regulation entered into force

Instrument / Act	Year	Organisation responsible	Main Objective	Link to the biogas sector
Renewable Energy Act[1]	2000; amended in 2004, 2009, 2012, 2014 and 2017	Federal Ministry for Economic Affairs and Energy (mainly)	The most important instrument for the support of renewable power. In order to maintain a flow of information to the decision makers, a monitoring system was implemented as a significant part of a legislative management cycle. This process aims at combining and condensing the broad range of data and information available from energy statistics, such as number of energy plants, their capacity, and incentives. An annual report on the progress of the "Energiewende" (the name of the German energy transition process) is published. After the experiment with open space solar power plants started in 2014, and in response to an EU guideline, the REA version of 2017 included tendering and expansion paths for all renewable energy technologies.	Main instrument for the biogas sector development is incentivising schemes, such as feed-in tariff and premiums.
Organic Waste Regulation (BioAbfV)[2]	1998	Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety, Federal Ministry for Food and Agriculture and Federal Ministry of Health.	Regulates the use of organic waste for agricultural soils.	Feedstock specification for biogas plants
Biofuel Sustainability Regulation (Biokraft-NachV)[3]	2009	The Federal Ministry of Finances, the Federal Ministry for Food and Agriculture, the Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety, the Federal Ministry of Transport and Digital Infrastructure and the Federal Ministry for Economic Affairs and Energy as well as the Federal Office for Agriculture and Food are responsible for the associated certification systems (ISCC and REDcert are accredited in Germany).	Regulates the sustainable production of liquid or gaseous transportation fuels from biomass. Since the harvest in 2010, only sustainably produced biomass of a greenhouse gas emission reduction potential of more than 35% has been used for the production of fuels.	Feedstock specifications in terms of sustainability
Biofuel Quota Regulation (BioKraftQuG)[4]	2006	Federal Ministry of Finances (mainly)	Required the petroleum industry to add an increasing share of biofuels to their diesel and gasoline.	Required development of biogenic fuels
Biomass Order (BiomasseV)[5]	2001	Federal Ministry for Food and Agriculture, Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety and Federal Ministry for Economic Affairs and Energy.	Regulates the types of biomass within the Renewable Energy Act.	Feedstock specifications
Federal Emission Control Act (BImSchG)[6]	1990	Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety (mainly)	Prevents harmful effects on the environment caused by air pollution, noise, vibration and similar phenomena.	Infrastructure and operation specifications
Combined Heat and Power Generation Act (KWKG)[7]	2002	Federal Ministry for Economic Affairs and Energy (mainly)	Regulates the purchase and financial incentives for power from combined heat and power plants.	Specifications of purchase and financial incentives for power produced in biogas plants
Circular Economy Act (KrWG)[8]	2012	Federal Ministry of the Environment, Nature Conservation, Building and Nuclear Safety (mainly)	Focuses on increasing the recycling and pre-treatment of waste.	Feedstock specifications
Farm Manure Regulation (WDüngV)[9]	2010	Federal Ministry for Food and Agriculture	Controls the recycling and transportation of fertilisers from animal excrements, plant residues (i.e. from biogas plants using energy crops) or fermentation residues.	Handling of biogas process residues

Table 1 German legislation influencing the biogas sector or addressing associated risks to sustainability. Year denotes the time when the act or regulation entered into force *(Continued)*

Instrument / Act	Year	Organisation responsible	Main Objective	Link to the biogas sector
Act on Fertilisers (DüngG)[10]	2009	Federal Ministry for Food and Agriculture	Secures plant nutrition and soil fertility, while averting damage to humans, animals and the environment.	Handling of biogas process residues
Fertiliser Regulation (DüV)[11]	2007	Federal Ministry for Food and Agriculture	Regulates the use of fertilisers, soil additives, culture substrate and pesticides and optimises the use of nutrients by plants.	Handling of biogas process residues
Fertiliser Ordinance (DüMV)[12]	2012	Federal Ministry for Food and Agriculture	Regulates the approval of fertilisers, including labelling, as well as hygiene and phytosanitary measures during epidemics.	Handling of biogas process residues

[1]https://www.gesetze-im-internet.de/eeg_2014/
[2]https://www.gesetze-im-internet.de/bioabfv/
[3]https://www.gesetze-im-internet.de/biokraft-nachv/
[4]https://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&bk=Bundesanzeiger_BGBl&start=//*[@attr_id=%27bgbl106s3180.pdf%27]#__bgbl__%2F%2F*%5B%40attr_id%3D%27bgbl106s3180.pdf%27%5D__1563521944428
[5]http://www.gesetze-im-internet.de/biomassev/
[6]https://www.gesetze-im-internet.de/bimschg/
[7]https://www.gesetze-im-internet.de/kwkg_2016/
[8]https://www.gesetze-im-internet.de/krwg/
[9] https://www.gesetze-im-internet.de/wd_ngv/
[10] https://www.gesetze-im-internet.de/d_ngg/
[11]https://www.gesetze-im-internet.de/d_v_2017/
[12]https://www.gesetze-im-internet.de/d_mv_2012/

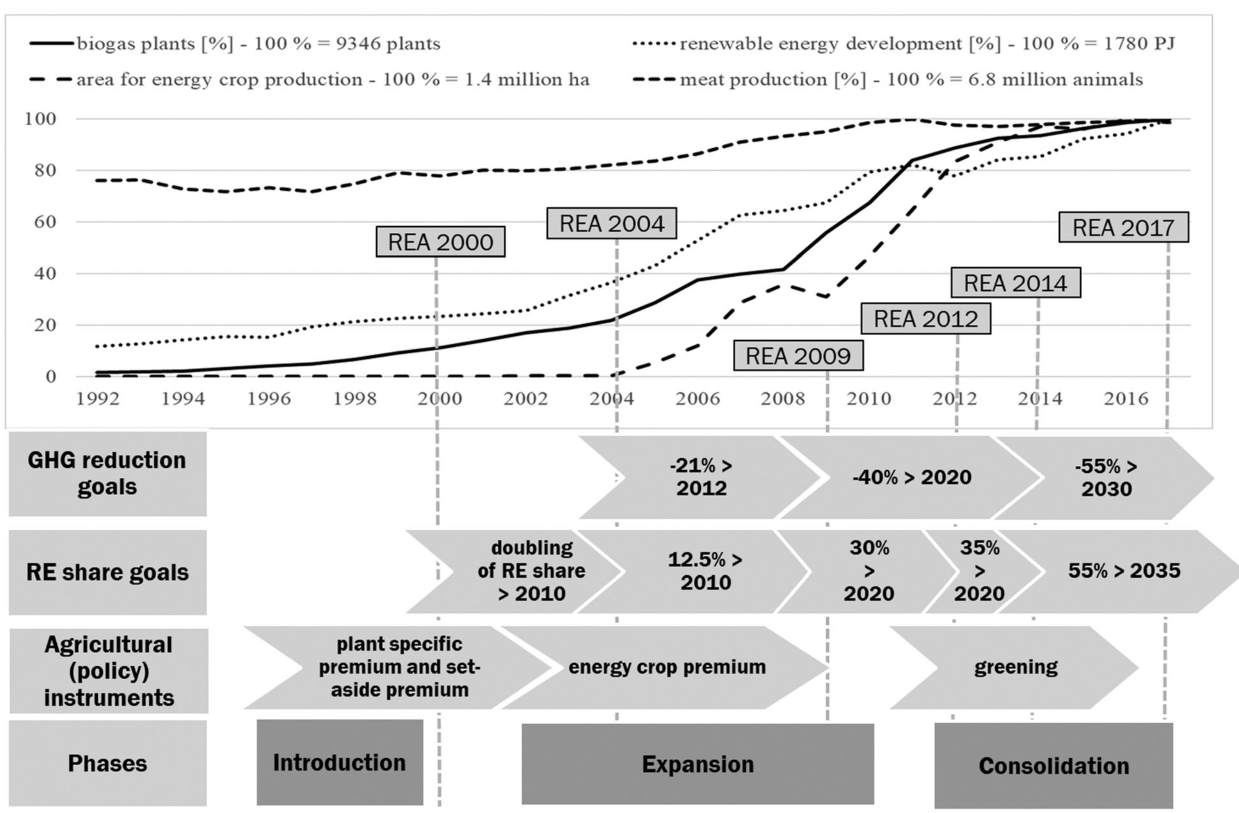

Fig. 2 Phases of market and legislative development in the German biogas sector, represented by the development in the number of biogas plants, the area of energy crop production, the amount of renewable energy, and meat production compared with the level in 2017 [25, 26]. The greenhouse gas (GHG) emission reduction goals are given relative to the level of emissions in 1990. The renewable energy (RE) goals are given relative to the overall share of energy production in the power sector

(Stromeinspeisegesetz) in 1990, which initiated the introduction phase of market development. For the first time, this guaranteed a fixed remuneration to producers of renewable electricity and thus enabled farmers to operate biogas plants together with combined heat and power (CHP) plants. In order to increase the efficiency of biogas and CHP plants, in particular, organic residues and waste were increasingly used as co-substrates. The incentive of the feed-in tariff (Table 3 in Appendix) stimulated a gradual increase in the number of biogas plants from around 100 in 1990 to 850 plants in 1999 (Fig. 3). During the same period, the installed capacity increased from 1 to 50 MW_{el}. However, the biogas plants built during this period were small compared with those built after 2000.

Early expansion phase

The Feed-In Tariff law [29] was a precursor to the REA, replacing it in 2000 to meet the new commitment under the Kyoto Protocol to reduce GHG emissions by 21% by 2010, because coupling financial incentives for renewable energy to electricity prices no longer ensured the economic operation of power plants using energy crops. For the first time, electricity from renewable sources was prioritised over conventionally generated electricity when a statutory minimum remuneration was introduced for electricity from hydropower, landfill, mine and sewage gas, biomass, geothermal energy, wind power, and solar radiation energy. The size of financial incentives varied amongst the different sources of renewable energy. The remuneration period was set at 20 years. Between 2000 and 2003, the number of biogas plants increased from 850 to 1750, with the average installed capacity increasing from 50 to almost 400 MW_{el} (Fig. 3). Monitoring and the adaptive legislative approach were already integrated into the 2000 version of the REA but the design of these system features was fairly simple. However, the complexity increased over time reaching its maximum in 2009 (Fig. 4). From 2014, the complexity was gradually reduced with a return to a simpler approach in 2017.

Late expansion phase

Based upon feedback from the first monitoring under the REA, changes were made to support electricity production from biomass. As the remuneration rates for small biogas plants were insufficient, an amended remuneration structure was introduced to include the following:

- specific remuneration for use of energy crops, especially for smaller biogas plant capacities,
- additional remuneration for innovative technologies,
- additional remuneration for upgrading biogas to biomethane if certain environmental requirements were fulfilled (maximum methane emissions thresholds from leakage, reasonable electricity input, and fossil-free process heat), and
- systems with a maximum upgrading capacity of 1000 Nm^3.

As a result, the conditions for electricity generation from biomass improved noticeably, which is evident in the development during this period (Fig. 3). Between 2004 and 2008, the number of biogas plants almost doubled to nearly 4000. This increase was also supported by amendments to the federal state Building Law [30] prioritising the establishment of biogas plants in land district areas.

The 2009 amendment to the REA was a fundamental and comprehensive revision. The focus of the revisions was on reducing the subsidy rates for new PV systems, but the revisions created a more favourable situation for biogas. In addition to the financial incentives under the

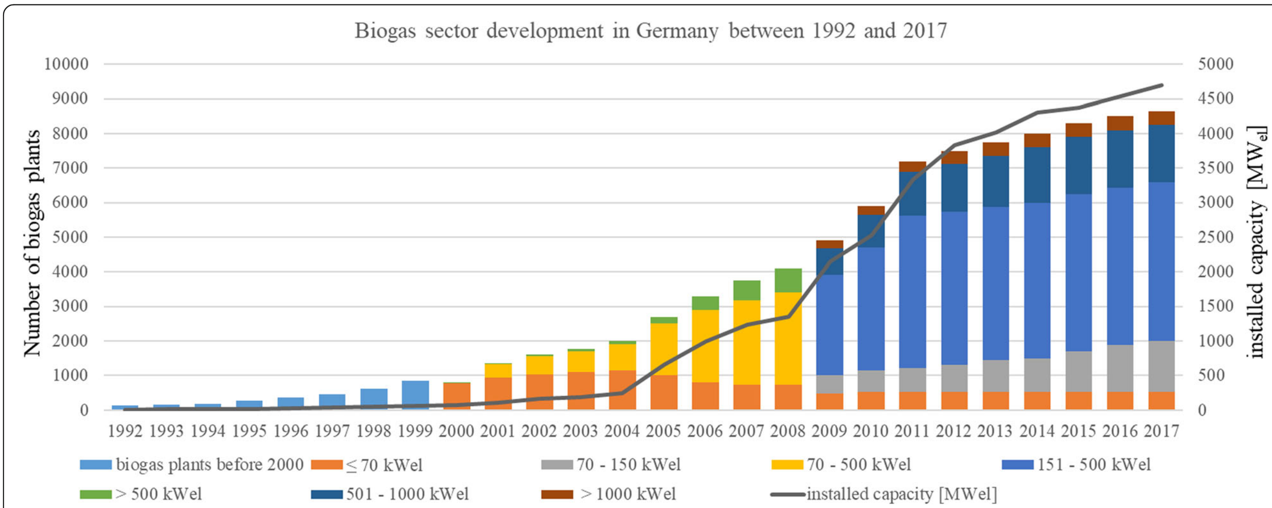

Fig. 3 Development of the German biogas sector from 1992 to 2017 [28]

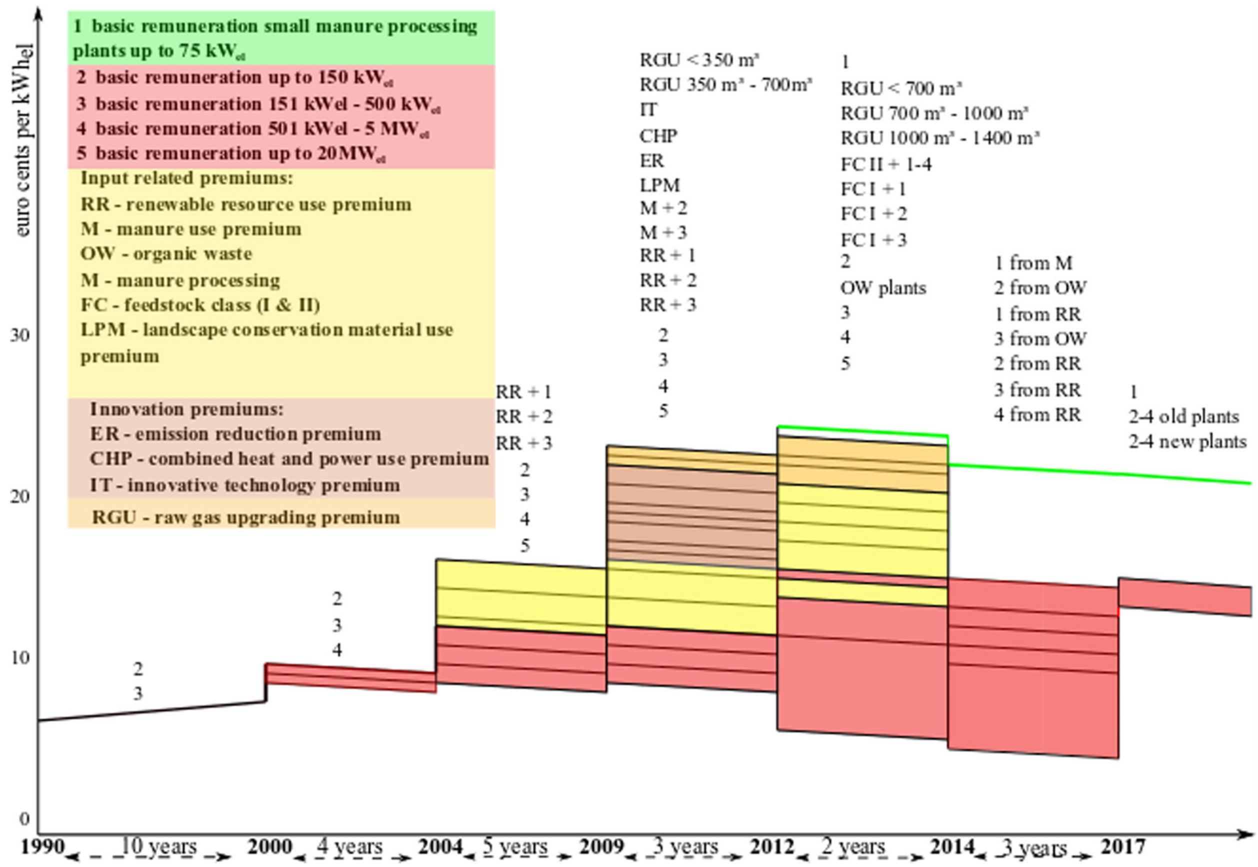

Fig. 4 Financial incentives for biogas in Germany from 1990 to 2017, as stipulated in the consecutive Renewable Energy Acts (REA) (see Tables 3, 4, 5, 6, 7 and 8 in Appendix for more details). Basic remuneration means remuneration from electricity production only without further premiums

2004 REA, several premiums were added, with key elements being premium for renewable resources, as well as the bonuses for manure utilisation and landscape care. These elements were linked in such a way that the manure and landscape care bonuses could only be claimed when the renewable resource premium had been received. Between 2009 and 2012, a large range of premiums were made available for the following activities (Fig. 4):

- increasing the use of manure in new plants (manure premium),
- increasing the proportion of utilised heat from electricity generation from biogas in combined heat and power plants (including the use for drying of feedstock and the use in local heating networks), and
- increasing the use of bio-waste for biogas production, especially municipal waste.

As a result of these incentives, the number of energy plants using renewable resources continued to rise sharply. The rate of increase peaked from 2009 to 2011 when about 3300 systems went into operation within 3 years (Fig. 3).

Early consolidation phase

In 2012, the amendment to the REA introduced changes in the technical settings, namely when new digestate storage facilities were located at the site of the biogas plant. These storages had to be technically gas-tight and the hydraulic residence time in the gas-tight system had to be at least 150 days. However, plants processing 100% manure were excluded from this rule. Furthermore, the method for calculation of premiums and the applicable premium rates were changed. In addition to the REA feed-in tariff, "direct marketing", using the market premium model, became interesting for marketing electricity from biogas plants. The reason was that more market-oriented plant operation began to be incentivised. Within the context of the "Energiewende", direct marketing means that producers of renewable energy, such as biogas plants, have to market the renewable energy themselves [29]. Between 2012 and 2014, about 500 new plants were built with an overall capacity of about 600 MW. In addition, the maize input was capped at 60% by mass.

Ongoing consolidation phase

With the 2014 amendment of the REA, RE plants and, in particular, bioenergy plants were further integrated into the market. The amendment allowed for a better cost control of renewable power and a decrease in agricultural feedstock production from continuous monocultures, mainly maize. From 2014, direct marketing under the market premium model became mandatory for all operators of large renewable energy systems with a capacity of more than 500 kW_{el}. As of January 2016, direct marketing also applies to all new systems with a capacity of more than 100 kW, hence for the majority of biogas plants. The additional support for energy crops has been removed, which is why the expansion of biomass for energy now focuses on the use of residual materials such as liquid manure and municipal solid waste. As a result, biogas capacity increased only marginally with 500 new plants between 2014 and 2016 (Fig. 3).

Late consolidation phase

Since 2017, incentives for biomass plants have been paid in a competitive tendering process under which new and existing plants take part on equal terms. In this tendering process, the national authority offered a certain amount of power from biomass for bidding. All parties, which were interested in installing or prolonging a biogas plant operation, applied for a tender, giving their necessary premia per kWh. The lowest bids were awarded, until the tender volume had been reached. For bids of the same amount, the system with the lower capacity again received the bid. With this initiative, an 8-year period has started with the goal of eliminating government support for biogas. The 2017 REA sets a goal for an annual gross expansion of a capacity of 150 MW from 2017 to 2019 and 200 MW from 2020 to 2022. Participation in the tendering process is obligatory for biomass plants of more than 150 kW. Small biomass plants of less than 150 kW could receive a fixed premium of €0.1332 kWh^{-1}. The maximum premium for energy from biomass was €0.1488 kWh^{-1} in 2017 for new plants and €0.169 kWh^{-1} for existing plants. Since 2018, this value has decreased by 1% annually. The proportion of maize allowed ("the maize cap") was further lowered to 50% in 2018, 47% in 2019, and 44% from 2021 and onwards. Financial support is only paid for the power produced that relates to the rated power of the installed capacity (50% for biogas plants and 80% for solid biomass plants), to promote more demand-oriented operation of biomass plants. This initiative has already been prepared for the flexible premiums introduced in the REA of 2012. In 2017, 143 new plants were built, of which 130 were small manure-processing plants with an overall capacity of 21 MW_{el}. Likewise, market consolidation for the future is expected to be achieved through the market integration of biogas.

Lessons learnt

A key lesson learnt from the German biogas market development is that the highly adaptive energy sector legislation is successful in triggering the market introduction, expansion, and consolidation phases over a period of 18 years, not only securing the transition from one phase to another but also in regulating the development within the different market development phases. This was possible because of the monitoring and revision cycles required by the legislation. The expansion of RE from biogas has contributed to the overall goals for the development of the RE sector (Fig. 2).

A second lesson learnt is that the development of biogas production was mainly triggered by legislation in the energy sector and the use of energy crops. This is in line with Scheftelowitz et al., who found that besides basic remuneration (Fig. 4), the introduction of different premiums steered the development of biogas production in the desired direction, although with different degrees of success [18]. Premiums for the use of renewable resources, including manure, had an immediate effect resulting in an increase of the cultivation area of energy crops (Fig. 4). Premiums, such as those for flexible electricity generation, needed more time than expected to achieve the desired market penetration, perhaps because of additional investment needs [18].

A third lesson learnt is that a strong focus on energy sector development (in this case, biogas) might lead to inadequate consideration of the impact on agricultural land use. During the expansion phase of energy crop production for biogas value chains (from 0% in 2004 to 80% in 2012 (2017 value represents 100 %, see Fig. 2), the fodder demand also increased due to the significant increases in meat production (from 80% in 2004 to 100% in 2012 (2012 value represents 100%, see Fig. 2). The total area cultivated for fodder production is larger than the area cultivated for energy crops. Consequently, the increase of the area used for energy crops (mainly maize) equals a one-third increase in the total crop production area.

Putting REA into perspective

One could argue that the market will regulate itself, and that a higher demand for energy crops and land to grow these would lead to higher land prices, but ultimately resulting in market equilibrium. However, the many and diverse pieces of agriculture and biogas legislation described in this study indicate it is unlikely that the system will be able to regulate itself. This study documented the overall success of the REAs to support the deployment of biogas for the achievement of renewable energy goals, but it is still useful to consider what the pitfalls are and how governance needs to develop in the future.

Lack of coordination leading to conflicting legislation in the energy and agriculture sectors

The biogas sector has intersections with the agriculture sector, and relevant legislation was enacted in both sectors. However, monitoring and revision cycles were only embedded in energy sector legislation (REA), while such systems were not integrated into the legislation for the agriculture sector. This resulted in a situation with relevant legislation for the two interacting sectors being under the responsibility of different ministries with different goals. Another difficulty is the separation between the impacts of general agricultural production and effects that occur because of the introduction of biogas production. For these reasons, it is hard to take account of impacts of biogas production when developing and revising agricultural legislation. Sustainability governance within the agriculture sector suffers from the fragmented legislation and several deficits are evident. For example, the Agriculture Law [31] took effect in 1955 with the aim of ensuring food security and providing economic support for farmers [32], but sustainability was not considered in this law. During the 1980s, the focus of the Agricultural Law [31] moved towards consideration of sustainability aspects, although economic issues were still the centre of attention [33]. Currently, sustainability of the agriculture sector is regulated through a large number of laws and ordinances, but the consecutive REAs and legislation associated with manure and fertilisation were largely introduced and implemented independently (Fig. 5).

Two examples illustrate the disconnect between the energy and agriculture legislation. First, about two-thirds of maize production, a crop usually cultivated in consecutive monocultures and often mentioned in the discussion of sustainability in the biogas sector, are used as fodder in the agricultural sector, the other third being used for biogas production in the energy sector [34]. Although the undesired effects of maize production are often ascribed to biogas production, the main cause can be found in the agricultural sector. Whereas a threshold for energy crops ("the maize cap") has been introduced in energy legislation, a corresponding threshold for maize is not in general included in agricultural legislation.

Second, a similar picture can be drawn for the risk of water pollution from biogas production, due to nitrate leaching into groundwater from fertilisers used in maize fields. Of the 204 billion cubic metres of liquid fertiliser used in Germany in 2015, about 54% came from cattle and 15% from pig manure in the agricultural sector, and 31% from biogas production residues, such as digestate from anaerobic digestion partly from the energy sector [35].

Since 2005, Germany has produced more meat than it consumed [36]. As a result, Germany has become a major meat exporter [36]. While the area of crop cultivation for biogas has increased since 2000, additional maize silage was also needed for fodder required for livestock production [36]. Many sustainability issues in the agricultural sector can be related to this development. The so-called DüngG law [37] came into force in 2009 at the same time as the introduction of premium for the use of manure for biogas in REA 2009, and it was amended in 2012 and 2017 (Fig. 5). Additionally, the new Fertiliser Regulation of 2017, replacing that of 2009, stipulated that the maximum limit of 170 kg ha^{-1} N $year^{-1}$ must include not only the total amount of N from manure of animal origin, but also N from all other organic fertilisers such as residues from biogas that are partly of plant origin [37]. This example shows how the largely separately developed regulation in the agricultural sector inhibited the achievement of the goals for biogas in the energy sector because barriers were introduced to handle residues from biogas production. It took about 13 years after the introduction of premiums for processing energy crops before the excess N from biogas production was included in fertiliser regulation.

Lack of coordination leads to land use change and conflicts with goals for nature and biodiversity conservation

Another example of a connection between policies in the agriculture and energy sector is conflicts between policy targets for energy and nature conservation, respectively, as seen in the initial phase of the REAs. In 1992, Germany implemented an element of the CAP through national agricultural legislation that required farmers to set aside part of their land as fallow. The purpose was to reduce the overall EU agricultural production capacity and avoid a decrease in prices for agricultural commodities [38]. The resulting fallow land became an important element in nature and biodiversity conservation. However, national legislation allowed the use of this fallow land for, amongst other things, the production of feedstocks for bioenergy. In combination with the REA, this created a strong incentive for the production of bioenergy feedstocks, such as maize, in direct competition with the goal to increase the amount of fallow land. In the early expansion phase, biogas production from energy crops was thus regarded as an option for agricultural land management. This was not in conflict with the goal of avoiding decreases in food prices, but conflicted with concerns related to nature and biodiversity conservation.

When biogas production increased dramatically in the late expansion phase, maize emerged as the most attractive energy crop, because of its high biomass yield and low requirement for crop rotation. Likewise, the emerging increase in livestock production contributed to the intensification of maize production. Loss of grassland was observed in some German regions (e.g. the western parts of Lower Saxony), with conversion of grassland to agricultural land, partly due to feedstock production for biogas. Indirect land use changes from the expansion of biogas production have not been observed or reported in the literature, perhaps because legislation exists to avoid indirect land use change from use of biofuel in the

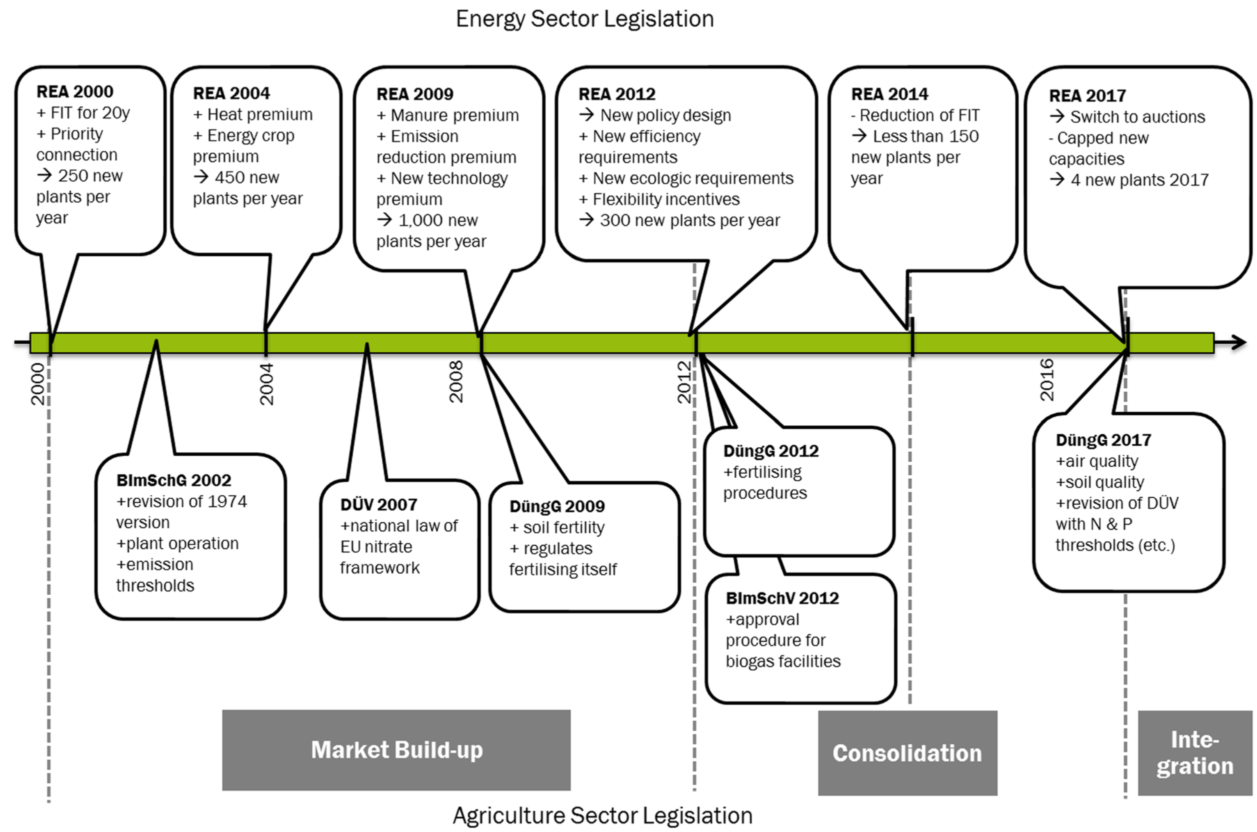

Fig. 5 Timeline for the introduction of legislation relevant to the German biogas sector. The upper timeline shows the consecutive REAs, and the lower timeline shows agricultural legislation associated with manure and fertilisation

transportation sector. This legislation is already supported by national and international biogas associations [39, 40]. The use of agricultural feedstocks remained stable or even decreased slightly in the late consolidation phase of the REA. Since indirect land use change is usually associated with new developments that result in increasing demands for biomass and land, this is not an issue of concern for the current biogas sector.

Sustainability and its coverage by legislation

Biogas can provide many environmental, economic, and social benefits, which is one reason for almost three decades of public financial support. The environmental impacts of biogas production greatly depend on factors such as the type of feedstock, the processing technology, the plant operation practices, and the final use of biogas. Furthermore, causes of environmental, social, and economic impacts of biogas production and utilisation differ significantly amongst the various process steps in of a biogas value chain. The existing biogas and biomethane infrastructure is a large asset for future reduction of many environmental impacts related to storage, handling, and disposal of agricultural waste streams.

Potential contribution of biogas to climate change mitigation and transition of the energy system

While the production of biogas might have many environmental, economic, and social advantages, the main rationale behind the political support for biogas production in Germany is the requirement to reduce GHG emissions in the energy sector [41, 42]. We consider reduction of GHG emission as the main precondition for the public acceptance of biogas value chains.

However, this study shows examples of undesirable impacts with significant trade-offs between the economic profitability and the environmental sustainability of some biogas production systems. As Fig. 2 shows, Germany recorded constant growth in the area of agricultural land used for the cultivation of biogas feedstocks, predominantly between 2004 and 2012. In particular in regions with high competition for agricultural land and high demand for maize silage, due to intensive livestock production, the intensification and area expansion of maize production amplified land prices and rents [43].

The intensified production of maize silage can also lead to losses in soil organic carbon, but Witing et al. demonstrated that biogas plants in the Saxony region can be sustainably operated to recycle organic matter for maintenance of soil organic carbon [44]. Biogas digestate contains a substantial part of the original organic matter from the biogas feedstock, and applying the digestate as fertiliser helps to maintain soil organic carbon. Further sustainability risks include potential pollution of water bodies because of nitrogen leaching from fertiliser application. Finally, maize cultivation involves relatively intense use of pesticides [45], even if a case-by-case assessment of biogas value chains indicates that an increase in the area of energy crops does not automatically increase or decrease the amounts of pesticides released to groundwater [46].

Sustainability risks also include GHG emissions, with emissions of nitrous oxide occurring due to high levels of fertiliser application in maize cultivation, emission of methane due to leakage from biogas plant components [47], and fossil fuel use for intense cultivation and transport [48]. A further important issue that needs to be considered is the concept of heat utilisation within these value chains [18]. The proportion of heat use from biogas-based electricity production will affect the total GHG emissions.

Contribution of biogas to the other sustainability dimensions

Biogas production from manure in intensive dairy farming areas has a high potential for diminishing the significant environmental impacts from livestock production. Anaerobic digestion of manure reduces odour and methane emissions compared with open storage of manure and produces a fertiliser (digestate) with the same amount of nutrients as before the anaerobic digestion process [49–51]. If this contribution to reducing GHG emissions could be monetised, this could create new business cases for biogas producers in addition to the existing incentives which are mainly motivated by goals to increase renewable energy production. This is in agreement with Majer and Oehmichen [52], who found that the reduction in GHG emissions from manure-based biogas varies depending on the reference fossil fuels and the specific biogas plant [16, 51]. Manure-based biogas systems in agricultural environment are able to save GHG emissions compared with open storage of manure and no production of renewable power. The resulting GHG emission savings from manure-based biogas systems are thus of a comparable size in the agriculture (manure treatment) and energy sector (substitution of fossil power) [17]. The size of individual livestock farms and related manure availability is a limiting factor for manure processing into biogas. Scheftelowitz calculated in 2016 that the share of farms which could use manure for biogas production would increase to 31.1% with use of 40% co-substrate and to 40.8% with 60% co-substrate [53]. This confirms that co-processing with other biogas feedstocks than manure is needed to unlock the full potential for manure processing.

Apart from environmental benefits, the production of biogas can also provide economic benefits in rural areas. In addition to government financial incentives, farmers can generate income through the sale of fuel and heat from biogas-based electricity production [18]. The use of digested manure as fertiliser might provide further economic benefits through not having to buy as much mineral fertiliser. However, this economic perspective focuses on the micro-scale, while a macro-economic assessment of biogas production is difficult to perform. Apart from macro-economic costs, domestic biogas production reduces dependencies on imported fuels, diversifies the energy portfolio, and provides a flexible power generation option with storage opportunities.

Biogas has both positive and negative effects in regard to social sustainability. There are presently about 40,000 jobs in the biogas supply chain [54]. Those jobs are mostly located in rural areas and help to secure income generation in areas with low industry density. However, the figures are disputed and hard to verify.

In summary, biogas value chains have both advantages and disadvantages in each of the three sustainability pillars, depending on the specific value chain and the individual viewpoints on biogas (e.g. farmer vs. resident). Sustainability issues mostly arise with increasing production and use, through use of land, water resources, soil and economic resources, amongst others. This has been recognised by legislators, who have created the necessary legislation and have revised it regularly in response to sector development. In this context, it is not only important to recognise sustainability risks, but also their severity, frequency, and timing.

Assessment of legislative coverage of sustainability issues of biogas

Currently, the European Union relies mainly on so-called co-regulation systems for governance of bioenergy sustainability through the EU-RED I [10] and, from 2021, EU-RED II [11]. The EU-RED accepts private certification systems as a means of showing compliance with current EU-RED's sustainability requirements for liquid biofuels, and from 2021 also sustainability requirements for solid and gaseous biomass used for heat, electricity, and cooling. At the national level, governance systems for sustainability of biogas value chains in Germany are based mainly on traditional top-down governmental approaches, with implementation of several acts, laws, and regulations related to the biogas sector. Although the main instrument, the REA, includes only a few sustainability requirements that were introduced and implemented over several revisions, a complex network of associated legislation was also put into force in other sectors. In their enacting of the legislation, policymakers have addressed the major sustainability concerns in biogas value chains (Table 2), with no need for other types of governance identified.

Governance

Stakeholders may be involved in the development of sustainability governance to a varying extent, but this study confirms the dominating influence of government in the case of biogas in Germany. This may increase the risk that politically inconvenient, but necessary, decisions are postponed due to pending elections.

Some studies of the democratic content of legislative processes have investigated the effect of increased participation in governance by institutions other than ministries, such as civil society (i.e. NGOs) [54, 55], or municipalities and city councils [56] or different other types of stakeholders [57]. More openness and transparency in the decision-making process through collaboration generally leads to higher legitimacy of regulations [5]. In addition, collaboration amongst several parties in developing legislation and other governance is likely to significantly improve the effectiveness of the environmental governance in achieving its goals [58].

Conclusions and recommendations

The REA has proved to be a very strong tool for development and implementation of a biogas market. The market phase model of Heuss [22], as modified here, was used to describe the different phases of biogas market development in Germany. This allows for knowledge transfer and comparison with experiences from other markets, which may learn from the development of the German biogas market, including markets in their infancy as well as mature ones. Legislation has been amended not only during the transition from one phase to another but also within the different phases, with annual reporting and monitoring forming an important foundation for decisions on needed revisions. However, the analysis shows that reporting is mainly focused on capacity building and economics, while sustainability issues have not been addressed.

Except GHG emission reductions, sustainability of the biogas sector in Germany has been and still is governed indirectly through a multitude of laws and regulations, including certification via EU-RED. Increased focus on sustainability issues started appearing during the transition from the expansion to the consolidation phase of market development. While a number of positive environmental effects of biogas provision from manure have been observed, the rapid growth in energy crop utilisation in the biogas sector, combined with a significant increase in meat and associated fodder production, fostered risks to sustainability. While energy legislation was designed to be adaptive, agricultural legislation has failed to keep up with the more dynamic approach of the energy sector. The implementation of sustainability measures such as the "maize cap" during the transition from the expansion to the consolidation phase was rather a late reaction to increasingly pressing concerns of the scientific community and the general public. We suggest that sustainability legislation might have been more effective if it had been implemented during the expansion phase through, for example, input-related caps for energy crops, as implemented in countries like Denmark [59].

Stronger and more targeted cross-linking of monitoring systems might be another option for improved governance. For example, nationwide monitoring of the impacts of biogas could be implemented, looking at the regional and local impacts on the environment and nature conservation. This could help ensure that market growth and uptake stay within sustainable levels, since risks to sustainability of biogas value chains can only be determined at a local scale. Interactions with the agriculture industry and high levels of meat production make it hard to determine the impacts on sustainability arising from biogas value chains alone. However, biogas value chains can affect, amongst others, land use, water and soil quality, and micro- and macro-economic factors. These risks to sustainability have also been recognised by legislators within the energy sector, which is why needed legislation has been put into force and regularly updated in response to sector development. In this context, it is not only important to recognise the risks to sustainability but also the time when such risks occur. Nevertheless, cross-sartorial risks were more difficult to include, because they occurred as indirect effects outside the energy sector.

In the past, the REA revision cycles did not always match the speed of biogas sector development and undesired developments, such as the excessive expansion of the area with energy crop production. However, the implementation of monitoring and revision of the legislation is perceived as a positive element, and it is known that governance mainly by governments can lead to delays in implementing necessary restrictions or adaptations compared with private systems, such as certification that can adapt more readily [23]. Creating legislation is usually a slow political process, which therefore considers the most pressing societal challenges first.

Recommendations from this study can be applied to biogas markets at different phases of market development, from governmental decision-makers wanting to create a new biogas market to those wanting to expand or consolidate an already existing market:

- Implementing biogas systems needs political support measures, if there are no other mechanisms for reducing GHG emissions; risk reduction for investors can significantly accelerate market implementation (early expansion phase).
- The potential for biogas production in the agricultural sector is large when energy crop production is incentivised; however, energy crop

Table 2 Classification of governance types in the German biogas sector

Major concern	Regulation	Act	Voluntary	Certification
Soil	Fertiliser regulation	Act on Fertiliser	No	No
	Organic waste regulation		No	No
	Federal Emission Control Act		No	No
	Farm manure regulation		No	No
	Fertiliser ordinance		No	No
Water	Federal Emission Control Act	Act on Fertiliser	No	No
	Farm manure regulation		No	No
Air	Biofuel sustainability regulation		Yes	Yes
	Biofuel quota regulation		No	Yes
	Federal Emission Control Act		No	No
	Fertiliser ordinance		No	No
Biodiversity	Biomass order		Yes	Yes
Economic		Renewable Energy Act	Yes	No
		Combined heat and power generation act	Yes	No
		Circular economy act	Partially	No
Social	n/a	n/a	n/a	n/a

production is difficult to govern, even if caps for feedstock-related input are helpful to reduce risks (early and late expansion phase).

- While dedicated measures can be very successful in accelerating the development of specific sectors of biomass utilisation, they need to be integrated into a coherent policy framework for the overall bio-economy in order to avoid leakage effects and barriers in other markets (until the late consolidation phase).
- Governance of sustainability should be transparent and broadly approved through consultations with participation of NGOs, companies, and the state (from the late expansion phase and onwards).
- Adaptive approaches with regular revision cycles are necessary if energy, as well as agricultural, legislation should continue to be in line with goals for the sector development (during the whole sector development).
- Monitoring of market growth as well as of sustainability indicators is necessary, as well as reporting developments in other related areas in the agricultural sector, e.g. meat production (during the whole sector development).

Secondly, recommendations are given for decision-makers dealing with the German biogas market and its ongoing shift to market integration:

- The existing biogas infrastructure in Germany could contribute greatly to the reduction of GHG emissions in the agricultural sector. Given that Germany is facing ambitious and challenging climate change mitigation targets, all sectors of the German economy must be considered in efforts to achieve them.
- The direct utilisation of waste streams from livestock production in integrated production systems can also lead to a considerable reduction in GHG emissions in the energy sector. However, to tap this potential, this service needs to be monetised in order to develop new business cases for biogas producers apart from the existing incentives, which are mainly focused on energy production (introduction phase would be specific to each case study).
- Governance of sustainability and its transparency could be improved through consultations with participation of NGOs, companies, and the state (should be implemented in the late expansion phase, and is also still necessary for the ongoing consolidation).
- Precautionary warning systems need to be improved to promote action and accelerate adoption of necessary legislation by politicians; it will contribute when results of regional studies are incorporated to form a national monitoring system of sustainability indicators, especially for water and soil contamination, air pollution, and GHG emissions (ongoing and late consolidation).

Adaptive, coordinated, and integrated governance of bioenergy supply chains is necessary and possible in order to support European Union actions to achieve a 40% reduction in greenhouse gas emissions by 2030 (compared with 1990 levels). The fragmentation of legislation regulating the biogas sector, and thus the sustainability of associated value chains, is a problem that cannot be solved with biogas legislation alone. It needs more coherent governance of the overall bio-economy [60, 61].

Appendix

Table 3 Remuneration for biomass plants between 1991 and 1999

Remuneration in euro cent per kWh_{el} (former currency converted to euro: 0.5 €-ct ≈ 10 Pfg)	1991	1992	1993	1994	1995	1996	1997	1998	1999
Biomass plants up to 499 kW_{el}	6.92	6.89	6.9	7.05	7.68	7.65	7.62	7.46	7.34

Table 4 Remuneration for biogas plants between 2000 and 2004

Remuneration in euro cent per kWh_{el} (former currency converted to euro: 0.5 €-ct ≈ 10 Pfg)	2000	2001	2002	2003	2004
Biomass plants	ct/kWh	ct/kWh	ct/kWh	ct/kWh	ct/kWh
Up to 500 kW_{el}	10.1	10.1	10.1	10.0	9.9
Up to 5 MW_{el}	9.1	9.1	9.1	9.0	8.9
From 5 MW_{el}	8.6	8.6	8.6	8.5	8.4

Table 5 Remuneration for biogas plants between 2004 and 2008

Remuneration in €-ct/kWh_{el}	2004	2005	2006	2007	2008
Biomass	without and (with use of renewable resources)				
Up to 150 kW	11.5 (17.5)	11.33 (17.33)	11.16 (17.16)	10.99 (16.99)	10.83 (16.83)
Up to 500 kW	9.9 (15.9)	9.75 (15.75)	9.6 (15.6)	9.46 (15.46)	9.32 (15.32)
Up to 5 MW	8.9 (12.9)	8.77 (12.77)	8.64 (12.64)	8.51 (12.51)	8.38 (12.38)
Up to 20 MW	8.4	8.7	8.15	8.03	7.91

Table 6 Remuneration for biogas plants between 2009 and 2011

Remuneration (annual degression of 1%)	Basic remuneration in €-ct/kWh	RR premium	Manure premium	LPM premium	ER premium
Up to 150 kW	11.55	5.94	3.96	1.96	0.99
150–500 kW	9.9	5.94	0.99	-	-
500 kW–5 MW	8.17	3.96	-	-	-
5 MW–20 MW	7.71	-	-	-	-
Additional	Technology premium:				
	Innovative technology up to 5 Mw_{el}		1.98		
	Raw gas upgrading up to 350 Nm^3		1.98		
	Raw gas upgrading 350 Nm^3–700 nm^3		0.99		
	CHP premium up to 20 Mw		2.97		

RR, renewable resources; *LPM*, landscaping material; *ER*, emission reduction

Table 7 Remuneration for biogas plants between 2012 and 2014

Remuneration (annual degression of 2%)	Basic remuneration in €-ct/kWh	Feedstock class I	Feedstock class II	Organic waste plants	Small manure processing
Up to 75 kW					25
Up to 150 kW	14.30	6	8	16	-
150–500 kW	12.30	5			-
500 kW–5 MW	11	4		14	
5 MW–20 MW	6	-			
Additional					
	Raw gas upgrading up to 700 Nm^3		3		
	Raw gas upgrading up to 1.000 Nm^3		2		
	Raw gas upgrading up to 1.400 Nm^3		1		

Table 8 Remuneration for biogas plants between 2014 and 2016

Remuneration in €-ct/Wh$_{el}$	2014 Biomass from renewable resources	2014 Biomass from organic waste	2014 Manure processing plants
Up to 75 kW	13.66	15.26	23.73
Up to 150 kW	13.66		-
Up to 500 kW	11.87		
Up to 5 MW	10.55	13.38	
Up to 20 MW	5.85		

From 01/01/2016 on, the above values are lowered by 0.5 % on a quarterly basis. After reaching 100 MW, the values are lowered by 1.27%

Abbreviations
CAP: Common Agricultural Policy; CHP plants: Combined heat and power plants; EU-RED I: Renewable Energy Directive of 2009; EU-RED II: Renewable Energy Directive of 2018; GHG emission: greenhouse gas emission; NGO: Non-governmental organisation; RE: Renewable energy; REA: Renewable Energy Act

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Authors' contributions
All authors contributed to the development, revision, and finalisation of this article. All authors read and approved the final manuscript.

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