Renewable Energy 146 (2020) 1471–1485

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Economic assessment of flexible power generation from biogas plants in Germany's future electricity system

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ARTICLE INFO

Article history:
Received 3 December 2018
Received in revised form
30 May 2019
Accepted 28 June 2019
Available online 2 July 2019

Keywords:
Biogas
Flexibility options
Electricity system
Total system costs
Cost-benefit analysis

ABSTRACT

When integrating intermittent renewable energies in the electricity system, additional technologies are needed to ensure that a sufficient power supply is maintained. Alongside storage technologies and conventional power plants, dispatchable biogas plants are one solution for balancing demand and supply in energy systems with a high proportion of renewable energies. In this study, we conducted an economic assessment of the different extension paths and modes of operation of the biogas plants in Germany's future electricity system for the period of 2016–2035. This entailed carrying out a cost-benefit analysis that included the costs incurred for the flexibilization and installation of new biogas plants and the costs saved with respect to onshore wind turbines and additional saved opportunity costs. The results show that adding biogas plants in Germany's future electricity system –compared to their phase-out– requires cost reductions and/or has to be accompanied by further benefits in other sectors and areas to ensure economically feasible operation. Differentiated from a substantial growth, higher net present values were obtained in the extension path characterized by a low construction rate of new biogas plants. Furthermore, the economic feasibility of biogas plants benefits from an early phase-out of lignite- and coal-fired power plants.

1. Introduction

Germany's government passed a Climate Action Plan in 2016 to reduce the negative impact of climate change and to fulfill the goals of the Paris Climate Accord [1]. The Climate Action Plan defines maximum greenhouse gas (GHG) emissions by sector; in the energy sector, GHG emissions have to be reduced by 61–62% by 2030 over the reference year 1990 [1]. Consequently, the proportion of renewable energies, based on intermittent wind and solar plants, has to increase and conventional power plants with high GHG emissions have to be phased out [2,3]. The intermittency of the power supplied by wind and solar plants requires further technologies to balance demand and supply and to ensure there is a sufficient supply of power. Dispatchable biogas plants are one way to integrate intermittent renewable energies into the system in addition to storage technologies, demand side management (DSM), the extension of grid capacities and (flexible) conventional power plants, [4–7].

In 2016, about 8500 biogas plants were generating electricity and heat in Germany. Their installed capacity was about 4400 MW. Approximately 95% of all biogas installations are agricultural plants using mainly energy crops and manure for anaerobic digestion [8]. Furthermore, biogas plants made up 17.6% of Germany's electricity generation from renewables [9]. However, their comparably high levelized costs of electricity (LCOE)[1] prompted the German government to limit the future extension of biogas plants in Germany. The amendment to the Renewable Energy Sources Act of 2016 limits new installations to a maximum of 150 MW (2017–2019) and 200 MW (2020–2022) annually [10]. From 2004 to 2014 the average annual installation of new biogas plants was 350 MW [11] and these plants will start to phase out after their 20-year remuneration period. Thus, the installed capacity and generated electricity will begin to decrease from the mid-2020s onwards [12]. Likewise, the

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[1] The LCOE is defined as the costs over the lifetime divided by the electricity generated (see Appendix B).

https://doi.org/10.1016/j.renene.2019.06.163
0960-1481/

2016 amendment to the EEG requires that new biogas installations with an installed capacity of more than 100 kW have to be flexibilized (EEG 2017, § 44b) in order to improve the integration of wind and solar plants into the system. Furthermore, the 2012 amendment to the EEG implemented a flexibility premium that partially refinances additional investments in flexible power generation from existing biogas plants. For existing installations, the flexible power generation is not mandatory but more than one third of Germany's plants received the funding in mid-2017 [8]. In contrast to their baseload generation, biogas plants need a higher installed capacity of combined heat and power units (CHPU) and/or gas storage capacity in order to shift their energy generation [13,14]. The basic idea of flexible power generation from biogas plants is to decrease the power generation when the supply from intermittent renewable energies is high and/or the energy demand is low and to increase in the contrary case, respectively.[2] In this paper, we compare the total system costs of three extension paths and modes of operation for biogas plants in Germany's future electricity system.

Several studies have looked at the cost-efficient transformation of the energy system towards an increasing proportion of renewable energies in the electricity, heating and mobility sector. Steinke et al. [15] analyzed the interdependency of grid extensions and storage capacities in a 100% renewable European power grid. They found that the lowest overall system costs were achieved by using small decentralized battery storage units to decrease the demand for grid extension. However, in most scenarios, the demand for back-up capacities in a 100% renewable power system exceeds what biomass could potentially provide. Dale et al. [16] compared the total costs of two scenarios in the UK for the year 2020: A scenario where the electricity is generated mainly by coal and gas-fired power plants, and a scenario where 20% of the electricity is generated by wind farms. Without taking into account the external costs of conventional power plants, the total annual costs of the wind scenario were about 10.7% higher than the conventional scenario. Timilsina and Jorgensen [17] examined the overall supply costs for Romania's power generation with respect to a GHG emissions reduction. The additional discounted supply costs of the green scenario, with a higher proportion of renewable energies and lower GHG emissions (compared to the reference scenario), for the period of 2015–2050 were €3 billion, which is about 1% of the total supply costs. However, by 2030 GHG emissions were reduced by about 26% over 2005 levels in the green scenario compared to 16% by 2050 in the baseline scenario. In contrast, Nitsch [18] calculated the differential costs of a scenario based on renewable energies in order to decrease Germany's GHG emissions by 80% by 2050 (over 1990 levels). He underscored that, starting from 2023, differential costs will be negative and the extension of renewable energies will slowly become economically feasible.

The role of biomass in future energy systems is not analyzed in detail in the above-mentioned studies except for in the study by Ref. [18]. Scholz et al. [19] calculated the cost of the European power system by using the energy system model REMix and varying the proportion of intermittent renewable energies between 0 and 140%. Due to the high capital costs of biomass (and geothermal power) plants, those technologies were not considered in all scenarios. Jensen and Skovsgaard [20] showed the impact of CO_2 prices on the use of biogas in Denmark. The increasing price of CO_2 leads to higher system costs when the target for manure use is reached in 2025; however, if these prices become very high, biogas will represent a significant proportion of the energy mix and overall system costs will decrease.

In Germany, Eltrop et al. [21] endogenously optimized the installed capacity of biomass plants (the electricity generated by biomass was set to constant) in three scenarios with renewable energies making up 40, 60 and 80% of gross electricity consumption respectively. Total system costs were reduced by up to €419 million per year by flexibilizing biomass plants. Based on this analysis, Fleischer [22] optimized Germany's power plant portfolio by varying the proportion of renewable energies in order to reduce total system costs in different scenarios. He found that in scenarios with a high proportion of renewable energies, biomass plants reduce annual generation costs due to a substitution of other renewable energies and a reduction in investments in flexibility options and grid extensions, among other things. In a previous study [23], we analyzed the effect that varying biogas extension paths and modes of operation would have on Germany's future electricity system for the period of 2016–2035. Increasing the proportion of biogas plants (compared to phasing them out) reduced the demand for additional flexibility options and the utilization of conventional power plants with comparably high marginal costs and GHG emissions. Furthermore, compared to baseload generation in biogas plants, the highest impact was achieved through flexible power generation. However, a comprehensive economic assessment of (flexible) biogas plants in the German electricity system has yet to be conducted that includes the benefits and costs starting from the initial time of the investment until the target system is reached.

Therefore, in this paper, we use a cost-benefit analysis to assess economically different extension paths and modes of operation of biogas plants in the German electricity system for the period of 2016–2035.

The objectives were as follows:

i. To analyze the costs and benefits of varying biogas extension paths and modes of operation in the electricity system.
ii. To economically assess the biogas extension paths and modes of operation through the use of a cost-benefit analysis.
iii. To determine the biogas extension path and mode of operation with the highest economic benefit.

2. Methodology

2.1. Extension paths and modes of operation of biogas plants

Following [4,23], we considered three extension paths and modes of operation of biogas plants.

2.1.1. Biogas extension paths

In previous studies, we defined three biogas extension paths in Germany for the period of 2016–2035 [4,23]. In all biogas extension paths, the net electricity consumption was set to constant over the period under consideration and the extension of photovoltaic (PV) plants was taken into account following [24]. The extension of offshore wind turbines was based on the goals of the EEG 2017 [25]. Furthermore, future electricity generated by run-of-river power stations and other biomass plants was also set to constant. The renewable energy target values of the EEG are based on gross electricity consumption; e.g., renewable energies have to represent between 40 and 45% of gross electricity consumption by 2025, and 55 and 60% by 2035 (EEG 2017, § 1).[3] Consequently, depending on

[2] Further details on the principles of flexible power generation from bioenergy are presented in Ref. [6].

[3] Based on the coalition agreement of Germany's current government, this target value has been increased to 65% by 2030.

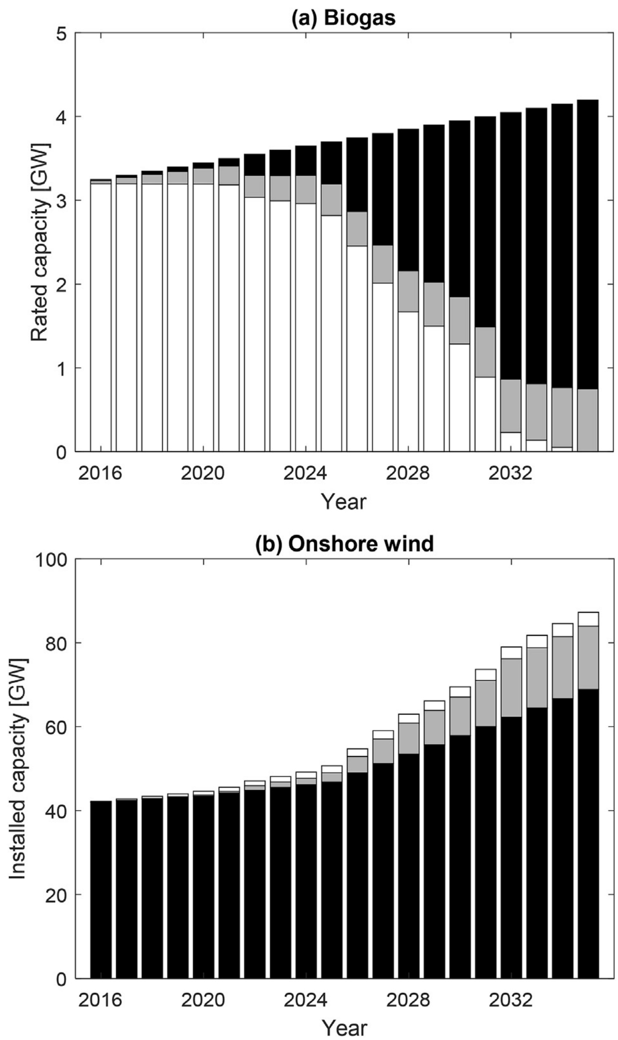

Fig. 1. Rated capacity of biogas plants (a) and installed capacity of onshore wind turbines (b) in the biogas extension paths *increase* (black), *back-up* (grey) and *phase-out* (white).

the extension of biogas plants and their annual electricity generation, we used new installations of onshore wind turbines as an "adjustment screw" to fulfill the EEG's renewable energy target values (Fig. 1).[4]

2.1.2. Modes of operation of biogas plants

Based on the financial incentives of the EEG, the majority of biogas plants in Germany operate in baseload operation. An amendment to the EEG in 2012 introduced a flexibility premium to spark a paradigm shift towards flexible power generation in existing biogas plants. In addition, since 2014 new biogas plant installations have to mainly generate electricity in a flexible way with a maximum of 4380 full load hours per year (see Table 2). In general, flexible power generation from biogas plants requires investments in additional CHPU and/or gas storage capacities compared to baseload generation. The period between electricity generation of biogas plants is dependent on the gas storage capacity and can be increased through flexible biogas production using various feedstock management strategies [26,27]. As a result,

Table 1
Scenarios based on extension paths and plant configurations of biogas plants [28].

Biogas extension path	Plant configuration	Scenario
Increase (INC)	Base (B)	INC-B
	Flex (F)	INC-F
	Flex+ (F+)	INC-F+
Back-up (BU)	Base (B)	BU-B
	Flex (F)	BU-F
	Flex+ (F+)	BU-F+
Phase-out	Base (B)	REF

we looked at three modes of operation[5]:

- Base: baseload generation of biogas plants.
- Flex: flexible power generation in biogas plants through increased CHPU and gas storage capacities.
- Flex+: flexible power generation in biogas plants through increased CHPU and gas storage capacities as well as flexible biogas production to increase flexibility.

The scenarios in this paper are designed to compare the costs and benefits and are based on combining extension paths and plant configurations of biogas plants (Table 1).

2.2. Cost-benefit analysis

To economically assess the scenarios defined in Section 2.1, we used a cost-benefit analysis typically utilized in public investment analysis [29]. In this paper, we compare scenarios with a higher proportion of (flexible) biogas plants to the reference scenario: the phase-out of biogas plants (scenario *REF*). Based on this definition, the costs and benefits[6] over the reference scenario are defined as follows:

Costs (Section 2.3):

- Additional investments in the flexibilization of existing biogas plants and increased operation and maintenance (O&M) costs (Section 2.3.1).
- Capital and operational costs of new installations of flexible biogas plants (Section 2.3.2).

Benefits (Section 2.4):

- Reduced investments in onshore wind turbines; a higher proportion of biogas plants leads to a lower demand for onshore wind turbines to fulfill EEG targets (Section 2.4.1).
- An increased proportion of (flexible) biogas plants reduces the demand for additional flexibility options (e.g. storage technologies and gas turbines) as well as the utilization of conventional power plants with comparably high marginal costs and GHG emissions (e.g. coal-fired power plants) (Section 2.4.2).

The benefit-cost ratio was included as an evaluation criterium and is calculated using the following equation [29]:

$$\text{Benefit-cost ratio} = \text{present value of benefits} / \text{present value of costs} \quad (1)$$

If the benefit-cost ratio is greater than 1, the investment is

[4] Further details on the biogas extension paths are presented in Refs. [4,20].

[5] Further details on the modes of biogas plant operation are presented in Ref. [23].

[6] Further benefits from flexible power generation of biogas plants are described in detail in Section 4.5.

Table 2
Design of existing biogas plants based on baseload and flexible power generation.

	Baseload power generation	Flexible power generation
Rated capacity	137.0–1872.2 kW	
Full load hours	8000	4380
Installed capacity	150–2050 kW	274.0–3744.3 kW
Power quotient (PQ)	1.1	2
No. of CHPU	1	
Biogas storage capacity[a]	6 h	10 h

[a] The biogas storage capacity is defined as a ratio of storage capacity [m^3] and hourly biogas production [$m^3\ h^{-1}$].

efficient from an economic point of view (benefits exceed the costs); otherwise, if the ratio is below 1 (benefits are lower than the costs), the investment is not beneficial [29]. The present value of benefits and costs was calculated for the period 2016–2035 using a (social) discount rate of 3% [30].

The costs and benefits in biogas plants and onshore wind turbines are indicated by effected and substituted investments respectively. The cash flow of the investment was correspondingly calculated and converted into the net present value based on the year the plant was commissioned. Because the period from 2016 to 2035 was considered, the capital costs include the residual value at the end of the year 2035.

Next, with the exception of the additional saved opportunity costs, the net present value of the investments in biogas and onshore wind turbines were converted to the annuity A by the following equations [29]:

$$A_C = PWC \times \left(\frac{i \times (i+1)^n}{(i+1)^n - 1}\right) \tag{2}$$

$$A_B = PWB \times \left(\frac{i \times (i+1)^n}{(i+1)^n - 1}\right) \tag{3}$$

where A_C is the annuity of the costs, PWC is the present value of cost, i is the discount rate, n is the operational life, A_B is the annuity of the benefits and PWB is the present value of benefits.

2.3. Costs

2.3.1. Flexibilization of existing biogas plants

To calculate the additional capital and O&M costs for the flexibilization of existing biogas plants, we defined their design based on baseload and flexible power generation (Table 2). In contrast to plants providing baseload generation, flexible biogas plants are characterized in this paper by a higher installed capacity of the CHPU and the gas storage capacity. Shifting power generation to a time where there is lower electricity demand requires a reduction in full load hours. Based on the (minimum) requirements of the current EEG, a power quotient (PQ) of 2, which is defined by the ratio of installed and rated capacity (annual average electricity generation[7]) [13], was taken into account. Consequently, the installed capacity of existing flexible biogas plants is two times higher than the rated capacity. The quotient of installed and rated capacity is a suitable indicator to describe the flexibility potential of biogas plants.[8] Consistent with [23], existing biogas plants begin flexible power generation when they reach their final 10 year period of EEG remuneration; older biogas plants are in baseload operation. Furthermore, flexible power generation is mandatory for biogas plants with an installed capacity of more than 100 kW (EEG 2017, § 44b). As a result, more than 85% of Germany's existing biogas plants will generate flexible power by 2025.

The additional costs for flexible power generation from existing biogas plants were calculated based on the methodology of [13]. Furthermore, we took no additional costs for the flexible biogas production into account. Depending on the date of flexibilization, additional investments in CHPU and gas storage capacities as well as further O&M costs were examined (Appendix, Table A1). This was done by determining additional costs for biogas plants with an installed capacity between 150 and 2050 kW using increments of 50 kW for the 2016–2025 period. To calculate the weighted average of additional costs of flexibilization per megawatt, the resulting costs were multiplied by the relative distribution of size classes of Germany's existing biogas plants, also using increments of 50 kW (based on the analysis of [32]). After 2025, existing biogas plants, which operate more than 10 years after flexibilization, will be closed down. Based on the net present value, the annuity was calculated by taking into account an (additional) 10-year operational life of existing biogas plants.

2.3.2. New installations of (flexible) biogas plants

To examine the costs of new biogas installations we defined one future plant design for baseload and flexible power generation (Table 3). According to existing biogas plants, the installed capacity of new installations has to be two times higher than the rated capacity (PQ = 2) (EEG 2017 § 39 h). In this paper, we focused on the cost-efficient biogas plant operation and considered a high installed capacity and the use of energy crops instead of a higher proportion of manure. The economic data of new biogas plants in baseload and flexible power generation were taken from Ref. [33]. These data were used to calculate the annuities based on the capital and O&M costs of new biogas installations for each year during the 2016–2035 period. The calculated annuities for each year were multiplied by the rated capacities of new, required biogas installations in the extension paths biogas *back-up* and *increase* (Appendix, Table A2).

2.4. Benefits

2.4.1. Reduction in onshore wind power plants

The annuity of new onshore wind turbines was based on the LCOE calculated by Ref. [34] (Appendix B). We used these LCOE for the period of 2016–2035 (missing values were linearly interpolated), the real discount rate, the operational life and the full load hours of onshore wind turbines, shown in Table 4, to calculate the missing capital and O&M costs of onshore wind turbines. The capital costs include the residual value at the end of 2035. Annuities of new installations for each year in the period under consideration (and LCOE derived from this) were calculated to be identical to the LCOE of the above-mentioned study. Following the methodology in our previous study [23], the annuities were then calculated with a

[7] Rated capacity [MW] is the quotient of the annual electricty generation [MWh per year] and 8670 h (8694 h in leap years).

[8] Further performance indicators of demand-driven power generation are presented in Ref. [31].

Table 3
Design and characteristics of new biogas installations.

	Baseload power generation	Flexible power generation
Rated capacity	0.913 MW	1 MW
Full load hours	8000	4380
Installed capacity	1 MW	2 MW
Power quotient (PQ)	1.1	2
No. of CHPU	1 x 1 MW	2 x 1 MW
Gas storage capacity	6 h	10 h
Feedstock (mass)	60% maize silage 30% grain silage 10% manure	
LCOE (including credit for heat)	183.4 € MWh^{-1} (2018) 198.5 € MWh^{-1} (2025) 211.5 € MWh^{-1} (2030) 226.0 € MWh^{-1} (2035)	191.6 € MWh^{-1} (2018) 207.2 € MWh^{-1} (2025) 221.0 € MWh^{-1} (2030) 236.7 € MWh^{-1} (2035)

Table 4
Assumptions about the economic assessment of onshore wind turbines.

Parameter	Assumption	Source/Note
Operational life	20 years	[34]
Annual full load hours	2000	[24]
Discount rate (nominal)	4.6%	[36]
Discount rate (real)	3.5%	Own calculations according to Ref. [37]
Operation and maintenance (O&M)	2.5% of initial investment per year	[38]
Capital-related rate of price increase	0.59%	Average annual increase in capital goods in Germany from 2000 to 2015 [39]
Operation-related rate of price increase	1.45%	Average annual increase of operating and maintenance costs in Germany from 2000 to 2015 [40]
LCOE	59.4 € MWh^{-1} (2015) 52.5 € MWh^{-1} (2020) 43.8 € MWh^{-1} (2030) 40.0 € MWh^{-1} (2040)	[34]

Table 5
Total discounted system costs (without onshore wind and biogas) in all scenarios considered for the 2016–2035 period [23].

Biogas extension path	Scenario	System costs [10^9 €]
Increase (INC)	INC-B	126.273
	INC-F	124.654
	INC-F+	124.524
Back-up (BU)	BU-B	127.099
	BU-F	125.929
	BU-F+	125.677
Phase-out	REF	127.353

nominal discount rate that included the capital- and operation-related price increase of capital and O&M costs respectively (Table 4). Based on the LCOE data of [34], the LCOE of new onshore wind farms in 2018 totals 55.2 € MWh^{-1} which is similar to the first auction of the German tendering system in 2018 (average of 57.3 € MWh^{-1}) [35].

Finally, the annuities, which were calculated for each year within the 2016–2035 period, were multiplied by the saved capacities of onshore wind turbines in the biogas extension paths *back-up* and *increase* and compared to the extension path *phase-out* (Appendix A, Table A3).

2.4.2. Additional saved opportunity costs

The reduced utilization of conventional power plants and decreased investments in further flexibility options, such as storage technologies, can be interpreted as additional saved opportunity costs of a higher proportion of (flexible) biogas plants compared to their phase-out. Thus, we took the system costs from a previous study [23] that analyzed the impact of flexible power generation in biogas plants on the electricity system. In this study, the system

Table 6
Installed capacities of conventional power plants and renewable energies when lignite- and coal-fired power plants are phased out [GW].

	2016	2020	2025	2030	2035	Source
Conventional						
Nuclear	10.8	8.1	–	–	–	[41,42]
Lignite	20.9	6.0	3.0	3.0	–	
Coal	28.7	8.0	8.0	7.0	4.0	
Gas	28.5	26.0	26.0	23.0	19.0	
Renewables						
Onshore wind						Own calculations based on [41,43,44]
Biogas phase-out	42.2	55.2	67.5	91.2	106.4	
Biogas back-up		54.4	65.9	88.7	103.1	
Biogas increase		54.1	63.7	79.5	88.1	
Offshore wind	3.9	7.0	14.5	23.0	26.8	
Photovoltaic	41.2	50.3	67.1	77.3	91.1	

Table 7
Capital and marginal costs of new installations of gas-fired and combined cycle power plants in the non-linear optimization model under consideration.

	2020	2025	2030	2035	Source
Capital costs (annuity) [10^3 € MW^{-1}]	82.6	87.9	93.7	100.0	Own calculations based on [45]
Marginal costs [€ MWh^{-1}]	59.0	73.1	76.7	80.3	Own calculations based on [24,45–47]

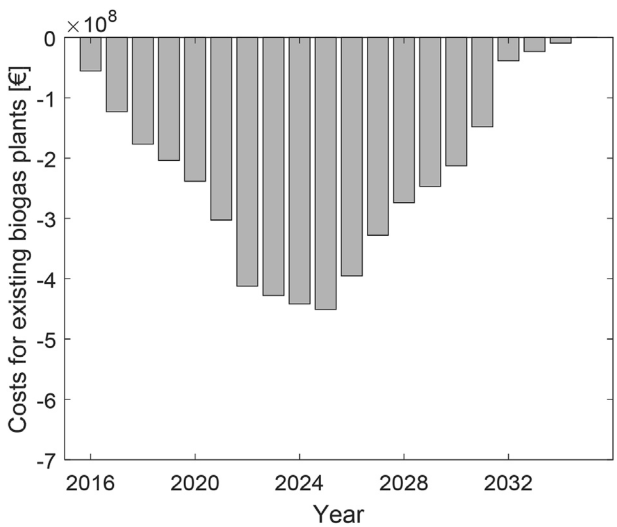

Fig. 2. Additional costs for the flexibilization of existing biogas plants in all scenarios with flexible power generation. Costs are not discounted.

costs included the marginal costs of conventional power plants and the investments in pumped-storage plants, Li-ion batteries and/or gas turbines as well as their marginal costs (Table 5). However, the capital and marginal costs of the flexibilization of existing biogas plants and/or the installation of new biogas and onshore wind turbines were not considered.

2.5. Early phase-out of lignite- and coal-fired power plants

According to the findings of [23], Germany's electricity system has a sufficient amount of flexible conventional power plants. Additional investments in pumped-storage plants, gas turbines and Li-ion batteries will start from the years 2030 and 2035 respectively [23]. However, an early phase-out of lignite- and coal-fired power plants is crucial in order to keep global temperatures to one and a half degree Celsius over preindustrial levels, [41]. To analyze if there is a difference when the energy transition towards renewable energies is accelerated, we compared the results of the cost-benefit analysis with an early reduction in conventional power plants. This was achieved by utilizing the methodologies described in previous studies [4,23], reducing the installed capacities of conventional power plants, and increasing the installed capacity of renewable energies based on [41] (Table 6).

Contrary to the methodology of [23], we considered the endogenous installation of gas-fired and combined cycle power plants instead of gas turbines in the non-linear optimization model. The early phase-out of lignite- and coal-fired power plants is expected to require conventional power plants that have a higher utilization rate than gas turbines. Assumptions regarding the capital and marginal costs are presented in Table 7.

We also analyzed how a higher installed capacity and a lower number of full load hours of biogas plants affects system costs. In addition to a PQ of 2, we considered a PQ of 3 which is characterized by 2920 full load hours per year. The additional costs of a higher

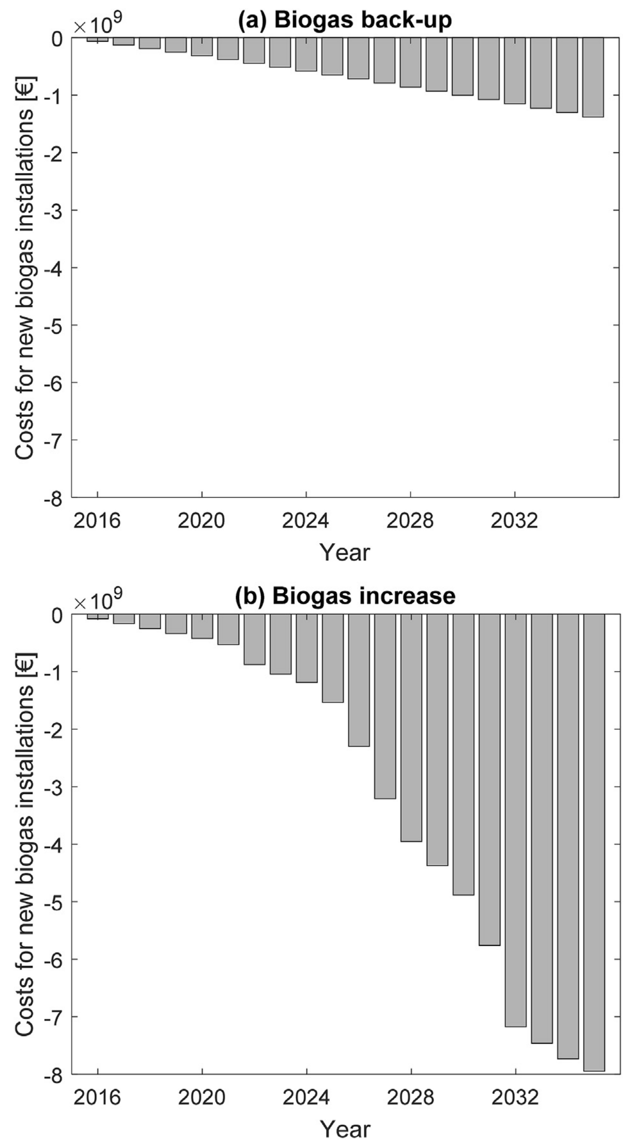

Fig. 3. Costs for new biogas plants in the extension path *back-up* (a) and *increase* (b). Costs are not discounted.

CHPU capacity were taken from the cost formula of [48]. The installed capacity of each CHPU was increased to 1.5 MW in new biogas installations.

2.6. Maximum LCOE of new biogas installations

In order to calculate the maximum LCOE of new biogas installations that would allow economically feasible operation as part of flexibility options for Germany's future electricity system (for the period of 2016–2035), costs were varied in the cost-benefit analysis until a net present value of 0 was achieved. This was carried out for an early and non-early phase-out of lignite- and coal-fired power plants.

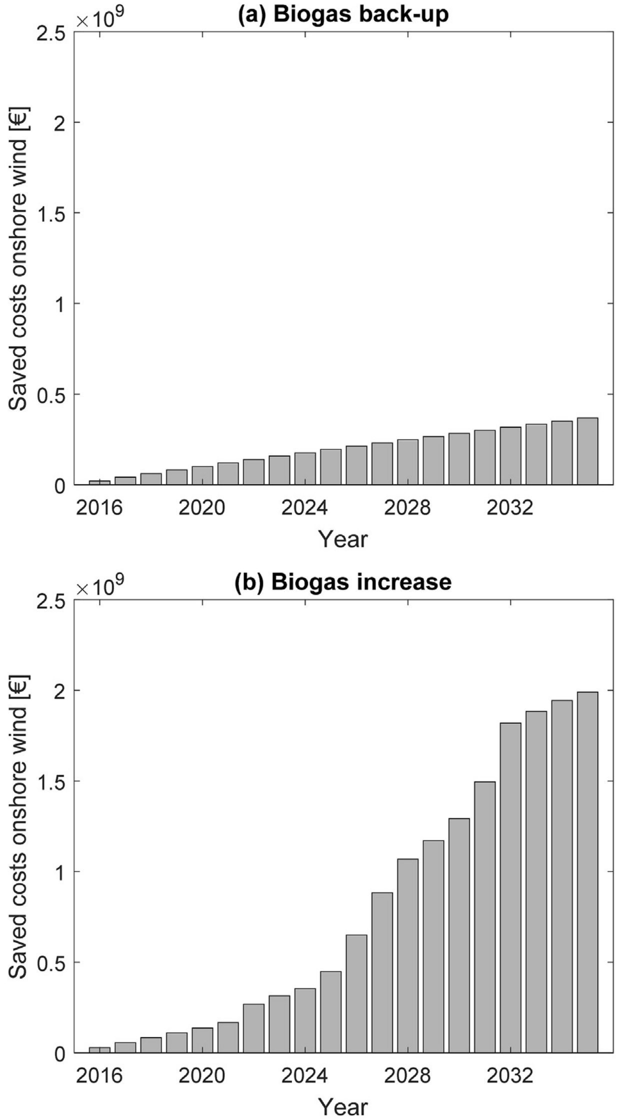

Fig. 4. Saved costs for onshore wind turbines by increasing the proportion of (flexible) biogas plants in the extension paths *back-up* (a) and *increase* (b). Benefits are not discounted.

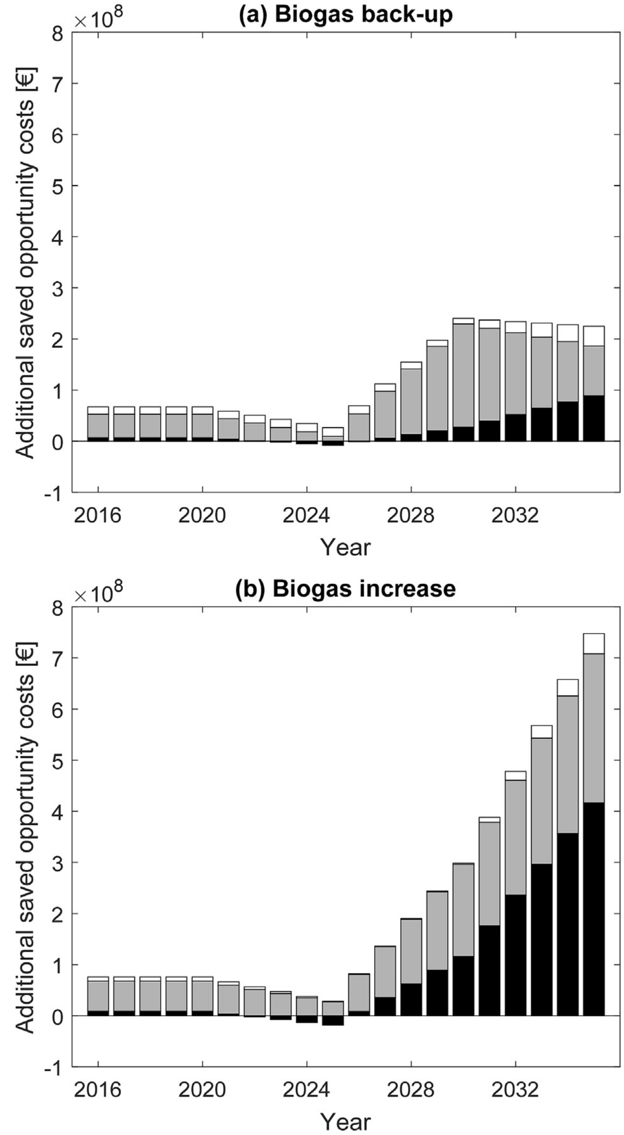

Fig. 5. Additional saved opportunity costs through a higher proportion of (flexible) biogas plants in the extension paths *back-up* (a) and *increase* (b). Plant configuration *Base* (black), *Flex* (grey), *Flex+* (white). Benefits are not discounted.

3. Results

3.1. Costs

3.1.1. Flexibilization of existing biogas plants

Depending on the commissioning year of existing biogas plants in Germany, the highest costs for the flexibilization of existing biogas plants occur in the mid-2020s (Fig. 2). This is why existing biogas plants start to phase out after an operational life of 20 years. The majority of Germany's biogas plants was commissioned between the years 2004 and 2012 [11]. In 2025, when the electricity generated by existing flexible biogas plants will peak, annual costs will be their highest at €0.45 billion. To summarize, the total costs for the flexibilization of existing biogas plants for the period of 2016–2035 amounts to €4.5 billion.

3.1.2. New installations of flexible biogas plants

In the biogas extension path *back-up*, the costs for new flexible biogas plants increase linearly through the constant annual installation of 75 MW (installed capacity) per year (Fig. 3). The highest costs for new biogas installations occur in the year 2035 (€1.4 billion) and the total costs for the period under consideration amount to €13.9 billion. In contrast, total costs for the installation and operation of new biogas plants increase to €61.2 billion in the biogas extension path *increase*. The phase-out of existing biogas plants causes a sharp increase in total costs in the years 2027 and 2032. The total annual costs in the biogas extension path *increase* vary between €0.08 and 7.9 billion.

3.2. Benefits

3.2.1. Reduction in onshore wind turbines

An increase in the proportion of biogas plants in the future German electricity system leads to a reduction in onshore wind turbines to fulfill the target values of the EEG. Therefore, the benefits of a reduction in onshore wind turbines in the biogas extension paths *back-up* and *increase* show a similar trend (Fig. 4). However, the replacement of onshore wind turbines is linked to

Table 8
Benefit-cost ratios and net present values in the scenarios under consideration (compared to the reference scenario). Non-early phase-out of lignite- and coal-fired power plants.

Biogas extension path	Scenario	Benefit-cost ratio	Net present value [B €]
Increase (INC)	INC-B	0.307	−25.82
	INC-F	0.308	−29.32
	INC-F+	0.311	−29.19
Back-up (BU)	BU-B	0.332	−5.98
	BU-F	0.324	−8.66
	BU-F+	0.343	−8.41

lower benefits due to their lower capital and O&M costs. In the extension path *back-up*, the total benefits of reduced onshore wind turbines for the period of 2016–2035 amount to €4.0 billion. Furthermore, the total benefits increase to €16.2 billion in the biogas extension path *increase.*

3.2.2. Additional saved opportunity costs

Increasing the proportion of (flexible) biogas plants in the future German electricity system reduces the utilization of conventional power plants, which are characterized by high marginal costs (and GHG emissions), and investments in further flexibility options. Having fewer additional biogas plants (*back-up* extension path)

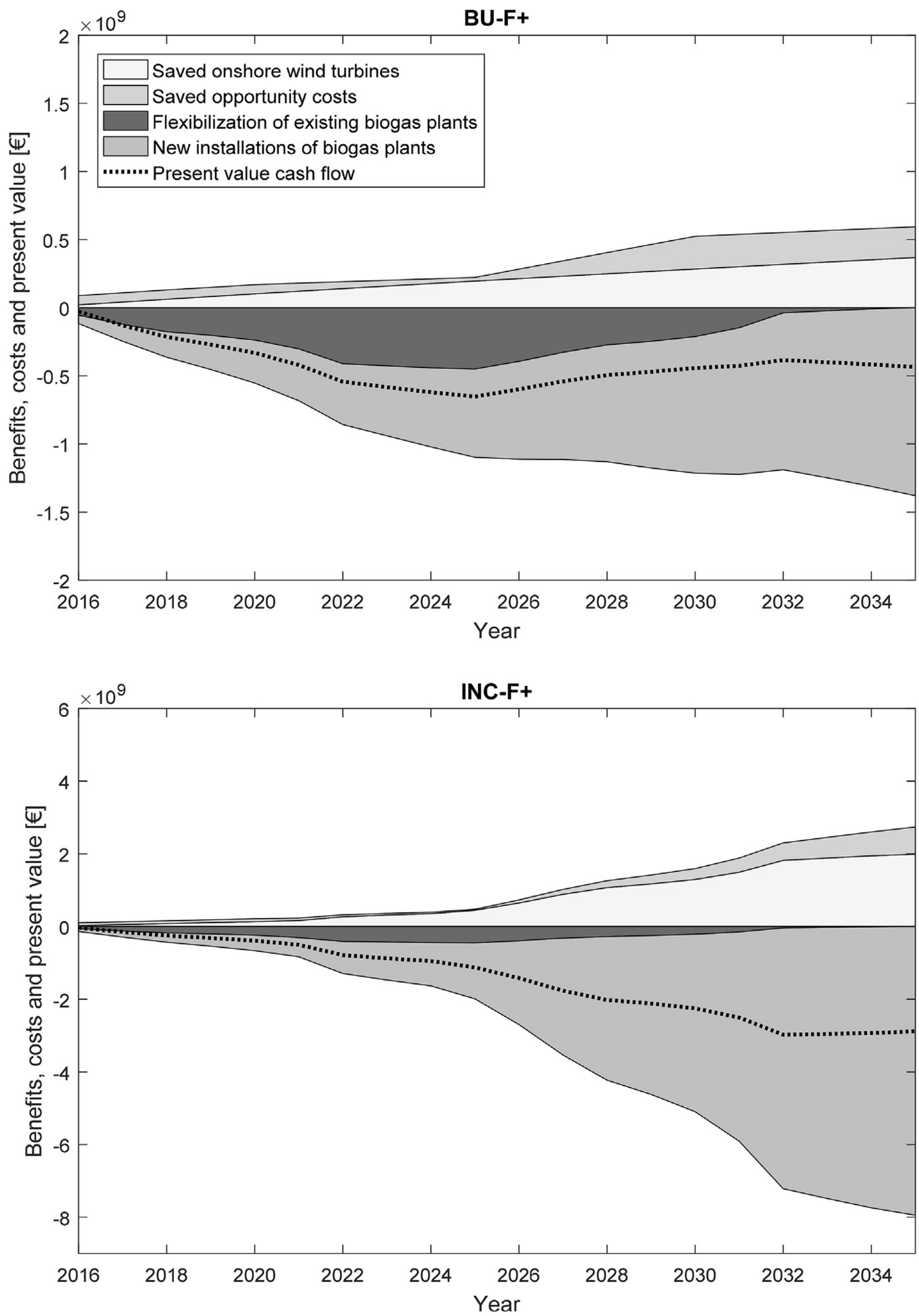

Fig. 6. Costs (negative values) as well as benefits (positive values) and present value of the annual cash flow in the scenarios *BU-F+* and *INC-F+*. Costs and benefits are not discounted.

Table 9
Benefit-cost ratios and net present values in the considered scenarios (in comparison to the reference scenario). Early phase-out of lignite- and coal-fired power plants.

PQ 2			
Biogas extension path	Scenario	Benefit-cost ratio	Net present value [B €]
Increase (INC)	INC-B	0.383	−22.98
	INC-F	0.527	−20.04
	INC-F+	0.528	−19.99
Back-up (BU)	BU-B	0.634	−3.28
	BU-F	0.718	−3.62
	BU-F+	0.759	−3.09
PQ 3			
Biogas extension path	**Scenario**	**Benefit-cost ratio**	**Net present value [B €]**
Increase (INC)	INC-F	0.545	−20.89
	INC-F+	0.566	−19.96
Back-up (BU)	BU-F	0.767	−3.71
	BU-F+	0.769	−3.68

results in total benefits of up to €2.5 billion (scenario BU-F+) for the period under consideration (Fig. 5). However, in the biogas extension path *increase*, the benefits are higher and are characterized by total benefits of up to €4.4 billion (scenario INC-F+). In both biogas extension paths, the highest savings are achieved in the Flex + mode of operation, when the biogas plants are most flexible. In contrast, baseload generation in biogas plants leads to the lowest overall benefits. Furthermore, the highest annual benefits are achieved in the INC-F+ scenario and the year 2035 (€0.75 billion). Due to the high installed capacity of conventional power plants, the benefits of a higher proportion of biogas plants start to become significant from the mid-2020s onwards.

3.3. Cost-benefit analysis

Table 8 shows the benefit-cost ratio for each scenario under consideration compared to the reference scenario. An increasing proportion of (flexible) biogas plants leads to an overall benefit-cost ratio of less than one in all scenarios. The costs of additional biogas plants exceed the benefits of their dispatchable electricity generation (Fig. 6). As a result, the investments in flexible power generation from biogas plants (and additional capacities) are thwarted by a sufficient installed capacity of conventional power plants and existing dispatchable pumped-storage plants. Focusing on the net present value, the best result was achieved in the scenario BU-B (-€6.0 billion); the lowest in the scenario INC-F (-€29.3 billion). This is explained by the fact that there is a sufficient amount of existing flexibility options in the electricity system and additional investments in flexible power generation from biogas plants lead to an oversupply of flexibility. Investments in flexible power generation from biogas plants have to be better coordinated with the installed capacity of further flexibility options, otherwise the efficiency of the energy transition process might be hampered by additional costs. Nevertheless, flexible power generation increases the benefit-cost ratio compared to baseload power generation. In both biogas extension paths, the highest benefit-cost ratio was calculated in the *Flex* + plant configuration.

4. Discussion

4.1. Study design

In this study, we focus on the energy transition pathways of Germany's biogas plants. An alternative approach might be the so-called "greenfield approach" optimizing power plants without taking into consideration the existing legal framework and power plants (e.g. the study by Ref. [22]). On the one hand, the advantage of our approach is that the dynamic development of decommissioning existing conventional power plants and increasing renewable energies can be analyzed in more detail. This also allows us to identify an advantageous time for investing in flexibility options such as storage technologies or biogas plants. From the perspective of policymakers, decisions on the future design of renewable energy systems and cost-efficient policy choices have to take into account currently installed capacities of power plants and legal frameworks. On the other hand, the greenfield approach ensures more degrees of freedom to optimize the future energy system. This might be a template for changing current frameworks. In summary, we calculate benchmarks for an economically feasible operation of (flexible) biogas plants in future electricity systems taking into account existing frameworks. Cost-efficient energy/electricity systems are defined in other studies.

In contrast to the results of this analysis, the study by Ref. [22] used a greenfield approach. It calculated lower annual generation costs in Germany's electricity system when its predominantly decarbonized renewable energies and bioenergy plants are included in this system. However, the author of [22] optimized Germany's power plant portfolio with regard to varying proportions of renewable energies without taking existing conventional power plants into consideration. Consequently, the optimization of the power plant portfolio in the target system was based on annualized costs of power plants and the potentials of their energy carriers, among other things. By concentrating on the target system and not taking into account existing power plants, biomass plants represent a way to reduce annual generation costs in renewable energy systems. However, our study took into account Germany's current power plant portfolio and the net present value of the total system costs for the period under consideration. This is why we did not calculate the cost-efficient impact of additional biogas plants on total system costs.

Cost-benefit analyses are subject to the risk of uncertainties surrounding the future cash flow generated by investment [30]. Consequently, a sensitivity analysis was carried out on the robustness of the results when changes are made to different parameters (Section 4.4).[9]

4.2. Early phase-out of lignite- and coal-fired power plants

The early phase-out of lignite- and coal-fired power plants leads to a higher benefit from flexible biogas plants. Instead of existing

[9] Further details on the limitations of the non-linear optimization model considered in this analysis, are shown in Ref. [23].

Table 10
Maximum LCOE [€ MWh^{-1}] of new biogas installations in the cost-benefit analysis that allows operations to be economically feasible. Commissioning year is 2018.

Scenario	*Phase-out of lignite- and coal-fired power plants*		
	Non-early	*Early, PQ 2*	*Early, PQ 3*
BU-B	60.9	116.2	
BU-F	14.1	117.5	116.8
BU-F+	19.3	128.3	117.6
INC-B	56.3	70.3	
INC-F	47.2	92.9	90.4
INC-F+	47.9	93.2	94.9

conventional power plants, biogas power generation substitutes new installations of storage technologies and gas-fired power plants (Appendix, Table A4). Therefore, the benefit-cost ratio and the net present value increases (Table 9). The higher flexibility resulting from an increased installed capacity of biogas plants (PQ 3) enhanced the benefit-cost ratio and lowered the net present value except for in the INC-F+ scenario. Nevertheless, the additional benefits through the early phase-out of conventional power plants does not result in an economically feasible operation of (flexible) biogas plants (benefit-cost ratio ≤ 1). If biogas plants are to remain a component of the future electricity system, their power generation has to be as flexible as possible. The highest net present values were achieved in *Flex* + mode of operation when lignite- and coal-fired power plants are phased out early.

The figure indicating annual costs, annual benefits and the present value of the early phase-out of lignite- and coal-fired power plants is shown in the Appendix (Figure A1).

4.3. Maximum LCOE of new biogas installations

A non-early phase-out of lignite- and coal-fired power plants limits the maximum LCOE of new biogas installations to 60.9 € MWh^{-1} for a net present value ≥ 0 in scenario BU-B, when these plants begin operation in 2018 (Table 10). In a non-early phase-out, the maximum LCOE of new biogas plants was calculated in base-load generation without investment in the flexibilization of existing plants (scenario BU-B). In contrast, an early phase-out of lignite- and coal-fired power plants allows higher LCOE for (flexible) power generation from biogas plants. In this case, their maximum costs

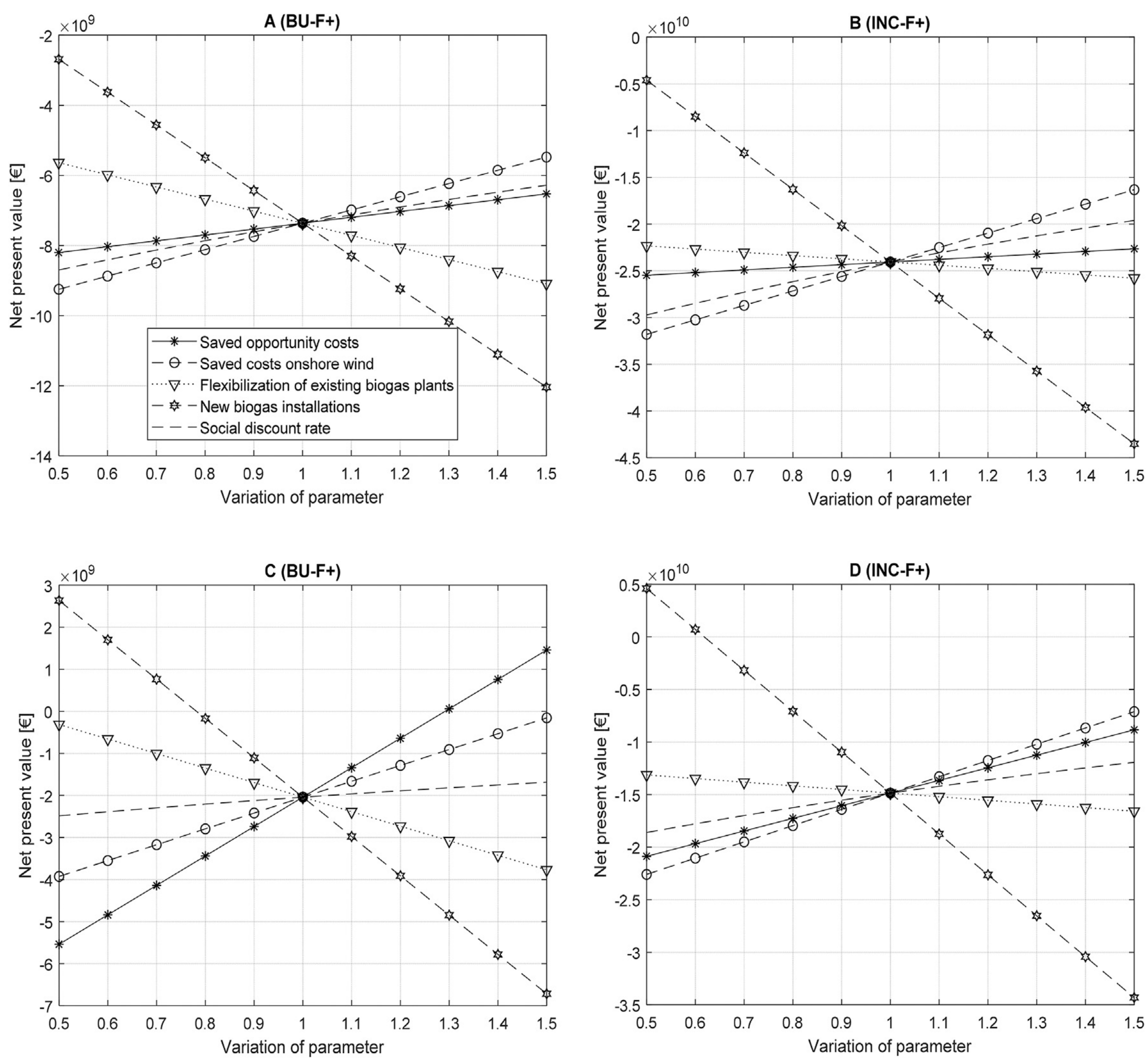

Fig. 7. Net present value in the scenarios BU-F+ and INC-F+ taking into account a non-early (A|B) and an early phase-out of coal- and lignite-fired power plants (PQ 2) (C|D).

Table 11
A selection of further benefits of biogas plants that are not taken into account in the cost-benefit analysis.

Energy system	Environmental/climate benefits	Economic benefits	Other benefits
• Lower demand for power grid extension [49] • Source of carbon for the methanation of hydrogen [50] • Cost savings from conventional power plants (e.g. lower amount of start/stop operations) [51] • (Decentralized) heat supply and substitution of fossil fuels [52]	• Reduction in agricultural GHG emissions through the use of manure and other organic waste products [53,54] • Substitution of inorganic fertilizer through the use of biogas digestate [55] • Reduction in GHG emissions and air pollution in the heating sector [56]	• Additional income for farmers [57] • Additional jobs in rural areas [58] • Positive effect on the added value in rural areas [58]	• Source of carbon dioxide for BECCS (bio-energy with carbon capture and storage) [59] • Reduction in odor and fewer pathogens when manure is used [60]

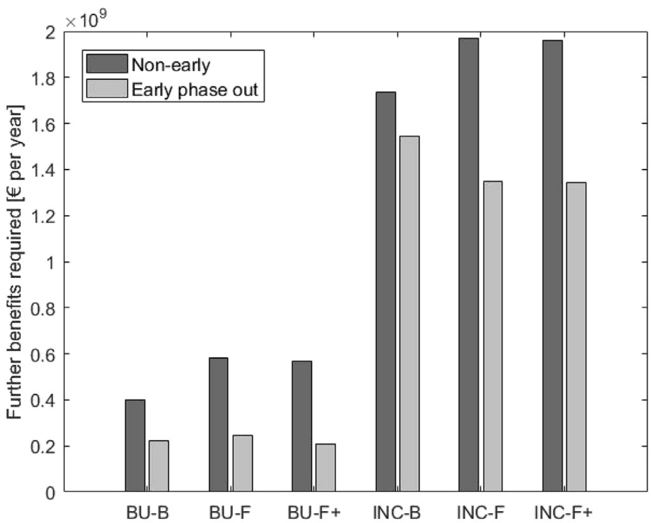

Fig. 8. Further benefits required from biogas plants to ensure an economically feasible operation (compared to their phase-out) with respect to a non-early and an early phase-out of coal- and lignite-fired power plants. Benefits are annualized by Formula (3), a (social) discount rate of 3% and a period of 20 years.

vary between 90.4 and 128.3 € MWh^{-1} in 2018 depending on their future plant design.

4.4. Sensitivity analysis

In terms of the net present value of the cost-benefit analysis, the highest impact was achieved in the BU-F+ and INC-F+ scenarios by varying new biogas installation costs (Fig. 7). In the BU-F+ scenario and in the non-early phase-out of lignite- and coal-fired power plants, the flexibilization of existing biogas plants is highly sensitive. The saved opportunity costs become more important when lignite- and coal-fired power plants are phased-out earlier (Fig. 7 C D). Otherwise, this benefit does not highly impact the net present value (Fig. 7 A B).

4.5. Further benefits of biogas plants

In this analysis, we focused on the benefits of (flexible) power generated by biogas plants in the electricity system. In addition to the aforementioned benefits, biogas plants create further benefits in the energy system and other areas (Table 11). Those effects were not monetarized in this analysis, but they have to be considered when biogas plants are ultimately assessed in economic terms. Therefore, the other annualized benefits that are needed for an economically feasible operation in the electricity system are calculated in Fig. 8. Lowest other benefits are achieved in the BU-F+ scenario when lignite- and coal-fired power plants are phased out earlier (approx. €0.2 billion per year). Whereas, a non-early phase-out of those plants in the INC-F scenario requires other annualized benefits of about €2.0 billion for a non-negative net present value.

If Germany's future electricity system is highly decentralized, the highest benefit from flexible power generation might be achieved by a lower demand for power grid extension. More decentralization leads to an increase in regional responsibility to ensure sufficient power supply.

5. Conclusions and policy implications

In this analysis, we assessed economically varying biogas extension paths and modes of operation in the future German electricity system for the period of 2016–2035. This was done by examining a cost-benefit analysis in order to evaluate the impact of (flexible) power generation from biogas plants on the substitution of further flexibility options and onshore wind turbines. The key findings are as follows:

- The maximum LCOE of new biogas installations in 2018 that enables economically feasible operation in the electricity system is about €128 MWh^{-1}. Otherwise, further benefits have to compensate for the economic results of the biogas impact on the electricity system.
- Without cost reductions, additional investments in biogas plants have to be accompanied by further benefits in other sectors and areas to ensure economically feasible operation, e.g. the substitution of fossil fuels in the heating sector and a reduction in GHG emissions in the agriculture sector.
- An early phase-out of lignite- and coal-fired power plants increases the economic feasibility of biogas plants. In such case, the power generated from biogas plants should be as flexible as possible through a combination of flexible biogas production and electricity generation. Nevertheless, only accelerating the decommissioning of conventional power plants does not enable an economically feasible operation of flexible power generation from biogas plants.
- Based on the plant design and feedstock under consideration, the best results were achieved in the biogas extension path *back-up*, characterized by a low construction rate for new biogas plants.

From the broader perspective of policymakers, we recommend the following strategies:

- The extension path, the mode of operation and the future design of biogas plants should be better coordinated with the demand

for flexibility in the future German electricity system. For example, decommissioning conventional power plants might be linked to the extension of renewable energies in the electricity system.
- Current overcapacities of conventional power plants should be lowered to avoid additional costs when transforming the energy system.
- Further benefits of biogas plants have to be monetarized to derive optimized extension paths and modes of operation for biogas plants.
- Optimization of biogas plants and an increasing use of organic waste products in biogas production might enhance the environmental/climate benefits and result in higher outcomes in the economic assessment of biogas plants.
- The further development of energy system models is needed to analyze energy transition paths in more detail. Advanced energy system models can be used as decision-making tools for policymakers.

For further research, we suggest a more detailed cost-benefit analysis of various biogas extension paths and modes of operation that take into account additional impacts of bioenergy on their economic assessment. Based on this methodology, further benefits from (flexible) power generation in biogas plants has to be monetarized. For example, a regional value creation from bioenergy, characterized by the generation of jobs and tax revenues in rural areas. In addition, sensitivity analysis dealing with varying extension paths of renewable energies (for example a higher proportion of PV plants) has to be carried out on the robustness of the results.

Acknowledgements

The project was supported by funds from the Federal Ministry of Food and Agriculture (BMEL) based on a resolution by the Parliament of the Federal Republic of Germany via the innovation support program of the Federal Office for Agriculture and Food (BLE).

Appendix A

Table A.1
Annuities and rated capacities for the flexibilization of existing biogas plants considered in the cost-benefit analysis for the period of 2016–2035.

Year	Annuity flexibilization of existing biogas plants [10^3 € (MW_{rated}*year)$^{-1}$]	Additional rated capacity of biogas plants in flexible mode of operation [MW_{rated}]
2016	−151.78	366
2017	−153.96	439
2018	−156.17	344
2019	−158.43	170
2020	−160.71	214
2021	−163.04	395
2022	−165.41	662
2023	−167.82	92
2024	−170.26	82
2025	−172.75	53

Table A.2
Annuities and installations (rated capacity) of new biogas plants considered in the cost-benefit analysis for the period of 2016–2035. Including credit for heat.

Year	Annuity new flexible biogas installations [10^3 € (MW_{rated} *year)$^{-1}$]	Annuity new baseload biogas installations [10^3 € (MW_{rated} *year)$^{-1}$]	Annual installations of new biogas plants [MW_{rated}]	
			Biogas extension path *back-up*	Biogas extension path *increase*
2016	−1638	−1567	37.5	50.0
2017	−1658	−1587	37.5	50.0
2018	−1679	−1606	37.5	52.3
2019	−1699	−1626	37.5	50.0
2020	−1719	−1645	37.5	50.0
2021	−1739	−1664	37.5	60.5
2022	−1759	−1683	37.5	197.9
2023	−1778	−1702	37.5	92.9
2024	−1796	−1720	37.5	82.1
2025	−1815	−1739	37.5	191.9
2026	−1833	−1757	37.5	415.7
2027	−1858	−1780	37.5	489.4
2028	−1884	−1804	37.5	394.4
2029	−1910	−1828	37.5	220.0
2030	−1936	−1853	37.5	264.4
2031	−1963	−1878	37.5	445.4
2032	−1990	−1903	37.5	711.8
2033	−2017	−1928	37.5	142.0
2034	−2045	−1954	37.5	132.5
2035	−2073	−1980	37.5	103.3

Table A.3
Annuities and installations of onshore wind turbines considered in the cost-benefit analysis for the period of 2016–2035 (installed capacity).

Year	Annuity onshore wind [10^3 € (MW*year)$^{-1}$]	Annual reduced installations of onshore wind turbines [MW] – compared to the biogas extension path *phase-out*	
		Biogas extension path *back-up*	Biogas extension path *increase*
2016	−128	164	221
2017	−126	164	221
2018	−123	164	221
2019	−121	164	221
2020	−118	164	221
2021	−117	164	265
2022	−116	164	867
2023	−114	164	407
2024	−113	164	359
2025	−112	164	840
2026	−110	164	1821
2027	−109	164	2144
2028	−108	164	1728
2029	−106	164	963
2030	−105	164	1158
2031	−104	164	1951
2032	−104	164	3118
2033	−104	164	622
2034	−103	164	580
2035	−103	164	453

Table A.4
Additional accumulated installed capacities of flexibility options taking into consideration an early phase-out of conventional power plants. Comparison to a non-early one in parenthesis (see Ref. [23]) [GW].

Scenario	Pumped-Storage				Li-ion				Gas-fired power plant			
Year	2020	2025	2030	2035	2020	2025	2030	2035	2020	2025	2030	2035
REF	0 (0)	2.22 (+2.22)	2.48 (+1.74)	4.71 (0)	0 (0)	0.02 (+0.02)	1.14 (+1.14)	3.22 (+2.00)	10.28 (+10.28)	16.71 (+16.71)	16.71 (+15.66)	20.88 (+19.83)
BU-B	0 (0)	0.86 (+0.86)	0.87 (+0.21)	4.29 (−0.42)	0 (0)	0.08 (+0.08)	1.35 (+1.35)	3.18 (+2.14)	10.18 (+10.18)	17.97 (+17.97)	17.97 (+17.13)	20.98 (+20.13)
BU-F	0 (0)	0.01 (+0.01)	0.79 (+0.13)	3.64 (−1.07)	0 (0)	0.02 (+0.02)	2.07 (+2.07)	3.22 (+2.45)	8.26 (+8.26)	15.45 (+15.45)	15.45 (+15.45)	20.94 (+20.63)
BU-F+	0 (0)	0 (0)	0.57 (0)	3.57 (−1.14)	0 (0)	0.01 (+0.01)	2.07 (+2.07)	3.18 (+2.53)	8.26 (+8.26)	15.45 (+15.45)	15.45 (+15.45)	20.94 (+20.51)
INC-B	0 (0)	0.77 (0)	0.77 (0)	3.05 (−1.66)	0 (0)	0.31 (+0.31)	0.80 (+0.80)	3.13 (+3.13)	10.14 (+10.14)	17.54 (+17.54)	17.54 (+17.51)	20.51 (+20.49)
INC-F	0 (0)	0 (0)	0.01 (0)	1.81 (−2.90)	0 (0)	0 (0)	0.23 (+0.23)	3.13 (+3.13)	8.16 (+8.16)	14.63 (+14.63)	14.63 (+14.63)	17.24 (+17.24)
INC-F+	0 (0)	0 (0)	0 (0)	1.00 (−3.71)	0 (0)	0.03 (+0.03)	0.26 (+0.26)	3.13 (+3.13)	8.16 (+8.16)	14.60 (+14.60)	14.60 (+14.60)	18.14 (+18.14)

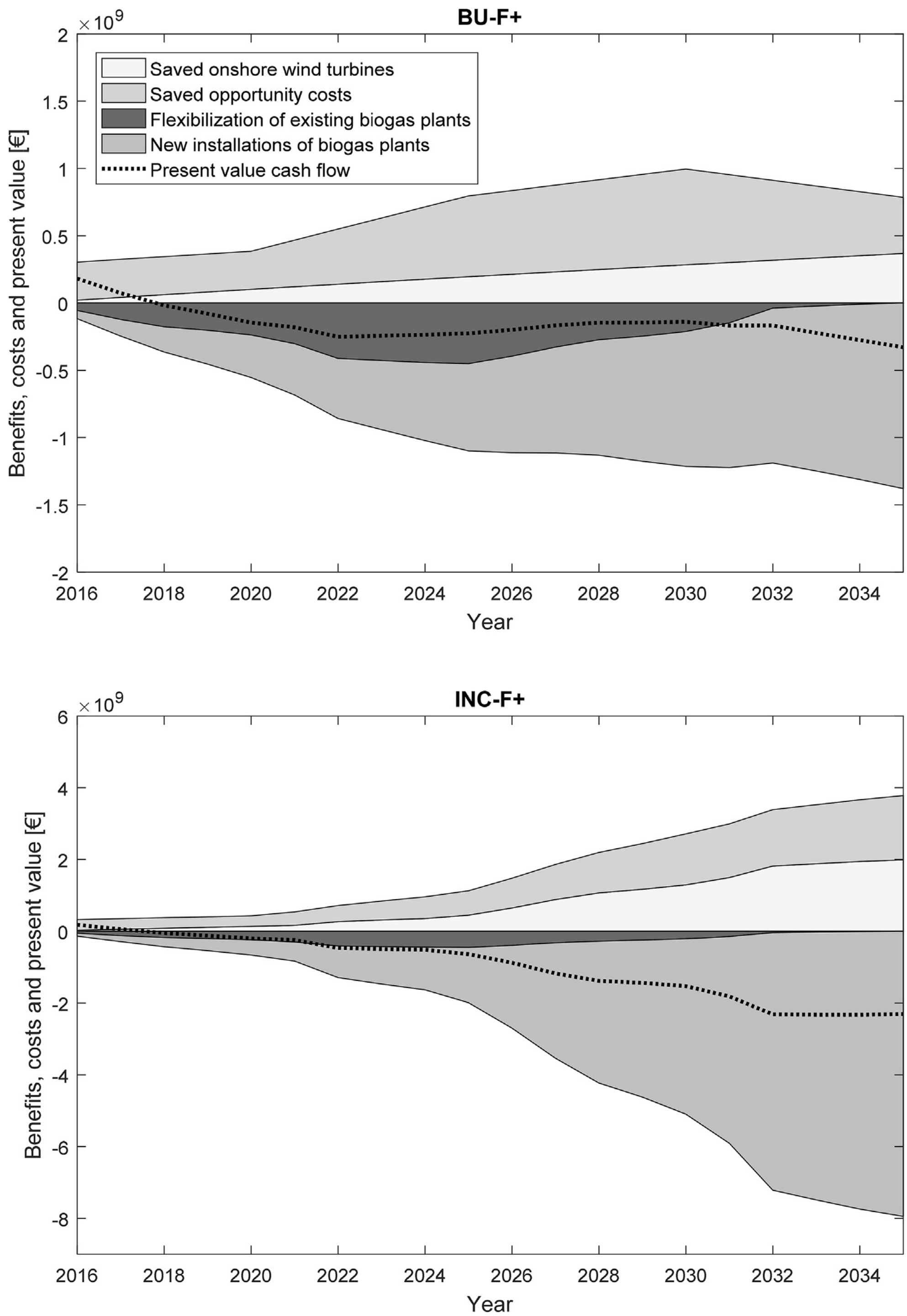

Fig. A.1. Costs (negative values) as well as benefits (positive values) and present value of the annual cash flow in the scenarios *BU-F+* and *INC-F+* (early phase-out of lignite- and coal-fired power plants). Costs and benefits are not discounted.

Appendix B

The LCOE can be calculated by the following equation (adapted from Refs. [36,61]):

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{E_t - R_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+i)^t}} \quad (4)$$

I_0 investment expenditures,
E_t total expenditures in the year t
R_t heat revenues in the year t (in the case of biogas plants)
G_t electricity generated in the year t
i discount rate
t year within the operational life

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