Effects of the German Renewable Energy Act and environmental, social and economic factors: biogas plants adoption and agricultural landscape change

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Abstract

Background: The German energy transition strategy calls for reform of the German energy sector. Against this background, the Germany Renewable Energy Sources Act, or EEG, was issued in 2000 and is widely regarded as a successful legislation for promoting bioenergy development, as more than 9000 biogas plants were built in Germany until 2017. However, the impact from different EEG periods on regional biogas plants' development and the long-term influence to regional landscape change are rarely simultaneously studied.

Methods: This study aimed to quantitatively analyse the impact of the EEG on promotion the biogas plant development in central Germany (CG) by using the event study econometric technique. A GIS-based spatial analysis was further conducted to provide insight into the changes of the agricultural landscape, which was resulted from the development of biogas plants during the EEG from 2000 to 2014.

Results: One of the main findings was that the EEGs had time-varying effects on motivating biogas plants construction and selecting the plants size. The comparison between different EEG emendations suggested that the EEG 2009 was the most successful one in market implementation. Besides, the adoption of the biogas plant in CG was mainly driven by the farmer's financial incentive and taken as an investment to secure the farming business. At the landscape scale, the expansion of silage maize was remarkable in CG from 2000 to 2014. The silage maize was intensively cultivated in the regions with high biogas plant installed capacity. Since EEG 2009, the regional livestock number increased rapidly, which was also associated with increasing pasture land area in CG. This phenomenon suggested a promising regional animal farming and its potential of manure as biogas feedstock.

Conclusions: These findings imply that the policy makers should take the EEG 2009 emendation as reference to promote the marketing of future new renewable energy technologies and cautions should be paid on the potential land conflicts of agricultural-based bioenergy development.

Keywords: Biogas plant, Event study, Renewable Energy Act, Central Germany, Land use change

Background

The 2015 UN 21st Conference of Parties was a critical step towards international solidarity to address climate change. According to the Paris Agreement reached at that meeting, it is compulsory for countries to reduce greenhouse gas (GHG) emissions to limit global warming to less than 2°C above the pre-industrial average [1]. Germany has committed to reduce its GHG emissions by 14% relative to 2005 levels by 2020 [2]. In 2016, the German government set new goals in the Climate Action Plan 2050, which aims to reduce GHG emissions by at least 55% by 2030, 70% by 2040, and 80-95% by 2050 compared to 1990 levels [3]. Given that around two-thirds of GHG emissions come from energy production and utilization, a transition from fossil fuels to low-carbon solutions can play a vital role in climate change mitigation [4]. The German energy transition strategy (German: Energiewende) focuses on nuclear phase-out, fossil fuels reduction and sustainable promotion of renewable energies [5]. Hard work towards these goals has made Germany the pioneer in the energy reform sector and a leader of the broader worldwide energy transition [6,7].

In Germany, the central instrument to promote renewable energy is the Renewable Energy Act (German: Erneuerbare-Energien-Gesetz, or "EEG"). The EEG is based on the previous Electricity Feed-in Law of 1990 and inherits its mechanism of payment of a fixed tariff for energy provision. First adopted on April 1, 2000, the EEG was amended in 2004, 2009, 2012, 2014 and 2017 with modifications of the subsidy policy and specification of application conditions for biogas plants [8-13] (see Fig. 1). The feed-in tariff (FIT), introduced in EEG 2000, prioritised the electricity generated from renewable sources like biogas over that produced from conventional non-renewable sources through subsidies. The FIT for each unit of electricity generated from renewable sources was guaranteed for a maximum of 20 years. The FIT started to differentiate among different feedstocks since EEG 2004 by introducing the premium scheme, i.e., premiums for technology innovation and using renewable resources as substrate [9] (see Appendix Table 5). Various new premium categories, such as emission reduction and bio-waste/manure, were included in the EEG 2009 [10]. A so-called "maize cap" was introduced in the EEG 2012 to suppress the rapidly increasing cultivation area of maize, which was also known as the "maizification of the landscape", and to increase the diversity of the crops grown for energy production [11,14]. The EEG 2014 represented a paradigm shift for German biogas plants. It made a major cut in the subsidies associated with biogas plants, particularly for agricultural plants fuelled by energy crops [12]. In 2017, the newly amended EEG introduced a tendering system to select renewable electricity producers. It established the expansion corridors and volumes for renewable energy to be auctioned. As a result of the limited market premiums for every auctioned renewable source, the level of the market premium actually declined [13].

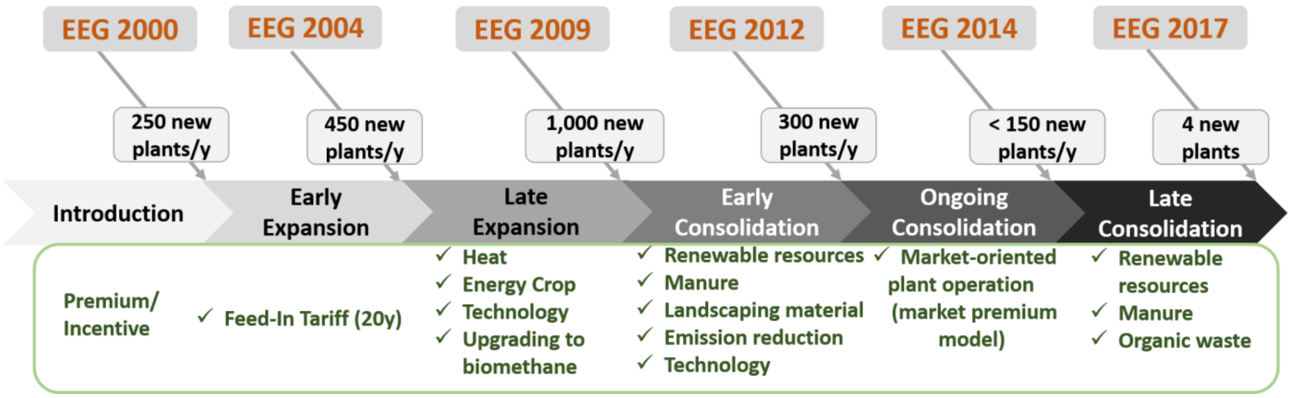

Fig. 1 The development phases of the German biogas sector along the timeline of the Renewable Energy Act [15]

In general, EEG is considered a successful approach for promoting renewable energy and biomass production by providing financial support. Between 2000 and 2017, the number of biogas combined heat and power plants in Germany increased from 850 to 9,331, with the cumulative installed capacity rising from 50 to 4,800 mWel. [16,17,15]. In 2017, energy consumption in Germany amounted to 13,550 PJ, of which the share of renewable energies was 13.1% (1,780 PJ). Within that, renewable energy sources contributed approximately 33.3% of the national gross electricity generation. Among them, biomass accounted for 7.8% of the national electricity generation. The dominant biofuel type was biogas, which contributed 63.2% of electricity generation, followed by biogenic solid fuels and biogenic fraction of waste, with shares of 20.7% and 11.5%, respectively [18].

Apart from the financial incentive provided by policies, such as EEG, the biogas plant adoption is also influenced by environmental, social and economic factors [19-23]. Some of these factors were well developed and served as indicators in biogas investment assessment. For example, the biogas technical potential representing the regional feasibility of biogas plants from an environmental perspective was proposed in previous research. Biogas technical potential considers the technical aspects and measures the quantity of different types of feedstock available for biogas production, e.g., sewage sludge, animal residues, energy crops and etc. [24-27]. As discussed in previous research, substrates transportation of energy crops and livestock excrement was inefficient from both economic and environmental perspectives [28]. Therefore, biomass was generally obtained from the immediate vicinity of a biogas plant. This finding was confirmed by the research of Csikos et al. [29], who found that biogas plants were concentrated in areas where energy crops were largely cultivated. In addition, it has been found that areas with higher biogas technical potential had biogas plants with higher capacities [25]. In terms of social factors, education level has been found to have a strong positive influence on biogas plant decisions in various studies [30-35]. The economic factors that have been systematically analysed and believed to have impacts on biogas plant adoption were income per capita at the household level and GDP density at the regional level [30,34,36]. These two variables reflect the general economic situation of a certain area in a certain year and enable cross-sectional comparisons.

Previous studies throughout Germany have demonstrated that maize silage had the highest potential for dry matter and methane yield compared to other energy crops [37,38]. From 2010 to 2019, the biogas production boom was accompanied by maize expansion. In particular, the cultivated area of silage maize increased from 1.8 to 2.2 Mha in Germany [39]. Besides, maize also strongly contributed to the development of cattle farming, as it is an important fodder source. The study by Lüker-Jans et al. [40] explored permanent grassland to maize conversion and related this to biogas plants and livestock farming. They concluded that biogas plant installed capacity concentration and livestock density could serve as indicators for regional land use change. Another important aspect is the exclusive cultivation of monoculture maize, which requires the intensive use of fertilizers and pesticides for yield improvement. Apart from these considerations, an important discussion has been raised about the potential ecological risks to important ecosystem services, such as biodiversity loss, soil erosion, reduction of groundwater and landscape modifications [41]. The environmentally compatible cultivation of maize has become a goal for sustainable farming to decrease these potential risks in Germany [42].

This study aimed to quantitatively analyse the impacts of EEG 2000, EEG 2004, EEG 2009 and EEG 2012 (EEG I, EEG II, EEG III and EEG IV, respectively), as well as other environmental, social and economic factors on the development of the biogas plants in Central Germany (CG). In this regard, the effects of biogas plants development on the agricultural landscape in CG was analysed using GIS-based spatial analysis. To achieve these goals, we first introduced the event study econometric technique to analyse the effects of different EEG emendations. The event study econometric technique, as a widely applied method to analyze event impact in economic research, could shed light on evaluating environmental relevant policy effectiveness [43-45]. As results, the impacts of each EEG version and other determined factors on biogas plants in terms of their quantity and installed capacity could be individually quantified. The quantified influence of each EEG made the comparison between different EEG periods possible. The comparison results could be used to further assess the effectiveness of each EEG emendation, helping policy makers in future policy design. Moreover, the pattern of agricultural landscape utilization, such as cultivation area of regional energy crops and livestock farming, was spatially analysed during each EEG period. In summary, by using the event study method, this study attempted to understand the effectiveness of each EEG version in promoting biogas plants as well as the consequence of booming biogas plants in agricultural landscape change in CG.

Methods and data

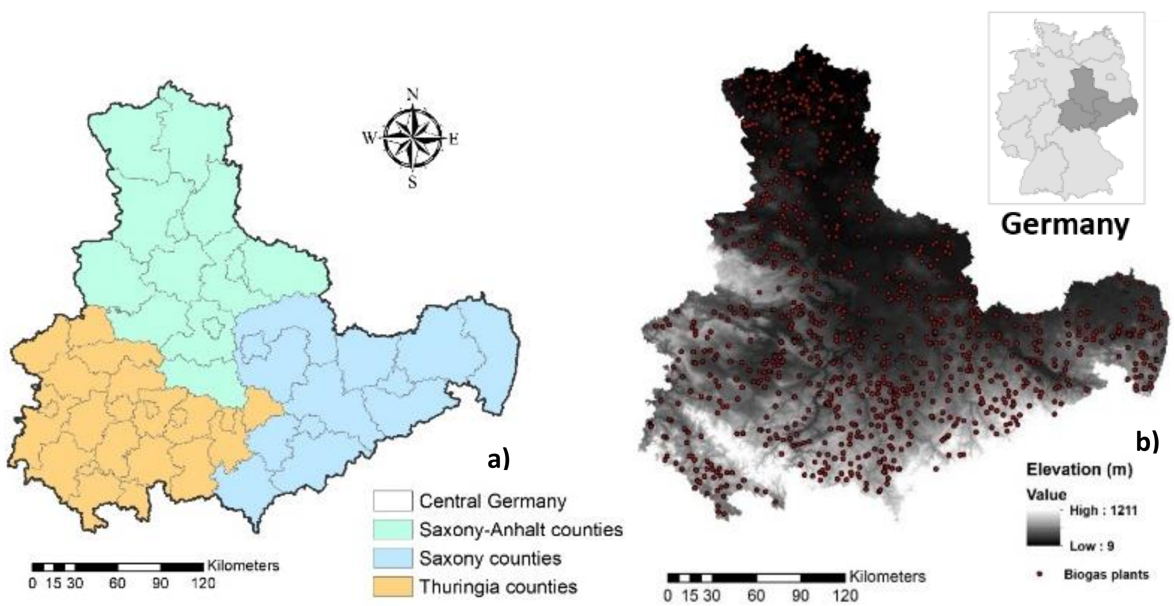

Fig. 2 Maps of Central Germany with a) administrative areas in central Germany and b) the distribution of biogas plants overlaid with a digital elevation map [49,50]

CG includes the federal states of Saxony, Saxony-Anhalt and Thuringia (see Fig. 2). The total area is approximately 55,105 km^2 (Saxony: 18,450 km^2, Saxony-Anhalt: 20,454 km^2 and Thuringia: 16,201 km^2) [46]. After several times local government reorganization, there are a total of 50 counties (German: Landkreis and Kreisfreie Stadt) in CG. The dominant forest types in CG are mixed forest, coniferous forest and deciduous forest [47]. The total forest area in 2018 was around 1,614,775 km² and occupied about 30% of the land area in CG [48]. Moreover, the arable land area in CG was approximately 23,073 km² in 2018, of which wheat occupied 33% and acted as the dominant agricultural crop in this region. Rapeseed, barley and maize made up 17%, 14% and 11% of the arable land, respectively. Other crops such as rye, triticale and sugar beet were also cultivated in CG but had relatively small proportions of arable land [46].

General information on event study methodology

For this research, the event study was deployed to study the effect of EEGs and environmental, social and economic factors on adopting biogas plant in CG. This method was originally designed in corporate finance research area. The usefulness of event studies is that the magnitude of abnormal performance of a stock price at the time of an event provides a measure of the (unanticipated) impact of this event on the mean stock price [51]. Among the different approaches to conducting an event study analysis, the multivariate regression with dummy variable technique was selected, which was suggested by Gibbons [43] and first implemented by Binder [44,52,53].

This technique is especially suitable for attempting to elicit the direction and magnitude of the effect of a regulatory event on the studied objects [52]. Moreover, this approach is flexible in the event time resolution. The event can be studied on a minute-by-minute, daily or even an annual basis, depending on the frequency of the collected data. Furthermore, different from other studies using costly survey data to study policy effectiveness, the event study method only requires time series or panel data collected from databanks, which are free bias, i.e., selection bias and survivor bias [54]. Last but not the least, by controlling other influential factors, this econometric method enables a clear differentiation of policy effect from other effects.

The multivariate regression with dummy variable approach relies on the traditional *t*-test statistic, and the dummy variables in this model are time dummy variables representing events [55]. The time dummy variable takes the value of 1 on the event date and 0 otherwise in each regression equation. The system of all regression equations can be estimated jointly as a multivariate regression model with dummy variables, where, in the below example regression equations system, the explanatory variables (*X* and *Z*) in the process are for each *n-th* of the dependent variable (*Y*), and the time dummy variable (*TD*) indicates the individual event date for each *n-th* of the dependent variable (*Y*) during the whole examined period from *t* to *t+m*:

$$
\begin{aligned}
Y_{1,t} &= \beta_{0,1} + \beta_{1,1} * X_1 + \beta_{2,1} * Z_1 + \beta_t * TD_t + \varepsilon_{1,t} \\
Y_{2,t+1} &= \beta_{0,2} + \beta_{1,2} * X_2 + \beta_{2,2} * Z_2 + \beta_{t+1} * TD_{t+1} + \varepsilon_{2,t+1} \\
&\vdots \\
Y_{n,t+m} &= \beta_{0,n} + \beta_{1,n} * X_n + \beta_{2,n} * Z_n + \beta_{t+m} * TD_{t+m} + \varepsilon_{n,t+m}
\end{aligned}
$$

In this example, the variables *X* and *Z* on the right hand side are the variables that can explain the response variable *Y*. Regarding the time dummy variable, *TD* is assigned to each certain *n-th* of the dependent variable *Y*. For example, the first dependent variable for an event on date *t* is written as $Y_{1,t}$, and the corresponding time dummy variable TD_t in the regression equation system only takes value 1 if the date is *t* and is 0 for all other dates during the whole study period, i.e., *t+1*, *t+2*,..., *t+m*. For each equation in the regression system, the regressand *Y* is regressed to the corresponding regressors *X*, *Z* and time dummy variable *TD*. If the coefficient on *TD* is significant, there is an event effect in the sample data set and the coefficient on dummy variable *TD* represents the effect of the event [56].

However, in a multivariate regression model with dummy variable, one may encounter the so-called dummy variable trap due to the inclusion of categorical variables, e.g., time dummy variables. The dummy variable trap is a situation where more than two independent variables are highly correlated with each other and together lead to a multi-collinearity problem. This problem could result in misleading interpretations of the coefficients on the time dummy variables [57]. Therefore, to avoid the dummy variable trap, at least one category of the time dummy variable has to be dropped from the specified regression model. The dropped time dummy variables can serve as the baseline for interpreting the coefficients on other time dummy variables in the regression model.

Data preparation for event study

As mentioned before, in the literature, the environmental, social and economic factors, i.e., biogas technical potential, education level and GDP density, have significant impact on accepting biogas plants. Therefore, these three variables were considered in this research to control their effects on adopting biogas plants. Besides, the market prices of electricity and land were also believed to be correlated with the decision of building biogas plant and choosing installed capacity. To compensate the high renewable electricity production cost, there is guaranteed price provided by the EEG, which is higher than the market electricity price [58]. As consequence, in Germany, we observed a rapid increase in the number of biogas plants from 140 in 1992 to approximately 7,720 by the end of 2013 [21]. Meanwhile, due to competition for land between biogas plants and traditional forms of agriculture, it was observed that land prices increased substantially [59]. Based on these facts, it can be reasoned that if a farmer is experiencing low market electricity and land prices, this farmer might have a stronger incentive to build biogas plant with a higher installed capacity (using more land). Taking the advantages of the low market electricity and land prices, this farmer can receive larger price difference between guaranteed tariffs for renewable electricity and market price with lower transaction costs. This is a typical arbitrage behaviour driven by the financial incentive, which can be understood as simultaneous purchase and sale of the same, or essentially similar, goods for advantageously different prices [60]. Therefore, both land and market electricity prices should have negative impact on adopting biogas plants.

Furthermore, the price received by the farmer for their agriculture production output might also play an important role in biogas plant decision making. In a period of high prices for agriculture products, farmers can gain more profits by increasing the number of livestock they breed or the area of land that they cultivate. In this situation, they are reluctant to build a biogas plant, but focus more on their agriculture business. In contrast, if the price they can obtain for their production is low, e.g., low milk prices, then traditional agriculture is less profitable. In that example, the biomass grown on the former pasture land could not be used for dairy feeding anymore. If the biomass is not put to an alternate use, e.g., as substrate for biogas production, the land would fall out of agronomical production [59]. To summarize, an increase in the price of the agriculture production output received by the farmer should have a negative influence on adopting biogas plants and on the selected installed capacity.

EEGs as well as biogas potential, education level, GDP density, electricity price, land price and price of the agriculture production output were considered as explanatory variables for the decisions about adopting a biogas plant and selecting its installed capacity. The annual county-level panel data were collected on these variables for the period from 1995 to 2015. Table 1 presents a general summary of the data collected for all variables. Missing data were estimated using linear interpolation technique. If the data were not available at the county level, state or national level data were used.

Data Source	**Variable**	**Abbreviation**	**Level**	**Unit**
Helmholtz-Centre for Environmental Research (UFZ) EE-Monitor [49,50]	Number of Existing Biogas Plants in County *x*, in Year *t*	$BP_{x.t}$	County	-
	Installed Capacity of *i* Biogas Plant in County *x*, in Year *t*	$IC^{i}_{x.t}$	Biogas Plant	kWel./h
Regional Statistics Database of Germany [46]	Headcount of Cattle in County *x*, in Year *t*	$Cattle_{x,t}$	County	head
	Headcount of Pigs in County *x*, in Year *t*	$Pig_{x,t}$	County	head
	Area of Cultivated Maize in County *x*, in Year *t*	$Maize_{x,t}$	County	ha
	Area of Grassland in County *x*, in Year *t*	$Grassland_{x,t}$	County	ha
	Number of Graduates with Abitur in County *x*, in Year *t*	$AbiGraduates_{x,t}$	County	person
	Total Number of Graduates in County *x*, in Year *t*	$TotGraduates_{x,t}$	County	person
	GDP of County *x*, in Year *t*	$GDP_{x.t}$	County	M€
	Administrative Area in County *x*, in Year *t*	$AdArea_{x,t}$	County	km^2
	Average Land Price in County *x*, in Year *t*	$LP_{x,t}$	County	$€/m^2$
Agency for Renewable Resources [61]	Annual Cattle Excrement Electricity Generation Rate per Headcount	EGR_C	-	kWhel./head
	Annual Pig Excrement Electricity Generation Rate per Headcount	EGR_P	-	kWhel./head
	Annual Maize Electricity Generation Rate per Hectare	EGR_M	-	kWhel./ha
	Annual Grassland Electricity Generation Rate per Hectare	EGR_G	-	kWhel./ha
German Biomass Research Center (DBFZ) [62]	Proportion of Biogas Plants with Livestock as Substrate	$SubPro_{Livestock,t}$	National	-
	Proportion of Biogas Plants with Feedstock as Substrate	$SubPro_{Energy\ Crops}$	National	-

Eurostat [63]	Electricity Price for German Household Consumers with Consumption between 2500 and 5000 kWel./h in Year *t*	Ele_t	National	€/kWel./h
Federal Statistical Office of Germany [64]	Index of Producer Prices of Agricultural Products in Year *t*	$PPAP_t$	National	-

Table 1 Description of variables.

While the collected data on number of existing biogas plants ($BP_{x.t}$), installed capacity of biogas plant ($IC^i_{x.t}$), electricity price (Ele_t), agricultural products index ($PPAP_t$) and land price ($LP_{x,t}$) could be directly used, three new variables were constructed based on the collected raw data.

The first constructed variable was the biogas technical potential index ($BPI_{x,t}$), which indicates the regional maximum volume of electricity generated from biogas plants using local energy crops and livestock manure as substrates. Considering that energy crops and livestock excrement occupy time-varying proportions of the substrate for biogas generation, for each year that biogas potential was calculated, the proportions of both feedstock types were adjusted accordingly. This variable was calculated as follows:

$$BPI_{x,t} = ((Cattle_{x,t} * EGR_C + Pig_{x,t} * \mathrm{EGR}_P) * SubPro_{Livestock,t} + (Maize_{x,t} * \mathrm{EGR}_M + Grassland_{x,t} * \mathrm{EGR}_G) * SubPro_{Energy\ Crops,t})/AdArea_{x,t} \quad (1)$$

Denoted as $BPI_{x,t}$ (mWel./km^2), this variable first used the numbers of cattle ($Cattle_{x,t}$) and pigs ($Pig_{x,t}$) and the cultivated areas of maize ($Maize_{x,t}$) and grassland ($Grassland_{x,t}$) in county *x* in year *t* together with the electricity generation rates of those feedstocks (EGR_C, EGR_P, EGR_M and EGR_G) to calculate the theoretical biogas plant electricity generation ability of county *x* for year *t*. Then, the yearly county-level electricity generation ability was adjusted according to the proportions of substrates and divided by the area of the county to obtain the biogas potential per squared kilometre.

As examined in the studies conducted in other countries, the education level of the people played a vital role in adopting biogas plants in terms of the ability to foresee the benefits and to operate the biogas plant [30-35]. Furthermore, people with a higher education level tend to have stronger environmental awareness and thus are more likely to embrace green energy sources such as biogas. The second constructed variable, intended to capture the education level, is the education index denoted by $Edu_{x,t}$:

$$Edu_{x,t} = AbiGraduates_{x,t}/TotGraduates_{x,t} \tag{2}$$

$Edu_{x,t}$ (%) was the ratio of high school graduates with university entrance permission to the total number of high school graduates from county *x* in year *t*. In Germany, students can complete their high school education in three types of schools, i.e., Realschule, Berufsschule and Gymnasium. Among these, only the graduates from Gymnasium can take the university entrance test (German: Abitur) and receive university entrance permission (German: allgemeine Hochschulreife). The graduates from the other two types of high school are not allowed to go directly to the university. Therefore, the higher the $Edu_{x,t}$, the higher the education level in county *x* in year *t*.

The third variable derived from the collected data is the GDP density, written as $GDPden_{x,t}$:

$$GDPden_{x.t} = GDP_{x,t}/AdArea_{x,t} \tag{3}$$

$GDPden_{x.t}$ (M€/km^2) represented the GDP of county x in year t divided by the administrative area of the county in the same year to calculate the GDP per unit area, i.e., GDP per squared kilometre. This variable, as conventionally used, measures the economic situation of a county in a given year.

The descriptive statistics of all selected variables were summarized in Table 2.

Variables	**Min**	**Mean**	**Median**	**Max**	**SD**	**Sample Size**
BP (number/county)	0	1.02	0	65.00	5.37	1000
IC (kWel./biogas plant)	15.00	478.54	494.50	5309.00	347.04	1023
BPI (mWel./km^2)	9.39	169.06	164.08	383.26	76.57	1000
Edu (%)	14.86	31.06	29.88	61.93	7.94	1000
$GDPden$ (M€/km^2)	0.52	9.09	2.39	131.38	17.28	1000
LP (€/m^2)	11.96	13.22	13.08	14.91	0.81	1000
Ele (€ cent/kWel./h)	11.96	13.22	13.08	14.91	0.81	20
$PPAP$	80.20	93.02	89.25	114.70	10.62	20

Table 2 Descriptive statistics of all the variables used in the model.

Model specification

Two multivariate regression models with dummy variables representing the EEGs were specified. It is obvious that the EEGs could only provide the farmers with remuneration after the farmers were informed of the EEG and responded to the opportunity. Besides, according to the EEG, only the biogas plants that began operating after the EEG went into effect were qualified for the subsidy [8]. Therefore, there was a lag in the effects of the EEGs and other factors on the biogas plants. Considering that the construction period of a biogas plant varied strongly from two months to two years according to the size of the plant and that construction technology has developed rapidly in the last two decades, the average building period of a biogas plant was assumed to be approximately one year based on the data from BiogasWorld [65]. This one-year construction period was taken as the length of the lag effect. For example, a biogas plant that is first fully functioning in year *t* is the consequence of a building decision made by the owner based on the environmental, social and economic conditions and the EEG in year *t-1*.

We selected the studied period from 2000 to 2014. This period was further divided into four sub-periods using the timeline of EEGs. These sub-periods were adopted as time dummy variables. The first period was from 2000 to 2003, corresponding to the EEG_I. EEG_{II} covered the years between 2004 and 2008. The last two periods were the EEG_{III} and EEG_{IV} with the time spans from 2009 to 2011 and from 2012 to 2013, respectively.[1] To avoid the dummy variable trap discussed before, the EEG_I dummy variable was dropped in the multivariate regression model and served as the baseline for interpreting the coefficients on EEG_{II} to EEG_{IV}. Besides, the EEGs, like all other environmental, social and economic factors, have a lagged effect on biogas plants. Therefore, if a biogas plant begins operating in year *t*, the EEG that motivated the decision about this biogas plant was the EEG in place in year *t-1*. The dummy variables EEG_k with *k* = *II*, *III* and *IV* defined in this study are as follows:

$$EEG_{II} = \begin{cases} 1, & t-1 = 2004, 2005, 2006, 2007\ and\ 2008 \\ 0, & otherwise \end{cases}$$

$$EEG_{III} = \begin{cases} 1, & t-1 = 2009, 2010\ and\ 2011 \\ 0, & otherwise \end{cases}$$

[1] The EEG_I and EEG_{IV} were active from April 1, 2000 to July 31, 2004 and from January 1, 2012 to July 31, 2014, respectively. However, due to data limitations, the effective periods of all EEGs are specified on a yearly level.

$$EEG_{IV} = \begin{cases} 1, & t-1 = 2012 \text{ and } 2013 \\ 0, & otherwise \end{cases}$$

If all of the dummy variables EEG_k take the value 0, the indicated period is the EEG_I. Against this background, the first model (Model I) aimed to explore the impacts of EEGs I to IV on the number of biogas plants in operation at the county level (for each of the 50 counties in CG) was constructed as follows:

Model I: $BP_{x,t} = ln(BPI_{x,t-1}) + ln(Edu_{x,t-1}) + ln(GDPden_{x,t-1}) + ln(LP_{x,t-1}) + ln(Ele_{t-1}) + ln(PPAP_{t-1}) + EEG_k$ (4)

$$with \;\; x = 1,2,\dots,50; t = 2001, 2002 \dots, 2014; and\; k = \begin{cases} II, & t-1 = 2004, 2005, 2006, 2007 \text{ and } 2008 \\ III, & t-1 = 2009, 2010 \text{ and } 2011 \\ IV, & t-1 = 2012 \text{ and } 2013 \end{cases}$$

where $BP_{x,t}$ denoted the number of biogas plants in operation in county *x* in year $t, BPI_{x,t-1}$, $Edu_{x,t-1}$, $GDPden_{x,t-1}$ and $LP_{x,t-1}$ were the environmental, educational and economic variables for county *x* one period before *t*, Ele_{t-1} and $PPAP_{t-1}$ were the lead electricity price and producer prices of the agricultural products index at the national level. The time dummy variable EEG_k with *k* = *II*, *III* and *IV* represented the EEG and took a value of 1 if *t-1* is within the corresponding time interval.

The second model for understanding the influence of EEGs I to IV on installed capacity was specified as below:

Model II: $ln(IC^i_{x,t}) = ln(BPI_{x,t-1}) + ln(Edu_{x,t-1}) + ln(GDPden_{x,t-1}) + ln(LP_{x,t-1}) + ln(Ele_{t-1}) + ln(PPAP_{t-1}) + EEG_k$ (5)

$$with \;\; x = 1,2,\dots,50; t = 2001, 2002, \dots, 2014; and\; k = \begin{cases} II, & t-1 = 2004, 2005, 2006, 2007 \text{ and } 2008 \\ III, & t-1 = 2009, 2010 \text{ and } 2011 \\ IV, & t-1 = 2012 \text{ and } 2013 \end{cases}$$

In contrast with Model I, the response variable in this model was on the basis of individual biogas plants. $IC^i_{x.t}$ was the installed capacity of the *i-th* biogas plant in county *x* in the year *y*. The set of independent variables was the same as before to explore the effects of the environmental, social and economic factors and the EEGs on the installed capacity of the operating biogas plant.

Data and methods for land use change analysis

The regional land use change pattern was derived from Corine land cover (CLC) change-maps which are prepared and released by European Environment Agency. CLC change-maps cover various EEG periods, namely CHA 2000-2006, 2006-2012 and 2012-2018. The CLC change-maps have a minimum mapping unit of 5 ha, which is finer than the CLC status map's 25-ha spatial resolution [66]. The original classes in the CLC change-maps consist of an inventory of 44 different land use classes, of which 34 classes are presented in CG. To facilitate this study, the classes were aggregated to eight land use classes: urban areas (UA), arable land (AL), pastures (PA), other agriculture land (OA), forests (FO), natural grassland (NG), other vegetated land (OV), and wetlands and waterbodies (WW) (see Table 3). To understand the developments of land use in CG during the study period, four change area matrices were prepared using ESRI ArcGIS 10.7 software [67]. The change patterns were visualized using Sankey diagrams package "networkD3" [68] from the R statistic software [69].

Land Use Types	Abbreviation	CLC Code	Specification
Urban Areas	UA	111	Continuous Urban Fabric
		112	Discontinuous Urban Fabric
		121	Industrial or Commercial Units
		122	Road and Rail Networks and Associated Land
		123	Port Areas
		124	Airports
		131	Mineral Extraction Sites
		132	Dump Sites
		133	Construction Sites
		141	Green Urban Areas
		142	Sport and Leisure Facilities
Arable Land	AL	211	Non-irrigated Arable Land
Pastures	PA	231	Pastures
Other Agriculture Land	OA	221	Permanently Irrigated Land
		222	Rice Fields
		242	Complex Cultivation Patterns
		243	Land Principally Occupied by Agriculture, with Significant Areas of Natural Vegetation
Forests	FO	311	Broad-leaved Forest
		312	Coniferous Forest
		313	Mixed Forest
Natural Grassland	NG	321	Natural Grasslands
Other Vegetated Land	OV	322	Moors and Heathland
		324	Transitional Woodland-shrub
		331	Beaches, Dunes, Sands
		333	Sparsely Vegetated Areas

		334	Burnt Areas
Wetlands and Waterbodies	WW	411	Inland Marshes
		412	Peat Bogs
		421	Salt Marshes
		422	Salines
		511	Water Courses
		512	Water Bodies
		521	Coastal Lagoons
		522	Estuaries

Source: Corine land cover change-maps, European Environment Agency.

Table 3 Land use types in current study

Data and method for agricultural landscape pattern analysis

For the agricultural landscape pattern analysis, the whole studied period was from 1995 to 2014. Apart from the above defined four sub-periods of EEGs, the Non-EEG period was introduced covering the years from 1995 to 2000. Considering CLC changed-maps only report arable land change as one land use type, which limits the analysis for silage maize area changes during various EEGs, the detailed agricultural crops area was derived from regional crop statistic record to facilitate evaluation. To relate dynamic changes in the agricultural landscape to biogas plant installed capacity density, we adopted the approach from Csikos et al. [29]. Three impact zones (A, B and C), representing different density categories (low, medium and high) of the installed capacity (kWel./km^2) of biogas plants, were delineated using the Kernel Density tool within ArcGIS 10.7 software. The separation of the single installed capacity density class into three intervals followed the Jenks natural breaks classification method. After that, the impact zones layer was overlaid with the county-level map of CG to assign each county to a zone. Once this classification was completed, based on the collected data on regional crop distribution, the changes in agricultural landscape pattern from the Non-EEG to EEG IV time periods were analysed for each impact zone. There was a two-level evaluation: 1) at the utilised agricultural area (UTA) level, the ratios of arable land and pasture land to UTA were calculated; 2) at the arable land level, the areas of CG cultivated with dominant agricultural crops, such as wheat, rye, triticale, maize, sugar beet and rapeseed, were divided by total arable land. This provided a general impression of the change in the cultivation pattern of energy crops between Non-EEG and EEG IV. In addition, considering that silage maize is the main feedstock for biogas plants, a detailed analysis of silage maize area related to total arable land within each impact zone was further explored.

Results

Impact of EEGs and environmental, social and economic factors on biogas plants

For each of the Model I and II, we first regressed the dependent variable only on the independent environmental social and economic variables and then we ran the whole model. The results of the multivariate regression with time dummy variables for both runs of each model were summarized in Table 4. In addition, the results of analysis of variance based on the first and second runs for both Model I and II are summarized in Appendix Table 6. The multicollinearity of the independent variables was checked using variance inflation factor and the result could refer to Appendix Table 7. The regression residuals of both models were also examined using regression diagnostic plots and reported in Appendix Fig. 9 and 10.

Variables	**Model I**		**Model II**	
	1. Run Coefficient β	**2. Run Coefficient β**	**1. Run Coefficient β**	**2. Run Coefficient β**
Environmental-social-economic variables				
ln(BPI)	**0.35***	**0.44****	-0.05	**-0.29*****
	(0.15)	(0.15)	(0.06)	(0.06)
ln(Edu)	-0.04	-0.51	**0.43*****	-0.09
	(0.31)	(0.33)	(0.10)	(0.11)
ln(GDPden)	-0.13	**-0.18·**	**-0.12*****	**-0.14*****
	(0.11)	(0.10)	(0.03)	(0.03)
ln(LP)	**-0.78*****	**-0.52****	**0.13****	**0.09***
	(0.17)	(0.17)	(0.04)	(0.04)
ln(Ele)	**9.74*****	**5.54*****	**2.27*****	**3.08*****
	(1.42)	(1.55)	(0.42)	(0.24)
$ln(PPAP_t)$	**-5.52*****	**-3.36*****	-0.23	0.39
	(0.80)	(0.85)	(0.23)	(0.24)
EEG dummy variables				
EEG_{II}	-	**1.12*****	-	0.01
		(0.20)		(0.09)
EEG_{III}	-	**1.47*****	-	**-0.25****
		(0.25)		(0.09)
EEG_{IV}	-	**0.50˙**	-	**-0.80*****
		(0.27)		(0.11)
Adjusted R^2		0.41		0.97
Sample size		700		1016

Note: "***","**","*" and "˙" denote 99.9%, 99%, 95% and 90% confidence levels, respectively. In the parentheses are the standard error. The interpretation of the coefficients of Environmental-social-economic variables in Model I:

Given an increase in an environmental-social-economic variable of one percent, the number of existing biogas plants is expected to increase by (β/100) units. The interpretation of the coefficients of time dummy variables in Model I: Given a change in a time dummy variable from zero to one, the number of existing biogas plants is expected to increase by β units. The interpretation of the coefficients of Environmental-social-economic variables in Model II: Given a change in an environmental-social-economic variable of one percent, the installed capacity of biogas plants is expected to change by β percent. The interpretation of the coefficients of time dummy variables in Model II: Given a change in a time dummy variable from zero to one, the installed capacity of biogas plants is expected to change by β*100 percent. The actual impacts of the variables in units or percentages were calculated and reported in the column next to the coefficient column.

Table 4 Results of multivariate regression for both Model I and Model II

We focus on the results of the 2. Run of both Model I and II. In Model I, compared to the EEG I period, EEG II led to an average of 1.12 more biogas plants built in each county, keeping all other variables constant. EEG III had the strongest impact among the four studied EEGs. During the EEG III period, on average, county each county had 1.47 units more operating biogas compared to the EEG I period. EEG IV prompted 0.5 more biogas plants in each of the 50 counties compared to the EEG I. The coefficients of EEG II and III were highly significant at 99.9% confidence level, and the coefficient of EEG IV was significant at 90% confidence level. In terms of the impacts of the environmental, social and economic variables, it was intuitive that given a 1% increase in the biogas technical potential in a county, on average 0.0044 more biogas plants were observed in this county. Surprisingly, the county education level did not play any role in prompting the adoption of biogas plants, and the GDP density showed a weak negative impact on the biogas plants. Keeping all other variables constant, a 1% increase in the land price of a county or in national-level electricity price could lead to 0.0052 fewer or 0.0554 more biogas plants, respectively, constructed in the county. Regarding the Germany producer prices of agricultural products index, an increase of 1% resulted in an average of 0.0336 fewer biogas plants in each county in CG, all other variables kept constant.

Different situation could be observed in Model II. The effects of EEGs II to IV on the installed capacity of the biogas plants built in CG were either 0 or negative, compared to the effect of EEG I. After controlling the effects of environmental, social and economic factors, the biogas plant constructed in EEG III and IV had, on average, 25% and 80% less installed capacity than the biogas plants built in EEG I period. Moreover, the biogas technical potential had a significant negative impact on the installed capacity; a 1%

increase of the biogas technical potential decreased the installed capacity by 0.29%. The coefficient of GDP density was also highly significant. A 1% increase in the value of GDP density in a county led to, on average, 0.14% less biogas plant installed capacity in that county, all other variables controlled. The land price, in contrast to Model I, had a mild positive influence on the installed capacity with a coefficient being 0.09. The market electricity price had a positive strong effect on the installed capacity of newly built biogas plants. Controlling all other factors, 1% increase in the electricity price led to 3.08% increase in the installed capacity. The coefficients on education level and agricultural products price had no statistical significance.

Land use change in central Germany from 2000 to 2018

As reported in Fig. 3, and in Appendix Tables 8-10, in CG, net losses of arable land with area of 35.15 km^2 and 22.25 km^2 were observed in the 2000-2006 and 2012-2018 periods, while a net gain of 22.89 km^2 was recognized during 2006 to 2012. Between 2006 and 2012, 78.08% of the total area of lost pastures were converted to arable land. In general, arable land continuously decreased and the lost arable land was mainly used for residential purposes. Otherwise, forest land, pastures and other vegetation land were three major contributors to the increase in urban area. The proportion of lost forested land converted to urban was approx. 55.97% over time. During the whole study period, some urban areas also changed to other land use types. The major acquirers were other vegetated areas, waterbodies and wetlands before 2006, and after 2006 the pastures also gain land from urban area. From 2000 to 2012, a large area of pastureland was converted to arable land, as pasture was becoming less attractive to farmers, whereas there was a growing demand on cultivating land for feed and energy crops. Concerning forest, apart from conversion to urban areas, some forested area also converted to other vegetated areas. During 2006-2012, about 85.80% of the lost forested area were due to degradation to other vegetated area. Moreover, 82.02% and 73.07% of the total natural grassland losses were due to the expansion of other vegetated area during 2000 to 2006. From 2006 to 2012, this change rate declined to 31.75%, and it was negligible in the following period from 2012 to 2018.

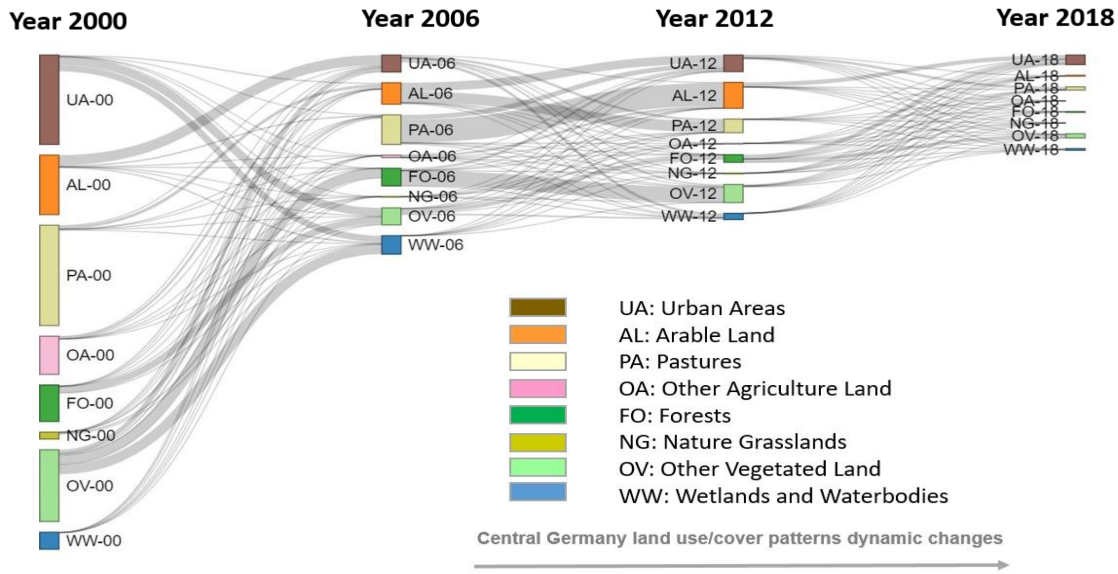

Fig. 3 Sankey diagram representing the changes in land use in central Germany from 2000 to 2018

Maize expansion influenced by biogas plant development

In total, three impact zones were identified in the studied area with value ranges of 0-3.80 kWel./km^2 for impact zone A, 3.80-10.00 kWel./km^2 for impact zone B, and 10.00-18.70 kWel./km^2 for impact zone C (see Fig. 4). If a certain impact zone occupied more than 50% of the area of a county, this county was assigned that impact zone. If no impact zone represented more than 50% of a county's area, the county was considered to be an impact zone B county. There were 12, 32 and 6 counties categorized into impact zones A, B and C in CG (see Fig. 4 a). From Non-EEG to EEG IV, the overall proportion of arable land in the UTA decreased from 72.06% to 53.59%, within which impact zone A showed a relatively higher proportion of arable land than impact zones B and C. After EEG III, there was a steep decline in the proportion of arable land in each impact zone (see Fig. 4 b). In contrast, the proportion of grassland area in the UTA showed a rapid increase in EEG III. In the study area, the grassland proportion increased from 21.59% to 45.91% across the whole examined period. The highest proportion of grassland was observed in impact zone C, with a mean value of 32.98% during all EEG periods. In comparison, impact zones A and B showed mean values of 22.05% and 29.40%, respectively during the EEG periods (see Fig. 4 c).

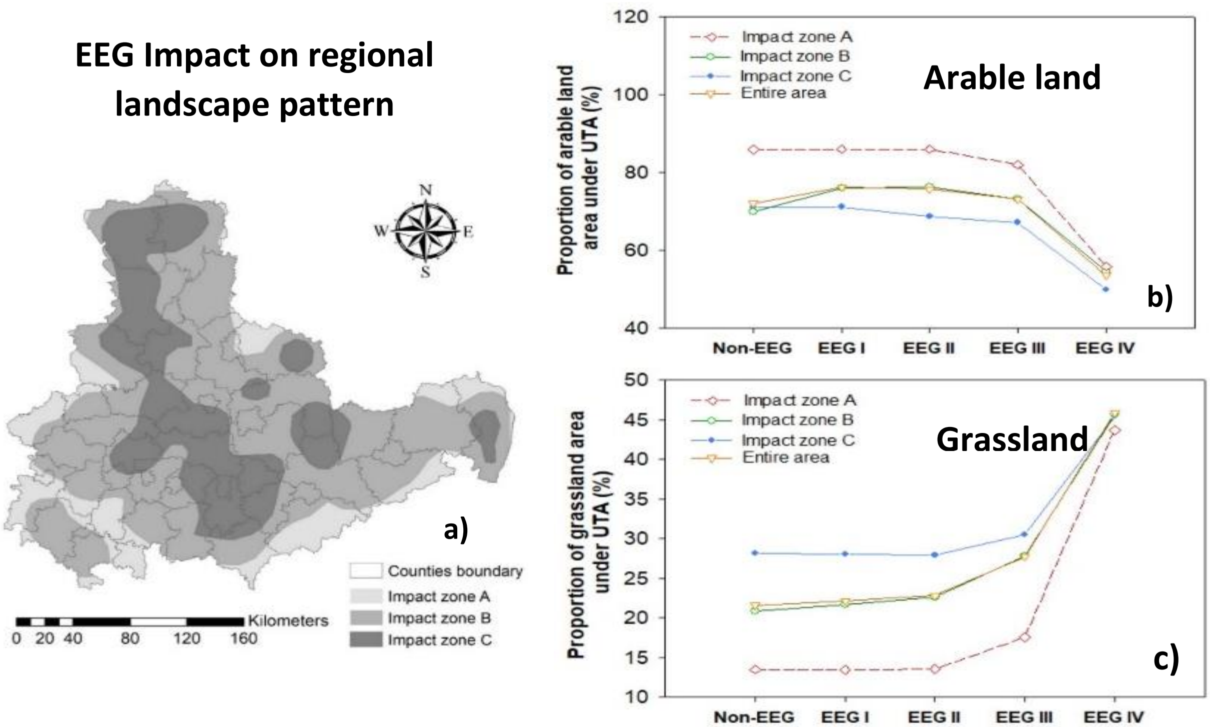

Fig. 4 Impact zone locations in study site. a) impact zone A = 0–3.8 kWel./km^2, impact zone B = 3.8–10.0 kWel./km^2, impact zone C = 10.0–18.7 kWel./km^2; b) from Non-EEG to EEG IV, the proportion of arable land area under UTA in each impact zone; c)) from Non-EEG to EEG IV, the proportion of grassland area under UTA in each impact zone.

The results of the change analysis for the areas of major agricultural crops showed that the areas of the energy crops silage maize and rapeseed increased by 57.85% and 76.49%, respectively from Non-EEG to EEG IV. Wheat, occupied around 45.79% of the area of major agriculture crops, was the largest proportion among all of the crops during the whole studied period. Compared to the Non-EEG period, the cultivated area of wheat in EEG IV increased by 37.53%, while rye, triticale and sugar beet shared a declined trend over the same period. Among them, the area of triticale decreased significantly by 25.74% (see Fig. 5 a).

In CG, the proportions of total arable land planted with silage maize in EEGs I to IV were higher than in the Non-EEG period. Compared to the proportion of silage maize in the Non-EEG period, the proportions in EEGs I to IV were 5.14%, 13.63%, 59.48% and 132.09% higher. However, when it comes to specific impact zones, the patterns differ. In Non-EEG period, the highest proportion of silage maize was detected in impact zone C, with a mean value of 7.28%. In comparison, impact zones A and B showed mean values of 5.81% and 5.89%, respectively. In impact zone C, a slight decline of 3.21% in the proportion of silage maize was observed in EEG II relative to EEG I. After EEG II, the proportion of silage maize increased strongly in each impact zone, especially in the EEG III period. Temporally, the proportion of arable land represented by silage maize increased significantly after the EEG was introduced. Spatially, strong increases were identified in impact zones A and B, while impact zone C showed a mild increment (see Fig. 5 b).

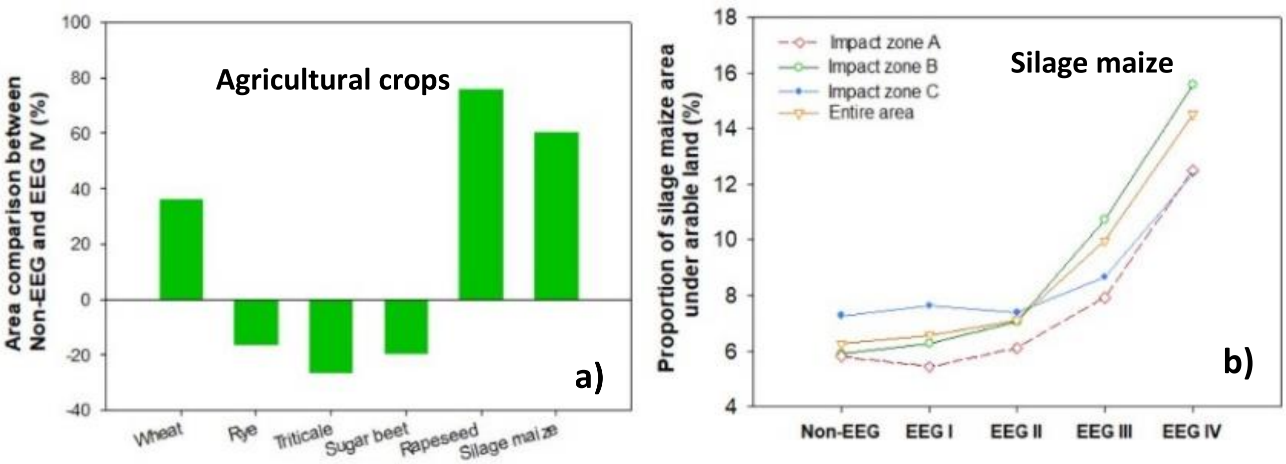

Fig. 5 Status of a) changes in the area of agricultural crops (%) between the Non-EEG and EEG IV periods in central Germany; and b) from Non-EEG to EEG IV, the proportion of arable land planted with silage maize in each impact zone.

Discussion

Implications based on event study results

As shown in the results, the EEGs could strongly motivate local farmers in CG to build biogas plants and influence the size of the built biogas plants. This could also be observed in Appendix Fig. 11; while the cumulative number of biogas plants increased rapidly during the EEG periods, the average installed capacity of each EEG period varied from each other. Aside from the EEGs, the environmental, social and economic variables showed different impacts on the construction of biogas plants and their installed capacity.

Key factors driving biogas plants adoption in CG

The biogas technical potential index had surprisingly different signs in Model I and II. The positive sign in Model I indicated that biogas plants were more likely to be built in regions where the substrates resources were rich. This result was in line with many previous studies [24-27]. However, the negative sign in Model II was against the finding from the research of Scarlat et al. [25]. In their study, they visualized that biogas plants with large installed capacity were concentrated in regions where the unit biogas potential was high. The difference might occur because most of the biogas plants in CG were constructed according to the individual farm feedstock availability, which was resulted from farming business volume (farm-scale plants) [70]. In high biogas technical potential area, the feedstock availability of each farm was enough to support a small to medium size farm-scale biogas plant. Whereas in low biogas potential counties, a larger biogas plant might be built and fed by several farms, since it is still not economic to build biogas plant for each farm even after considering the cost on feedstock transportation [70].

In contrast with most of the existing literature, the education factor was not shown in this study to play any role in adopting biogas plants. In previous research in Kenya, Bangladesh and Pakistan, only households with a certain level of education were willing to adopt and, more importantly, able to operate biogas plants [71,31,34]. Due to the huge difference in domestic education quality between Germany and other researched countries, education lost its significance in this study [72,73]. Germany as a developed country has an advanced “Education for All” system. According to the latest release of the Federal Statistical Office of Germany, 79.4% of Germans have at least higher education entrance qualification or vocational qualification, about 17.6% have even higher education degree [74]. Therefore, in a country like Germany where the population generally has a high level of education, the education level of the household loses its importance in adopting and operating biogas plants.

A reverse relationship was observed between GDP density and the adoption of biogas plants in this study, in contrary to the results of many previous studies, in which this relationship was found positive [36,75,30]. It seems like there is a break-even point in the relationship between wealth level and adoption of biogas plants. If the economic development is below the break-even point, the nature of the correlation is positive. In fact, in Germany where the GDP density is higher than most of countries in this world, the regional GDP density factor says less about the economy, but rather indicates whether a county is rural (Landkreis) or urban (Kreisfreie Stadt). The mean yearly GDP density of 12 cities in CG from 1995 to

2013 was 29.49 M€/km^2, whereas that of all rural regions was only 2.48 M€/km^2. The negative influence of GDP density could be thus interpreted to mean that the biogas plants, especially those with a high installed capacity, tend to be built in rural areas.

Land price had its expected effect on the decision to build a biogas plant. In contrast, the market electricity price had an unexpected strong positive effect on the number of constructed biogas plants CG. The result did not directly support that the decision to build a biogas plant was driven by arbitrage incentives. However, it should be pointed out that the biogas plant operators did not arbitrage by purchasing and selling the electricity. Compared to the amount of green electricity that the biogas plants owners sold to national grids, the amount of electricity they bought back for their daily farming use was considerable small. The plants owners actually arbitraged the difference between biogas production cost and EEG FIT for electricity generated from biogas. The positive impact of market electricity price further indicated that in the period of high market electricity price, the farmers had even stronger financial incentive to arbitrage the price difference to subsidize their own electricity consumption. This conclusion was supported by Scheftelowitz et al. [23], who stated that the financial incentives, provided by EEG, have the potential to lead the biogas plants development. In terms of the installed capacity of the biogas plant, land price and electricity price maintained their significance. The positive impact of land price on installed capacity was a good example of economies of scale [76]. If the decision is made to construct a biogas plant in an area with a relatively high land price, the biogas plant tends to be built large to balance the cost of the land. The positive effect of electricity price on installed capacity choice was in line with the survey findings in Austria, where farmers tended to intensify the energy production, when the electricity price went up [77]. Therefore, it could be concluded that the adoptions of biogas plants in CG were strongly driven by the farmers' financial incentive.

Increases in the price of agriculture products could reduce willingness to build plants but did not influence their installed capacity. This implicated that the biogas plants in CG were mainly built to be an investment to secure the farm business. If agricultural products are profitable, farmers aim to increase their agricultural production capacity by investing more money and increasing the production area. Under those conditions, they are reluctant and also lack the money to build and operate biogas plants. In periods with low prices for agricultural products, they are willing to build biogas plants to reduce their daily business costs on electricity to survive. This finding went in line with Thiering [28] and Fuchs et al. [78]. However, the biogas plant size did not vary with the price index, supporting the hypothesis that the installed capacity depends on the farmer's own farming business volume.

EEG performance in promoting biogas plants

All EEGs together have the ultimate goal of increasing the contribution of renewable energy to total electricity consumption in Germany [8-12]. Therefore, these acts have created many advantageous conditions for the access of biogas plants to electricity markets and grids as well as provided a secure investment and financing of biogas plants through remuneration [15]. The remuneration policies of EEGs I to IV are summarized in the Appendix Table 11.

The EEG I had a one-track biogas plant remuneration system and the subsidy categories were set according to the installed capacity. As the first EEG version, the regression result only confirmed a mild success of this act in motivating the adoption of biogas plants in CG. The EEG II targeted on the promotion of biogas plants using energy crops as substrates by introducing the NaWaRo-Bonus [79]. On average, biogas plants with renewable energy source receives approximately 5.3 Euro cents more per-unit subsidy across all installed capacity categories. Furthermore, a new allowance category for biogas plants with an installed capacity of up to 150 kWel. was specified in the new remuneration tariff. Stronger subsidy policy and of EEG II led to a better performance than EEG I. In the EEG III, the basic remuneration plus premium subsidy model was introduced. Aside from the premium for renewable resources inherited from EEG II, subsidies for manure, landscaping material, among others as substrates were introduced. This was obviously to attract farmers who still hesitated to adopt a biogas plant because their farming type did not apply to previous EEGs subsidy schema. Besides, for each installed capacity category and substrate type, there was a unique allowance amount combined by basic remuneration plus premium subsidy. This could help the potential biogas plants operators to place themselves into the most attractive remuneration categories according to their own farming situation. Despite the general decrease in the magnitude of the per-unit subsidy, the increased reward scopes for feedstock types, more tailored remuneration categories and less remuneration degression rate led to a strong increase of marginal acceptance of biogas plants in CG. Therefore, the EEG III was the most successful emendation in prompting the adoption of biogas plants in CG. In the EEG IV, to encourage the use of manure which has relatively low electricity generation ratio in biogas production, a new subsidy program is added for extremely small livestock waste based biogas plants (up to 75 kWel.). Different from the EEG III remuneration programs, the EEG IV focused more on supporting the biogas plants with straw, landscaping material, and manure. The result of the EEG IV, was generally satisfactory.

In terms of installed capacity, compared to EEG I, EEG III and IV had significantly impacts on reducing the newly built biogas plants size in their periods. This observation was in line with the findings of Sauter et al. [80]. They reported that there was a strong increase in the number of small and medium scale power plant since 2009. This result was mainly due to the enlarging of the rewards scopes for feedstock types in EEG III period and the newly introduced remuneration installed capacity category of 75 kWel. for manure in EEG IV emendation. These two EEG emendations were interpreted that the EEG III and IV were focusing on promoting larger scopes of small scale biogas plants. Since smaller size biogas plants were not economically efficient compared to large scale plant in terms of productivity and operation, the significantly reduced average size of biogas plants constructed in during the EEG III and IV periods in CG was the evidence of the success of these two emendations.

Maize expansion and changes of agricultural landscape

The landscape analysis indicated an increase in demand on substrates (e.g. silage maize or grass, etc.) resulted from growing number of biogas plants in CG. To decrease the pressure on permanent grassland, the EU's Common Agricultural Policy reform in 2013 regulated “greening” obligations to finance farmers to conduct environmentally sound farming practices, such as crop diversification and maintaining ecologically rich landscape features [81]. Besides a higher premium for biogas production using manure, the EEG IV also introduced the “maize cap”, which emphasized that the share of feedstock represented by maize and cereal grain kernels must not exceed 60% of the total mass [11]. All of these regulatory forces resulted in a visible increase in pasture area during 2012-2018 in the CLC change-maps as well as an expansion of permanent grassland. This indicated for the future development of the agricultural-based biogas industry that animal manure should be more favourable than energy crops as a substrate. Another possible reason was the complementarity of biogas and livestock production could lead to an additional intensification of land use and more investments in livestock production [82]. Germany is known as the largest milk and pork producer in EU and after France the second-largest producer of beef and veal [83]. As shown in Appendix Fig. 12, the prices of dairy products and meat showed upwards trends in the last two decades and might attract more farmer to start animal farming. The evidence could be found in the increasing numbers of livestock, especially cattle and pigs, in CG (see Fig. 7). Moreover, the German export value of animal products increased significantly from 2000 and exceeded the import value in 2005 (see Fig. 8a).

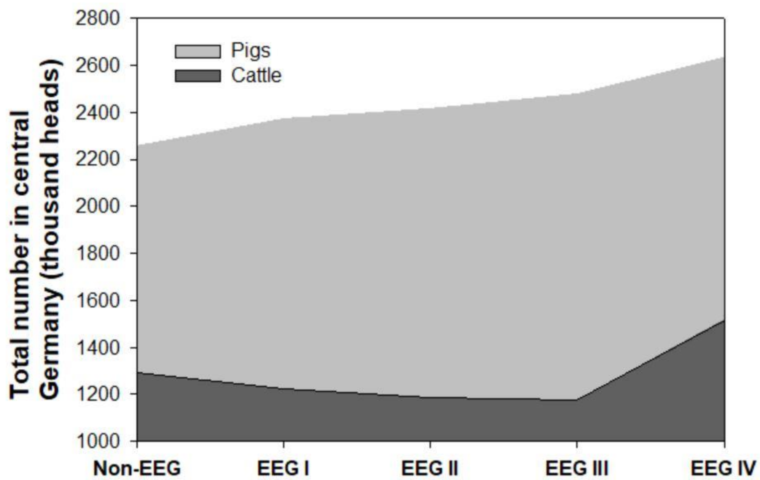

Fig. 7 Numbers of cattle and pigs (in thousands of heads) from the Non-EEG to EEG IV period [46]

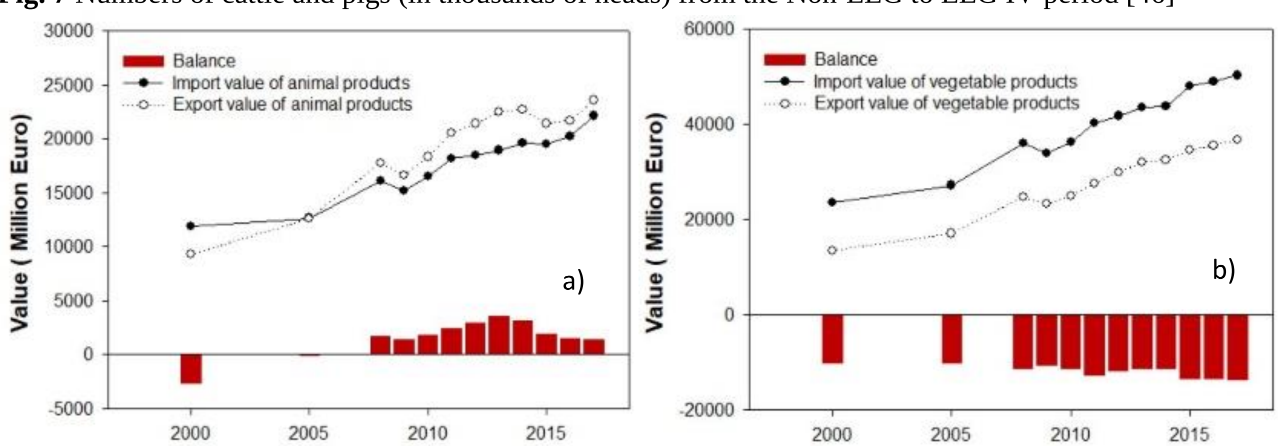

Fig. 8 The import and export price of a) animal products and b) vegetable products in Germany from 2000 to 2017 [84]

Apart from this, a widely discussed concern was the indirect land-use effects (iLU, leakage) that resulted from meeting a given demand of feedstock for bioenergy production. The report showed that the digestion of manure for biogas production had no iLUC at all, while the production of ethanol/biodiesel from energy crops did have iLUC [85,86]. Public concern has been raised regarding the potential for iLUC due to energy crop cultivation and transportation for biogas production. For example, the evaluation of biogas production sustainability in Italy would be different if iLUC was considered, since maize, the major substrate for biogas production, was partially imported from other countries [87]. In addition, the findings from Britz and Delzeit [88] showed the land demand in Germany for biomass used for biogas production could reduce Germany's exports, or the another way around, increase its imports of agricultural goods. Based on their research, the comparison between EEG III and IV suggested the increasing demand on land for biogas production, which consequently attributed to agricultural products (e.g. cereals, oilseeds and animal products) price increase in EU market. This also accompanied with agricultural land use expansion in the EU outside of Germany. In addition, we found a higher import value of vegetable products in Germany after EEG I, which also supports this statement (see Fig. 8b). This indicated the potential iLUC of arable land utilisation in other countries. We did not consider iLUC in the current study, not only because it was beyond our research focus, but also with the consideration of the large uncertainty for iLUC calculation, which resulted from missing of standard evaluation approach. However, this would be a very crucial aspect if direct land use changes and iLUC were linked to evaluate the environmental impacts and sustainability of biogas plants, considering aspects such as GHG emissions and global warming potential.

In Germany, there has been an upward tendency in the area of organically farmed land, which increased from 2,721.39 to 15,213.14 km^2 from 1994 to 2018. Meanwhile, the number of organic farms increased from 5,866 to 38,713. In 2018, the total area of organic farming in CG made up around 13.40% of the total area of organic farms in Germany, but the UTA of CG occupied 17.10% of the national total UTA [89]. Therefore, it is high feasibility for future organic farming development in CG. Additionally, as concluded in previous study, there was a large potential for the use of biogas slurry as a fertilizer for organic farming systems [90]. In this way, the booming of biogas plants during the EEGs could facilitate the development of organic farming in CG. Moreover, as pointed out in Siegmeier et al. [91], biogas-production-integrated organic farms may further contribute to renewable resource supplies without an additional need for land. More importantly, this could simultaneously increase food production and reduce GHG emissions from livestock manure. These concepts together could be tailored into an effective approach for sustainable biogas plant management in an agricultural landscape by considering potential land use change and environmental impacts.

Outlook and implications for future study

Beyond the current study, we advise considering the costs of agricultural waste disposal in future studies, since it also plays a vital role in farmers' decision making on adopting biogas plants. In Germany, among agricultural wastes, the disposal of livestock excrement is most strictly regulated. In each region, there is an upper limit for livestock waste production set to maintain the soil nutrient cycle in the regional landscape. Once the upper limit is reached, the excess slurry must be transported out of the region to avoid potential groundwater pollution. Therefore, so-called liquid manure exchanges (German: Güllebörse) operate in Germany to facilitate the transaction of agricultural waste. For instance, after the exchange is negotiated, surplus livestock excrement from livestock-intensive regions is transported to regions where the farmers mainly practice agriculture and need the liquid manure as free fertilizer. This process generates transaction and waste transport costs. If the cost of agricultural waste disposal is high, the meat and dairy farm owners are prone to building their own biogas plants to dispose of the waste and gain extra profits. However, data on the cost of agricultural waste disposal could not be collected properly in our study, since the transportation cost varies from deal to deal depending on the type of waste, transport distance, etc., and the transaction cost is not easy to quantify. Additionally, in the current study, the importance of spatial analysis was emphasized. Considering the regional heterogeneity caused by spatial characteristics, e.g. topographic, soil, climatic, and other social-economic variations, the EEGs impacts on different regions in Germany still contain large discrepancy. Therefore, to understand policy effectiveness on national level, future studies should take both environmental, social and economic factors, as well as spatial-temporal regional agricultural landscape change into account. In addition, if time series data on crop distribution could be obtained or generated using models, it would be possible to conduct more detailed landscape analysis such as resource optimization and trade-off analysis between the environmental costs and economic gain of adopting biogas plants.

Conclusion

Two research goals were pursued in our study. The first was to deploy the event study technique to quantitatively analyse the EEGs and environmental, social and economic factors on the adoption of biogas plants in CG. It was proven that the event study method could be used in analysing the effectiveness of energy policy such as EEG. The results showed that EEGs had efficient and time-varying performances in motivating biogas plants construction and influencing plant size choice. The comparison among the studied four emendations of EEG suggested that the EEG III was the most successful emendation in promoting the adoption of biogas plants in CG. According to the features of EEG III, future energy policy should have large remuneration scope to cover different types of energy source and tailored remuneration schema for each installed capacity under those energy types. By doing so, each potential policy responder could easily position himself into a corresponding subsidy category to increase the marginal acceptance. Furthermore, the environmental, social and economic factors also played vital roles in biogas plants decision making process. Especially, the test results indicated that the adoption of biogas plant was strongly driven by the financial incentive in CG and considered as alternative investment to secure their farming business. Besides, the size of the biogas plant was selected mainly based on farming business volume. Another purpose of this study was to understand the agricultural landscape patterns change under the promotion of biogas plants. Generally, the spatial CLC-maps can provide a dynamic change patterns of regional land use/cover. It is useful to identify if direct land use change (e.g. forest changes into arable land) happens. The analysis of agricultural landscape change illustrated the development of biogas plants was associated with maize expansion, especially in high biogas installed capacity regions. Besides, it is interesting to observe that in EEG III, the arable land area showed sharp declined while the pastures area showed rapid increase. This might be the result of increasing livestock farming in CG. The booming of animal farming and the expansion of maize could lead to an additional intensification of agricultural land use, as well as utilized agricultural land demand. Therefore, we advise to consider the land requirement during biogas promotion, which might increase the import of agricultural products in Germany and might lead to iLUC in other countries.

Abbreviations

EEG: Erneuerbare-Energien-Gesetz; CG: Central Germany; GIS: Geographic Information System; GHG: Greenhouse Gas; FIT: Feed-in Tariff; GDP: Gross Domestic Production; CLC: Corine Land Cover; UA: Urban Areas; AL: Arable Land; PA: pastures; OA: Other Agriculture Land; FO: Forests; NG: Natural Grassland; OV: Other Vegetated Land; WW: Wetlands and Waterbodies; UTA: Utilised Agricultural Area; NaWaRo: Nachwachsende Rohstoffe; iLUC: indirect Land-Use Change

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Authors' contributions

XY and YL designed the underlying model, analyzed the literature and carried out the results interpretation. The event study part was mainly conducted by YL. The spatial analysis part was mainly assessed by XY. The manuscript was constructed primary by XY in close cooperation with YL. All authors contributed significant feedback for improving the overall manuscript. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

As described in the method section, the raw data used for the study was collected from many different sources. Most of these are publicly available. The analyzed datasets in current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

Appendix

	Whole Sample	EEG I	EEG II	EEG III	EEG IV
Panel A: Mean Comparison of Installed Capacity between Central Germany and Germany					
Central Germany	475.58***	431.76	541.98**	442.60***	381.27$^{\cdot}$
Germany	411.28	374.88	475.05	372.39	332.54
Panel B: Mean Comparison of Installed Capacity between EEGs in Central Germany					
I and II	-	431.76	541.98**	-	-

I and III	-	431.76	-	442.60	-
I and IV	-	431.76	-	-	381.27
II and III	-	-	541.98***	442.60	-
II and IV	-	-	541.98***	-	381.27
III and IV	-	-	-	442.60*	381.27
Panel C: Mean Comparison of Installed Capacity between EEGs in Germany					
I and II	-	374.88	475.05***	-	-
I and III	-	374.88	-	372.39	-
I and IV	-	374.88˙	-	-	332.54
II and III	-	-	475.05***	372.39	-
II and IV	-	-	475.05***	-	332.54
III and IV	-	-	-	372.39*	332.54

Note: “***”,“**”,“*” and “˙” denote 99.9%, 99%, 95% and 90% confidence levels, respectively. Source: Helmholtz-Centre for Environmental Research (UFZ) EE-Monitor.

Table 5 Mean installed capacity comparison between Germany and central Germany

Environmental-social-economic Variables	Variance Inflation Factor	EEG Dummy Variables	Variance Inflation Factor
Model I: $\boldsymbol{BP = ln(BPI) + ln(Edu) + ln(GDPden) + ln(LP) + ln(Ele) + ln(PPAP) + EEG}$			
ln(BPI)	1.37	EEG_{II}	5.58
ln(Edu)	1.35	EEG_{III}	7.80
ln(GDPden)	1.32	EEG_{IV}	8.24
ln(LP)	1.21		
ln(Ele)	3.68		
$ln(PPAP_t)$	2.21		
Model II: $\boldsymbol{ln(IC) = ln(BPI) + ln(Edu) + ln(GDPden) + ln(LP) + ln(Ele) + ln(PPAP) + EEG}$			
ln(BPI)	1.77	EEG_{II}	3.17
ln(Edu)	1.38	EEG_{III}	5.17
ln(GDPden)	2.71	EEG_{IV}	8.71
ln(LP)	2.26		
ln(Ele)	5.77		
$ln(PPAP_t)$	2.50		

Note: Here we choose the variance inflation factor threshold of 10.

Table 6 Results of ANOVA for linear model fits test for both Model I and Model II.

Environmental-social-economic Variables	Variance Inflation Factor	EEG Dummy Variables	Variance Inflation Factor
Model I: $\boldsymbol{BP = ln(BPI) + ln(Edu) + ln(GDPden) + ln(LP) + ln(Ele) + ln(PPAP) + EEG}$			
ln(BPI)	1.37	EEG_{II}	5.58
ln(Edu)	1.35	EEG_{III}	7.80
ln(GDPden)	1.32	EEG_{IV}	8.24
ln(LP)	1.21		

ln(Ele)	3.68		
ln$(PPAP_t)$	2.21		
$\boldsymbol{Model\ II: ln(IC) = ln(BPI) + ln(Edu) + ln(GDPden) + ln(LP) + ln(Ele) + ln(PPAP) + EEG}$			
ln(BPI)	1.77	EEG_{II}	3.17
ln(Edu)	1.38	EEG_{III}	5.17
ln(GDPden)	2.71	EEG_{IV}	8.71
ln(LP)	2.26		
ln(Ele)	5.77		
ln$(PPAP_t)$	2.50		

Note: Here we choose the variance inflation factor threshold of 10.

Table 7 Results of variance inflation factor of independent variables for both Model I and II

Table 8 The land use/cover area change metrics from 2000-2006 in central Germany (unit: km^2)

	To								
From	UA	AL	PA	OA	FO	NG	OV	WW	Loss to Others
UA	-	6.55	0.00	1.75	0.10	0.50	41.04	32.72	82.65
AL	51.16	-	7.59	1.06	0.00	0.00	0.82	6.89	67.51
PA	4.63	15.14	-	0.00	0.00	0.00	4.23	1.90	25.89
OA	3.08	10.40	0.00	-	0.00	0.00	0.00	1.14	14.61
FO	6.19	0.00	0.21	0.00	-	0.00	33.52	0.51	40.43
NG	0.63	0.06	0.08	0.00	0.39	-	7.11	1.46	9.73
OV	18.69	0.23	8.22	0.00	47.93	0.45	-	49.52	125.03
WW	1.91	0.00	0.11	0.00	0.00	0.00	0.00	-	2.02
Gain from Others	86.28	32.37	16.21	2.81	48.41	0.95	86.72	94.14	
Total Balance	3.63	-35.15	-9.68	-11.81	7.98	-8.78	-38.31	92.12	

Note: The total balance is difference between contribution from others and contribution to others. Positive value indicates that this land type increase its area in the examined period, while negative value means loss.

	To								
From	UA	AL	PA	OA	FO	NG	OV	WW	Loss to Others
UA	-	2.50	11.97	0.00	0.08	0.84	7.99	13.23	36.62
AL	43.39	-	55.64	2.11	0.21	0.00	2.63	5.02	109.00
PA	24.32	117.21	-	0.49	0.37	0.25	3.62	3.86	150.12
OA	0.26	11.74	0.09	-	0.00	0.16	0.00	0.00	12.25
FO	12.15	0.10	0.36	0.00	-	0.00	76.60	0.07	89.28
NG	0.65	0.00	0.00	0.00	0.00	-	0.87	1.22	2.74
OV	3.30	0.34	1.46	0.00	21.03	2.14	-	8.45	36.72
WW	0.13	0.00	0.19	0.00	0.07	0.49	0.00	-	0.88
Gain from Others	84.20	131.89	69.71	2.60	21.76	3.88	91.72	31.85	
Total Balance	47.58	22.89	-80.41	-9.65	-67.52	1.14	55.00	30.97	

Note: The total balance is difference between contribution from others and contribution to others. Positive value indicates that this land type increase its area in the examined period, while negative value means loss.

Table 9 The land use/cover area change metrics from 2006-2012 in central Germany (unit: km^2)

To

From	UA	AL	PA	OA	FO	NG	OV	WW	Loss to Others
UA	-	2.16	12.57	0.00	0.16	0.00	3.52	1.29	19.70
AL	21.01	-	2.21	0.00	0.00	0.00	0.13	2.76	26.10
PA	0.00	1.63	-	0.00	0.00	0.00	0.56	0.80	2.99
OA	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
FO	21.69	0.00	0.55	0.00	-	0.00	16.41	0.10	38.75
NG	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00
OV	5.67	0.00	1.19	0.00	3.65	0.00	-	3.17	13.68
WW	0.05	0.06	0.10	0.00	0.00	0.00	0.27	-	0.49
Gain from Others	48.42	3.85	16.62	0.00	3.82	0.00	20.88	8.12	
Total Balance	28.72	-22.25	13.63	0.00	-34.93	0.00	7.21	7.62	

Note: The total balance is difference between contribution from others and contribution to others. Positive value indicates that this land type increase its area in the examined period, while negative value means loss.

Table 10 The land use/cover area change metrics from 2012-2018 in central Germany (unit: km^2)

Year	Installed Capacity	Remuneration in €-ct/kWel./h							
		Basic	RR[1]	M[2]	LM[3]	ER[4]	FC I[5]	FC II[6]	OW[7]
Panel A: EEG I from March 29. 2000 to July 31. 2004									
2000 to 2002	Up to 500kWel.	10.10							
	Up to 5mWel.	9.10							
	Above 5mWel.	8.60							
2003	Up to 500kWel.	10.00							
	Up to 5mWel.	9.00							
	Above 5mWel.	8.50							
2004	Up to 500kWel.	9.90							
	Up to 5mWel.	8.90							
	Above 5mWel.	8.40							
Panel B: EEG II from August 1. 2004 to December 31. 2008 with annual Basic Remuneration Degression: 1.5 %									
2004 to 2008	Up to 150kWel.	11.5	6.00						
	Up to 500kWel.	9.90	6.00						
	Up to 5mWel.	8.90	4.00						
	Up to 20mWel.	8.40							
Panel C: EEG III from January 1. 2009 to December 31. 2011 with annual Basic Remuneration Degression: 1.0 %									

2009 to 2011	Up to 150kWel.	11.55	5.94	3.96	1.96	0.99			
	Up to 500kWel.	9.90	5.94	0.99					
	Up to 5mWel.	8.17	3.96						
	Up to 20mWel.	7.71							
Panel D: EEG IV from January 1. 2012 to July 31. 2014 with annual Basic Remuneration Degression: 2.0 %									
2012 to 2014	Up to 75kWel.[8]	25.00							
	Up to 150kWel.	14.30					6.00	8.00	16.00
	Up to 500kWel.	12.30					5.00	6.00	
	Up to 5mWel.	11.00					4.00	6.00	14.00
	Up to 20mWel.	6.00							

Table 11 Remuneration Policy for EEGs I to IV

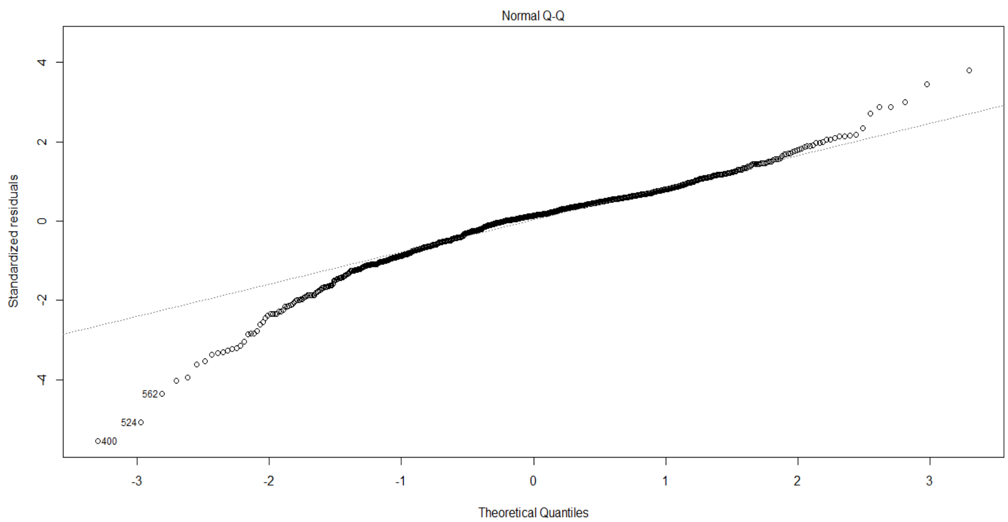

Fig. 9 Quantile-Quantile Plot of regression residuals of Model I

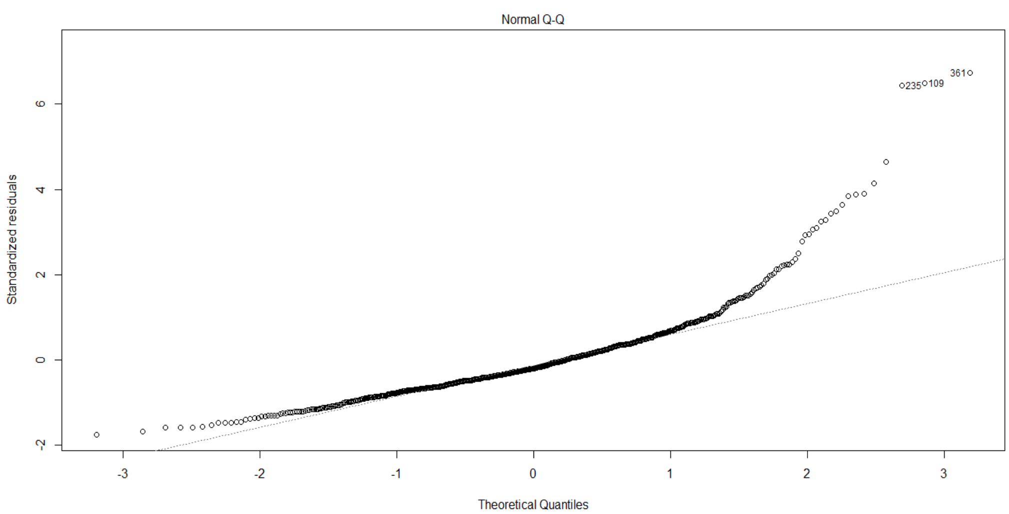

Fig. 10 Quantile-Quantile Plot of regression residuals of Model II

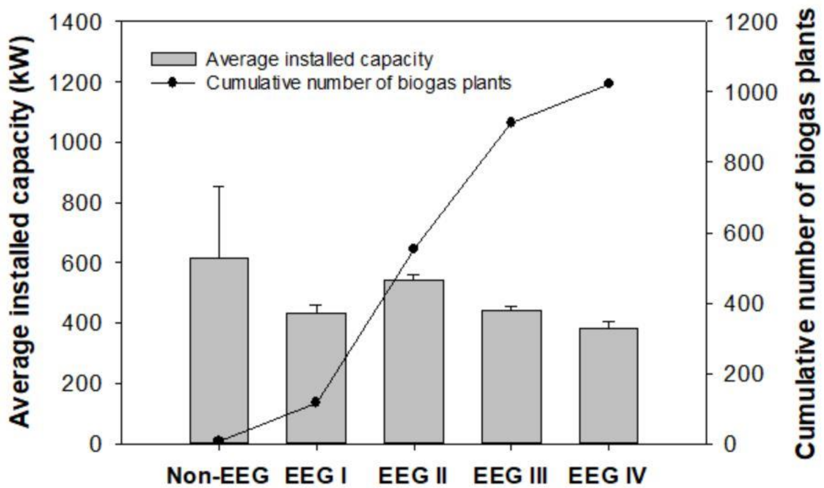

Fig. 11 Cumulative number of biogas plants from the Non-EEG to the EEG IV period and the average installed capacity in each period

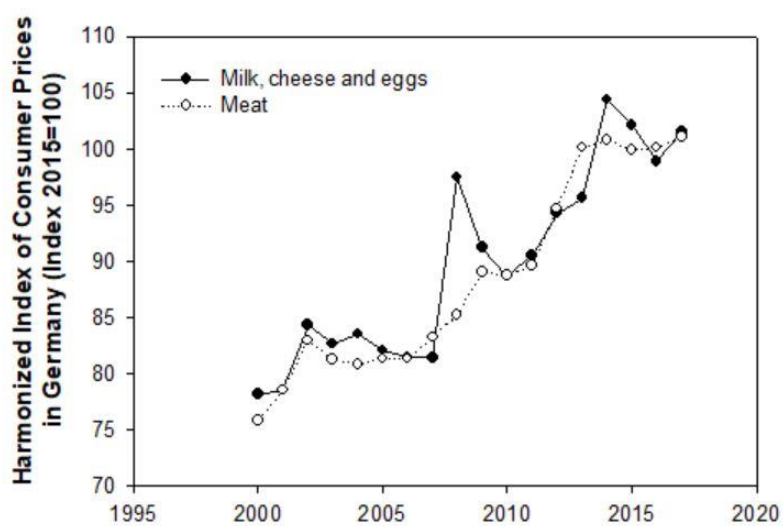

Fig. 12 The harmonized index of consumer prices for products like milk, cheese, eggs and meat in Germany (Index 2015 = 100) from 2000 to 2017

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