Effects of the German Renewable Energy Sources Act and environmental, social and economic factors on biogas plant adoption and agricultural land use change

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Effects of the German Renewable Energy Sources Act and environmental, social and economic factors on biogas plant adoption and agricultural land use change

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Abstract

Background: The German energy transition strategy calls for a reform of the German energy sector. As a result, the Germany Renewable Energy Sources Act (EEG) was passed in 2000 and is widely regarded as successful legislation for promoting bioenergy development. More than 1,000 biogas plants were constructed in Central Germany (CG) between 2000 and 2014. Despite this, few studies have been conducted for this period that systematically investigate how environmental, social and economic factors, as well as various EEG amendments have impacted biogas production and what the environmental consequence of biogas production development in CG have been.

Methods: The impacts of environmental, social and economic factors and different EEG amendments on biogas production decisions in CG were quantified using multivariate linear regression model and the event study econometric technique. A GIS-based spatial analysis was also conducted to provide insight into the changes to agricultural land use that resulted from the development of biogas plants during the EEG period.

Results: The main finding was that the income diversification effect resulting from biogas production was the most important factor in a farmer's decision to adopt biogas production. In addition, all of the EEG amendments had a significant influence on the adoption of biogas production, however EEG III and IV, which tried to promote small-scale plants, were unable to reduce the average size of the plants constructed in these two amendment periods. From a landscape perspective, there was a striking increase in the cultivation of silage maize in CG from 2000 to 2014. Silage maize was intensively cultivated in regions with a high installed biogas plant capacity. Since the first EEG amendment, permanent grassland area slightly increased while arable land area declined in CG.

Conclusions: The adoption of biogas production in CG was strongly driven by economic incentives for the farmers, more precisely, by the incentive to diversify their income sources. In addition to increase the subsidy, future EEG amendments should find new measures to encourage the adoption of small-scale biogas plants, which had been unsuccessful in EEG amendments III and IV.

Keywords: Biogas plant, event study, Renewable Energy Sources Act, Central Germany, land use change

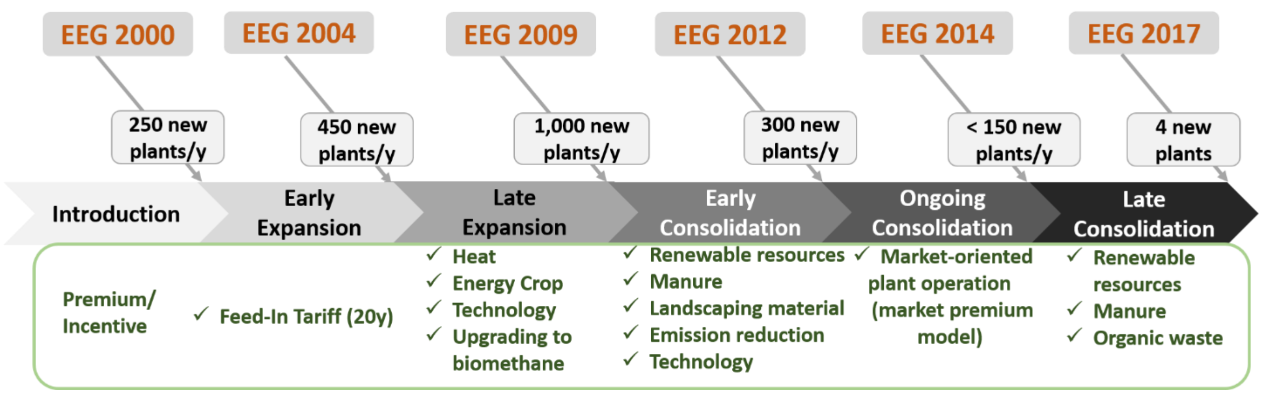
1. Background

The 2015 United Nations Climate Change Conference in Paris was a critical step towards international solidarity in addressing climate change. According to the Paris Climate Agreement reached at that meeting, it is now compulsory for countries to reduce greenhouse gas (GHG) emissions in order to limit global warming to less than 2°C above the pre-industrial average [1]. Germany has committed to reducing its GHG emissions by 14% relative to 2005 levels by 2020 [2]. In 2016, the German government set out new goals in its 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 a nuclear phase-out, reduction in fossil fuels and a sustainable promotion of renewable energies [5]. Major efforts towards reaching these goals has made Germany a pioneer in the energy reform sector and a leader of the broader worldwide energy transition [6,7].

In Germany, the central instrument for promoting renewable energy is the Renewable Energy Sources Act (German: Erneuerbare-Energien-Gesetz, or "EEG"). The principal founder of this law is German parliamentarian Hans-Josef Fell of the Bündnis 90/Die Grünen faction, who drafted a key issues paper for the Green faction in early 1999. After his faction had adopted the draft paper, talks began with the Social Democratic Party (SPD) faction. Hermann Scheer of the SPD was the primary supporter and advocator of the proposed measures. After the SPD reviewed the bill in September 1999, it was sent to Germany's federal parliament, the Bundestag. With the support of the SPD, the bill was adopted by the Bundestag on February 25, 2000 and went into effect on April 1, 2000 [8]. The overarching goal of the EEG is to promote electricity generation from different types of renewable energy so that the share of renewables in Germany's electricity consumption is at least 30% by 2020 [9-11]. One segment of the EEG policy focuses on the promotion of bioenergy production, which has been widely considered to be a significant contributor to global renewable energy production [12]. The EEG's ability to promote biogas production has been deemed successful. Between 2000 and 2017, the number of biogas plants in Germany increased from 850 to 9,331, with the cumulative installed capacity rising from 50 to 4,800 MW/h [13-15]. In 2017, the proportion of renewable energies in the total gross electricity generation in Germany was 34%, of which the share of biomass was 23.42% [11].

The German biogas sector can be divided into four phases of market and legislative development [15] (see Fig. 1) In light of the feedback following the introductory phase of the EEG as well as environmental issues and the availability of new bioenergy technology, the EEG was revised in 2004, 2009, 2012, 2014 and 2017 with subsidy modifications [16-21] (Appendix Table A1). Starting with the 2009 EEG amendment, the subsidy for small-scale plants was raised to promote the adoption of this type of biogas plant, as the large-scale biogas plants caused several problems, such as a threat to food production, soil health and natural resources conservation [22-24]. Furthermore, upgrades in bioenergy technology resulted in a significant widening of the scope of the subsidy in the EEG 2009 amendment. Various new premium categories, such as manure, landscape material and emission reduction, were included in the remuneration scheme [18]. In the 2012 version of the EEG, a so-called "maize cap" was introduced to suppress the rapidly increasing cultivation area of maize and to increase the diversity of the crops grown for energy production [19,25]. The EEG 2014 represented a paradigm shift for German biogas plants. It made major cuts in the subsidies associated with biogas plants, particularly for agricultural plants fueled by energy crops [20]. In 2017, the newly amended EEG introduced a tendering system to select renewable electricity producers. It established expansion corridors and volumes for auctioning renewable energy.



Source: Thrän et al. (2020)

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

The EEG's primary measure for promoting biogas production is to provide subsidies to biogas plant operators [15,26,27]. Apart from these financial incentives, the decision to adopt a biogas plant is also influenced by several environmental, social and economic factors, which have been systematically examined in previous studies [28-32]. For example, the availability of feedstock was identified as having a strong influence on a farmer's decision to adopt biogas technology [33-38]. In Germany there is a large concentration of biogas plants in regions with high livestock densities [30]. In terms of social factors, the farmers' education level plays a vital role in the adoption of biogas plants with respect to their ability to foresee the benefits and to operate the biogas plant [35,37,39,40]. Closely connected to education level, the farmer's awareness of renewable energy technologies also has a strong influence on whether biogas production is adopted [41,42]. In addition, there is a correlation between the environmental protection awareness of local residents and the adoption of renewable energy technologies [43-46]. Furthermore, local political governance is also regarded as an important factor in the implementation of renewable energy policies at a local level [47,48]. In terms of economic factors, the income of local farmers is a determining factor involved in the decision to take up biogas production [33-38]. Finally, land for biomass cultivation and biogas plant construction positively correlates with the adoption of biogas technology [37,38,49].

The current study aimed to both empirically and spatially analyze: 1) the effects of environmental, social and economic factors on biogas production decisions at a county level in Central Germany (CG); 2) the impacts of EEG 2000, EEG 2004, EEG 2009 and EEG 2012 (EEG I, EEG II, EEG III and EEG IV, respectively) on biogas production decisions and agricultural land use change in CG. The flowchart of the current study is presented in Fig. 2. There are many differences between our study and previous studies. Our study investigated the effects of environmental, social and economic factors and different EEG amendments on both the decision to adopt biogas production and the size of the plant. In addition, county-level data was used in our research to study a greater area. Furthermore, we linked the empirical analysis with the spatial analysis to study the impact of the EEG and other factors on the adoption of biogas production. Finally, we attempted to introduce the event study econometric technique in the environmentally relevant policy impact study to quantitatively analyze the effect of each EEG amendment on biogas production decisions [50-52].

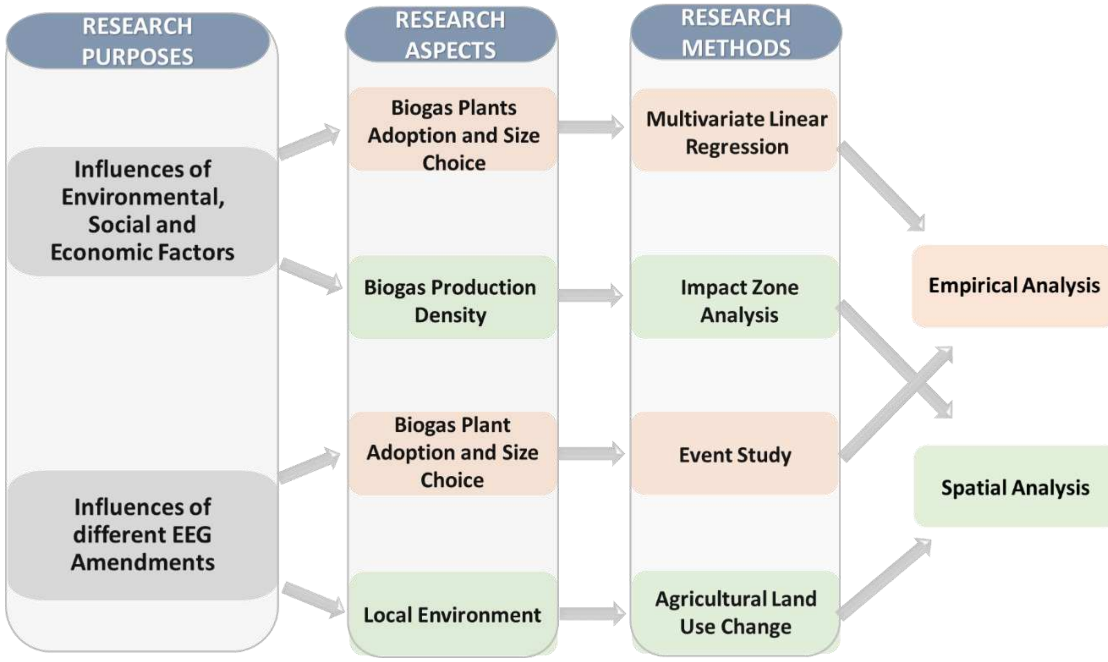
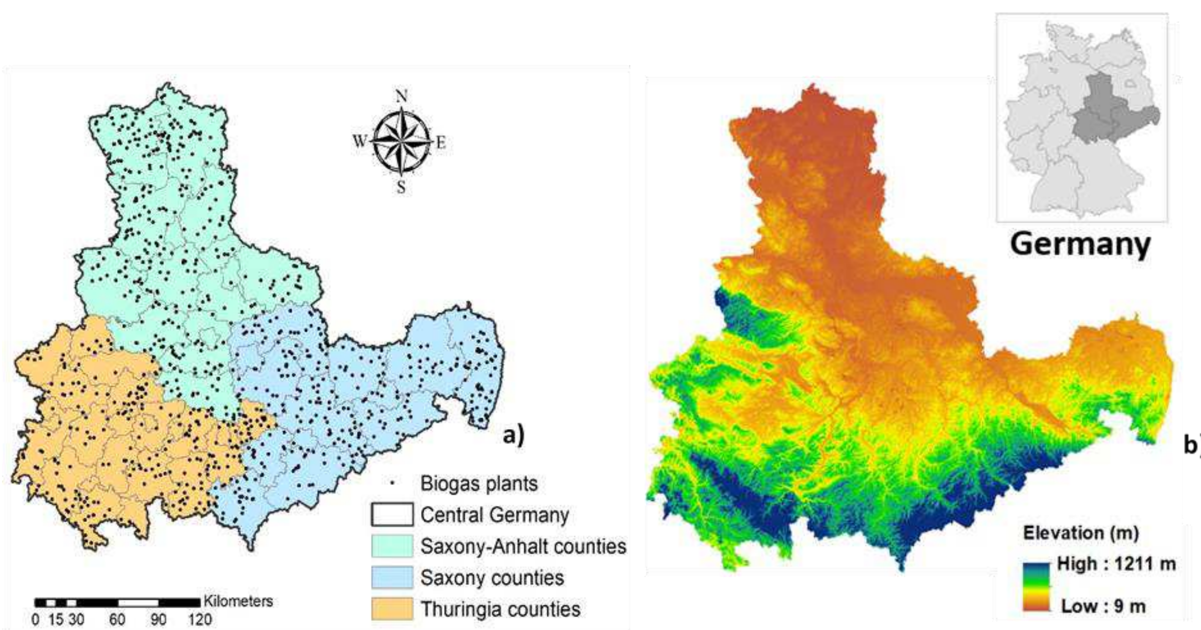


Fig.2 Flowchart of the current study

2. Methods and data

2.1 Study site



Source: EE-Monitor, Shuttle Radar Topography Mission (SRTM) and Germany administrative Area (NUTS3)

Fig. 3 Maps of Central Germany with a) the distribution of biogas plants overlaid with administrative areas in Central Germany and b) the digital elevation map

Central Germany includes the federal states of Saxony, Saxony-Anhalt and Thuringia (see Fig. 3). The total administrative area is approximately 55,105 km^2 with Saxony comprising 18,450 km^2, Saxony-Anhalt 20,454 km^2 and Thuringia 16,201 km^2 of the total area [53]. After several local government reorganizations, there are now a total of 50 counties (German: Landkreis and Kreisfreie Stadt) in CG. In 2018, the largest land use type was arable land which, at around 23,073 km^2, made up about 42% of the total CG area. Wheat was the dominant crop among all the crops in this region. It was cultivated on around 33% of the total arable land. The cultivation areas of rapeseed, barley and silage maize made up 17%, 14% and 11% of the total arable land in CG respectively. Other crops, such as rye, triticale and sugar beet, were also cultivated in CG. In addition to this, the total area of permanent grassland with its three types of utilization, i.e. mowing pastures, pastures and meadows, comprised 5,485 km^2 or about 10% of the total CG administrative area [53].

2.2 Method and data for empirical analysis

2.2.1 General information on event study methodology

We used the event study econometric technique to quantify the influences of different EEG amendments on biogas production decisions in CG. This method was originally designed to be used in the corporate finance research [54]. Among the different approaches for conducting an event study analysis, our study used the technique of multivariate regression with a dummy variable, which was suggested by Gibbons [50] and first implemented by Binder [51,55,56]. This technique is especially suitable for eliciting the magnitude of the effect of a regulatory event on a studied object [55]. Unlike other studies that use costly survey data to study policy effectiveness, the event study method only requires time series or panel data collected from databases which are bias free, i.e., selection bias and survivor bias [57]. Finally, by controlling other influential factors, this econometric method enables policy effects to be clearly differentiated from other effects.

The multivariate regression with dummy variable approach relies on the traditional *t*-test statistic; the dummy variables in this model are time dummy variables that represent events [58]. In each regression equation the time dummy variable takes the value of 1 on the event date and otherwise 0. The system of all regression equations can be estimated jointly as a multivariate regression model with dummy variables where, in the sample regression equation system below, the explanatory variables in the process (*X* and *Z*) are each an *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 entire period under examination, from *t* to *t+m*:

$$Y_{1,t} = \beta_{0,1} + \beta_{1,1} * X_1 + \beta_{2,1} * Z_1 + \beta_t * TD_t + \varepsilon_{1,t} \quad (1)$$

$$Y_{2,t+1} = \beta_{0,2} + \beta_{1,2} * X_2 + \beta_{2,2} * Z_2 + \beta_{t+1} * TD_{t+1} + \varepsilon_{2,t+1} \quad (2)$$

$$\vdots$$

$$Y_{n,t+m} = \beta_{0,n} + \beta_{1,n} * X_n + \beta_{2,n} * Z_n + \beta_{t+m} * TD_{t+m} + \varepsilon_{n,t+m} \quad (3)$$

In this example, variables *X* and *Z* on the right-hand side are the variables that explain the response variable *Y*. In terms of 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 on the value of 1 if the date is *t*. Otherwise it is 0 for all other dates during the entire period under investigation, 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 the time dummy variable *TD*. If the coefficient of *TD* is significant, there is an event effect in the sample dataset and the coefficient of dummy variable *TD* represents the effect of the event [59].

2.2.2 Preparing data for empirical analysis

In previous international studies, several factors were identified as having effects on the adoption of biogas production and choice of plant size. For our research on CG, we selected from the literature the factors feedstock availability, awareness for the environment, income and local political governance. Our models also included the explanatory variables land price and the price for agriculture production received by the farmer as they might have an impact on adopting biogas production within the German context.

Unlike most of the previous research, which uses farm-level survey data [34,36,60,61], our study used county-level data to quantify the impact of environmental, social and economic factors on the adoption of biogas production and choice of plant size. Different annual CG county-level panel data were collected from various sources for the period from 2000 to 2014. While the data could be directly obtained for some of the variables, for other variables, we needed to process the collected data first. Table 1 presents a general summary of the collected data. Missing data were estimated using the linear interpolation technique. If the data were not available at the county-level, national-level data were used.

Table 1. Description of the collected data for empirical analysis.

Data Source	**Variable**	**Abbreviation**	**Level**	**Unit**
Helmholtz-Centre for Environmental Research (UFZ) EE-Monitor [62,63]	Number of newly established biogas plants in county *x*, in year *t*	$BP_{x.t}$	County	-
	Installed capacity of *i* newly established biogas plants in county *x*, in year *t*	$IC_{x.t}^{i}$	Biogas Plant	kW/h
Regional Statistics Database of Germany [53]	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 silage 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
	Disposable per capita income in county *x*, in year *t*	$DI_{x,t}$	County	€
	Average transaction-based land price in county *x*, in year *t*	$LP_{x,t}$	County	€/m^2
Statistical Office of Saxony [64] Statistical Office of Saxony-Anhalt [65] Statistical Office of Thuringia [66]	Proportion of seats in Kreistag parliament held by SPD and Bündnis 90/Die Grünen in county *x*, in year *t*	$GN_{x,t}$	County	-
	Total valid votes in Landtag parliamentary election in county *x*, in year *t*	$TV_{x,t}$	County	-
	Total valid votes for Bündnis 90/Die Grünen in Landtag parliamentary election in county *x*, in year *t*	$VG_{x,t}$	County	-
Agency for Renewable Resources [67]	Annual cattle excrement electricity generation rate per headcount	EGR_C	-	kWh/head
	Annual pig excrement electricity generation rate per headcount	$E\text{GR}_P$	-	kWh/head
	Annual maize electricity generation rate per hectare	$E\text{GR}_M$	-	kWh/ha
	Annual grassland electricity generation rate per hectare	$E\text{GR}_G$	-	kWh/ha
German Biomass Research Center (DBFZ) [68]	Proportion of biogas plants with livestock as substrate	$SubPro_{L,t}$	National	-
	Proportion of biogas plants with feedstock as substrate	$SubPro_{EC,t}$	National	-
Federal Statistical Office of Germany [69]	Index of Producer Prices of Agricultural Products in year *t*	$PPAP_t$	National	-

As dependent variables in the regression model, county-level data on the annual number of newly established biogas plants ($BP_{x.t}$) and the installed capacity of each newly established biogas plant ($IC^{i}_{x.t}$) were directly collected from the database.

In terms of the explanatory variables, the first variable was feedstock availability for biogas production ($BPI_{x,t}$), which was proxied in this study by the technical biogas potential. This indicator measures the total quantity of different types of feedstock, e.g., sewage sludge, animal residues, energy crops, etc., that is available for biogas production in a region [70-73]. As discussed in previous research, substrate transportation of energy crops and livestock excrement is inefficient from both an economic and an environmental perspective [74]. Therefore, the biomass for biogas production is generally obtained from the immediate vicinity of the plant. This finding was confirmed by the research of Csikos et al. [75], who found that biogas plants are concentrated in areas where energy crops are widely cultivated. In addition, a relationship between technical biogas potential and biogas plant size was also identified [71]. This variable was calculated as follows:

$$BPI_{x,t} = ((Cattle_{x,t} * EGR_C + Pig_{x,t} * \mathrm{EGR}_P) * SubPro_{L,t} + (Maize_{x,t} * \mathrm{EGR}_M + Grassland_{x,t} * \mathrm{EGR}_G) * SubPro_{EC,t})/AdArea_{x,t} \quad (4)$$

Denoted as $BPI_{x,t}$ (mW/km^2), this variable first used the number of cattle ($Cattle_{x,t}$) and pigs ($Pig_{x,t}$) and the cultivated areas of silage maize ($Maize_{x,t}$) and grassland ($Grassland_{x,t}$) in county *x* in year *t* together with the electricity generation rates of those feedstock types (EGR_C, EGR_P, EGR_M and EGR_G) to calculate county *x*'s theoretical ability to generate electricity from biogas plants for year *t*. Then, the annual ability to generate electricity on a county level was adjusted according to the percentages of the substrates and divided by the area of the county in order to obtain the biogas potential per square kilometer.

The second independent variable was the awareness for the environment ($AE_{x,t}$). As reported in many previous studies, awareness for the environment influences the willingness to adopt renewable energy technologies [76]. In the current study, we used the Bündis 90/Die Grünen approval rating in the Landtag parliamentary election in each studied county to proxy the county-level awareness for the environment since

Green party supporters are noted for being environmentally conscious [77]. Therefore, a county with a higher approval rating for the Green party should indicate that this county has a higher acceptance of biogas production. This variable was constructed as follow:

$$AE_{x,t} = VG_{x,t}/TV_{x,t} \tag{5}$$

The county-level awareness for the environment, denoted as $AE_{x,t}$, was calculated by dividing the total number of valid votes for Bündnis 90/Die Grünen in the Landtag parliament election ($VG_{x,t}$) by the total number of valid votes in the Landtag parliament election from county *x*, in year *t* ($TV_{x,t}$).

The third variable was income ($DI_{x,t}$), which we proxied using annual disposable per capita income at the county level. As found in previous studies, a large number of biogas plants are privately operated in Germany [30]. Farmers who adopt biogas plants anticipate this and regard it as an investment that diversifies and increases their income [78,74]. Even though the disposable per capita income in Germany is high, local farmers still need credit to finance their investment in biogas production [79]. Apart from the cost of construction and installation, investment in biogas production requires a series of other long-term costs, such as feedstock and annual operating costs [80]. As reported, the investment behavior of European households is largely influenced by changes in their disposable income and European households are cautious when taking out loans [81]. Therefore, we incorporated this variable in the model to study whether, in a developed country like Germany, disposable income still influences the adoption of biogas plants.

The fourth variable was local political governance, which was denoted as $GN_{x,t}$. In Germany, the Bündnis 90/Die Grünen and the SPD parliamentary factions took the initiative, drafted the bill and secured allies in favor of the EEG [82,83]. Therefore, we used the proportion of seats in the Kreistag parliament held by the SPD and Bündnis 90/Die Grünen in each county as the proxy for local political governance.

The fifth variable was land price ($LP_{x,t}$). Arable land is one of the most important but scare production resources needed for both building plants and supplying feedstock. Farmers will only invest in a biogas plant if the production factors, e.g. farmland, are available or at least affordable [84]. The land market in Eastern Germany is similar to other European land markets and characterized by a high percentage of rental contracts [85]. Investors in biogas production often lease or buy agricultural land for their production activities [86]. Therefore, many previous studies reported that the competition for land between biogas plants and traditional forms of agricultural lead to a substantial increase in land prices [84,86-88]. However, increasing land prices would eat up profits from biogas production investments since the guaranteed subsidy is fixed. Therefore, the transaction-based land price should affect biogas production decision-making.

The last variable was the agriculture production price received by farmers ($PPAP_t$), which was proxied by Germany's annual Producer Price Index of Agricultural Products. As reported in other studies, operating a biogas plant is an alternative investment for farmers that allows them to diversify their income sources [74,78]. In periods of high prices for agricultural products, farmers are reluctant to start biogas production and focus more on their agriculture business. In contrast, in periods of low prices for agricultural products, it is expected that farmers adopt biogas production to earn the guaranteed subsidies. Besides, in the dairy farming industry, when milk prices are unprofitable, the biomass grown on this pastureland would not be used for dairy feeding. If there is no alternative use for the biomass, e.g. for biogas production, the land would fall out of agronomic production. Therefore, to justify future cultivation of the grassland, biomass utilization must be diverted to energy production and concomitantly generate an income for the farmer [30].

The data on income, local political governance, land price and agriculture production price received by farmers were directly collected from database. The descriptive statistics of all selected variables are summarized in Table 2.

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

Variables	Min	Median	Mean	Max	SD	Sample Size
BP (number/county)	0.00	1.00	1.45	16.00	2.21	700
IC (kWh/biogas plant)	15.00	494.50	477.53	5,309.00	344.80	1016
BPI (MWh/km^2)	60,733	197,765	207,168	383,263	72,566	700
AE (%)	1.50	3.98	4.05	12.96	1.41	700
DI (€ per capita)	12,170	15,564	15,596	19,064	1,282	700
GN (%)	9.50	21.54	20.44	40.38	5.70	700
LP (€/m^2)	1.74	19.14	21.03	156.82	13.33	700
$PPAP$	83.10	95.00	93.97	114.70	10.00	14

2.2.3 Model specification

The EEGs could only remunerate farmers after the farmers had been informed about the EEG and had responded to the opportunity [16]. Therefore, there is a lag in the effects of the EEGs and environmental, social and economic factors on the biogas plants. Considering that the construction period of a biogas plant varies strongly from two months to two years depending on the size of the plant, we estimated the average building period of a biogas plant to be one year based on the data from BiogasWorld [89]. This one-year construction period was taken as the length of the lag effect. For example, a biogas plant that isn't fully operational until year *t* is the result 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 period 2000 to 2014 for our study. This period was further divided into four sub-periods based on the timeline of the EEGs. The first period was from 2000 to 2003, corresponding to EEG_I. EEG_{II} covered the years between 2004 and 2008. The last two periods were EEG_{III} and EEG_{IV} spanning 2009 to 2011 and 2012 to 2013 respectively. Except for EEG_I, all the other three sub-periods were adopted in the EEG dummy variable categories to avoid the dummy variable trap [90]. Like all other environmental, social and economic factors, the EEGs have a lag effect on biogas production investment. The EEG dummy variables EEG_k, with *k* = *II*, *III* and *IV*, are defined in this study as follows:

$$EEG_{II} = \begin{cases} 1, & t-1 = 2004, 2005, 2006, 2007 \; and \; 2008 \\ 0, & otherwise \end{cases} \quad (6)$$

$$EEG_{III} = \begin{cases} 1, & t-1 = 2009, 2010 \; and \; 2011 \\ 0, & otherwise \end{cases} \quad (7)$$

$$EEG_{IV} = \begin{cases} 1, & t-1 = 2012 \; and \; 2013 \\ 0, & otherwise \end{cases} \quad (8)$$

If all of the EEG dummy variables EEG_k take the value 0, the period indicated is EEG_I.

In the current study, we specified two model sets: Model I and Model II. In order to control for the biogas plant location effect, we further included the $City$ variable in both model sets. If the biogas plant was constructed in an urban area, the $City$ variable took the value of 1, otherwise 0. Model I had two sub-models

(Model I.1 and Model I.2) and was a multivariate linear regression model to quantitatively study the effects on biogas production decisions. Model I.1 was used to explore the impact of environmental, social and economic factors on the decision to adopt biogas production. Model I.1 was constructed as follows:

Model I.1: $BP_{x,t} = \alpha + ln\ (BPI_{x,t-1}) + ln\ (AE_{x,t-1}) + ln\ (DI_{x,t-1}) + ln\ (GN_{x,t-1}) + ln\ (LP_{t-1}) + ln\ (PPAP_{t-1}) + City + \varepsilon$ *(9)*

Model I.2 was used to study the influences of environmental, social and economic factors on the choice of biogas plant size and was defined as follows:

Model I.2: $ln\ (IC^{i}_{x,t}) = \alpha + ln\ (BPI_{x,t-1}) + ln\ (AE_{x,t-1}) + ln\ (DI_{x,t-1}) + ln\ (GN_{x,t-1}) + ln\ (LP_{t-1}) + ln\ (PPAP_{t-1}) + City + \varepsilon$ *(10)*

Applying the event study econometric technique, we designed the model set Model II with sub-models Model II.1 and Model II.2 to quantify the impacts of EEG I to IV on the adoption of biogas production and choice of plant size after accounting for the environmental, social and economic effects. Compared to Model I.1 and Model I.2, Model II.1 and Model II.2 included the EEG dummy variable EEG_k to measure the EEG impacts. Model II.1, whose purpose was to study the EEG effects on adopting biogas production, was constructed as follows:

Model II.1: $\boldsymbol{BP_{x,t}} = \alpha + ln\ (BPI_{x,t-1}) + ln\ (AE_{x,t-1}) + ln\ (DI_{x,t-1}) + ln\ (GN_{x,t-1}) + ln\ (LP_{t-1}) + ln\ (PPAP_{t-1}) + City + EEG_k + \varepsilon$ *(11)*

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

Model II.2 aimed to quantitatively analyze the impacts of different EEG amendments on the choice of plant size and was designed as follow:

Model II.2: $ln\ (IC^{i}_{x,t}) = \alpha + ln\ (BPI_{x,t-1}) + ln\ (AE_{x,t-1}) + ln\ (DI_{x,t-1}) + ln\ (GN_{x,t-1}) + ln\ (LP_{t-1}) + ln\ (PPAP_{t-1}) + City + EEG_k + \varepsilon$ *(12)*

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

2.3 Methods and data for spatial analysis

2.3.1 Methods and data for the impact analysis of environmental, social and economic factors on biogas production

To spatially study the impacts of environmental, social and economic factors on biogas plant production density, we adopted the impact zone analysis approach of Csikos et al. [75]. Using the spatial join function of the ArcGIS 10.7 software, the data used in the empirical analysis on each investigated environmental, social and economic factor except for *PPAP* was assigned to the corresponding county to create the factor map. Then we utilized the Kernel Density tool within the ArcGIS 10.7 software to delineate three impact zones (A, B and C), which represent different biogas production density categories (low, medium and high). The separation of the biogas production density zones (impact zones A, B and C) followed the Jenks natural breaks classification procedure. In the end, we overlaid the impact zones layer with each factor map in CG to spatially illustrate the connection between the studied factor and the biogas production density.

2.3.2 Methods and data for impact analysis of EEG on agricultural land use

In addition to the four previously defined EEG sub-periods, the Non-EEG period was introduced, covering the years from 1995 to 2000, in order to detect the influences of various EEG amendments on agricultural land use. We first overlapped the three impact zones on the county-level map of CG to assign each county to a certain zone. Once the county impact zone assignment was completed, the annual data on various county-level agricultural areas were spatially linked to each corresponding county. After finishing the data preparation, we began a two-level evaluation: 1) at the utilized agricultural land (UTA) level, we calculated the ratios of arable land and grassland to UTA; 2) at the arable land level, we calculated the percentages of wheat, rye, triticale, silage maize, sugar beet and rapeseed of the total arable land. This spatial assessment was able to provide a general impression of the agricultural land use change from 1995 to 2014. In addition, a detailed analysis was made of the cultivation area of silage maize, the dominant energy crop, to the total arable land in each impact zone. A brief description of the data used in the spatial analysis is presented in Table 3.

Table 3. Description of the collected data for spatial analysis.

Data Source	Data	Type	Level	Unit
Own Calculation	$BPI_{x,t}$	Statistical	County	MWh/km^2
	$AE_{x,t}$	Statistical	County	-
	$DI_{x,t}$	Statistical	County	€
	$GN_{x,t}$	Statistical	County	-
	LP_t	Statistical	County	€/m^2
Helmholtz-Centre for Environmental Research (UFZ) EE-Monitor [62,63]	$BP_{x,t}$	Spatial	Biogas Plant	-
	$IC^i_{x,t}$	Spatial	Biogas Plant	kW/h
Regional Statistics Database of Germany [53]	Area of utilized agricultural land in county *x*, in year *t*	Statistical	County	ha
	Area of arable land in county *x*, in year *t*	Statistical	County	ha
	Area of grassland in county *x*, in year *t*	Statistical	County	ha
	Cultivation areas of wheat, rye, triticale, maize, sugar beet and rapeseed in county *x*, in year *t*	Statistical	County	ha
Eurostat [91]	Germany administrative Area (NUTS3)	Spatial	County	-

3. Results

In this section, the primary results of both the empirical and spatial analyses are presented in two sub-sections. The analysis of variance between the sub-models of Model I and II are summarized in Appendix Table A2. The multi-collinearity of all independent variables was verified using a variance inflation factor and the result can be found in Appendix Table A3. The regression residuals of all the sub-models were examined using regression diagnostic plots and reported in Appendix Fig. A1, A2, A3 and A4.

3.1 Influences of environmental, social and economic factors on biogas production decisions

3.1.1 Results of the empirical analysis

The regression results of Model I.1 and I.2 are summarized in Table 4. The regression result of Model I.1 showed that all of the environmental, social and economic variables we studied were significant to at least a 95% confidence level. The coefficients of all the variables had their expected sign. The number of county-level biogas plants *BP* positively correlated with the availability of feedstock *BPI*, awareness for the environment *AE*, income *DI* and local governance *GN* on a county level in CG. Additionally, the correlations between the number of biogas plants and the land price *LP* at the county level as well as the agriculture production price *PPAP* received by farmers were found to be negative. Of all the factors, disposable per capita income and the price of agriculture production had comparably strong effects on the decision of whether to adopt a biogas plant in CG. The result of Model I.2 indicated significantly negative impacts of the availability of feedstock, income, and price of agriculture production on the choice of biogas plant size. In contrast, the awareness for the environment and local political governance positively correlated with choice in plant size. Furthermore, land price played no role in influencing the choice in biogas plant size.

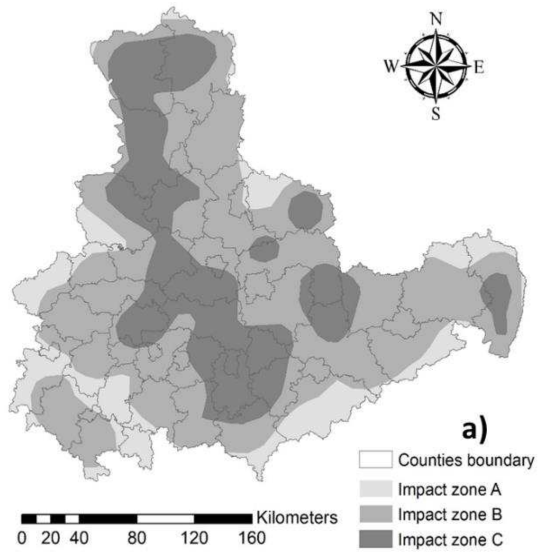
Table 4. Results of the multivariate regression for both Model I.1 and Model I.2.

Variables	Model I.1 (Number of biogas plants *BP*)		Model I.2 (Installed capacity *IC*)	
	Coefficient	Standard Error	Coefficient	Standard Error
Intercept	**-30.09****	11.08	**21.03*****	3.77
Environmental, social, economic variables				
ln(BPI)	**0.34***	0.16	**-0.25*****	0.06
ln(AE)	**0.78****	0.26	**0.28****	0.10
ln(DI)	**5.53*****	1.40	**-1.01***	0.46
ln(GN)	**0.64***	0.27	**0.26*****	0.07
ln(LP)	**-0.81*****	0.18	0.00	0.04
$ln(PPAP_t)$	**-5.70*****	0.99	**-0.76****	0.27
Control variables				
City	**-1.36*****	0.29	**-0.51****	0.18
Adjusted R^2	0.21		0.08	
Sample size	700		1016	

Note: "***","**","*" and "•" denote 99.9%, 99%, 95% and 90% confidence levels respectively.

3.1.2 Results of the spatial analysis

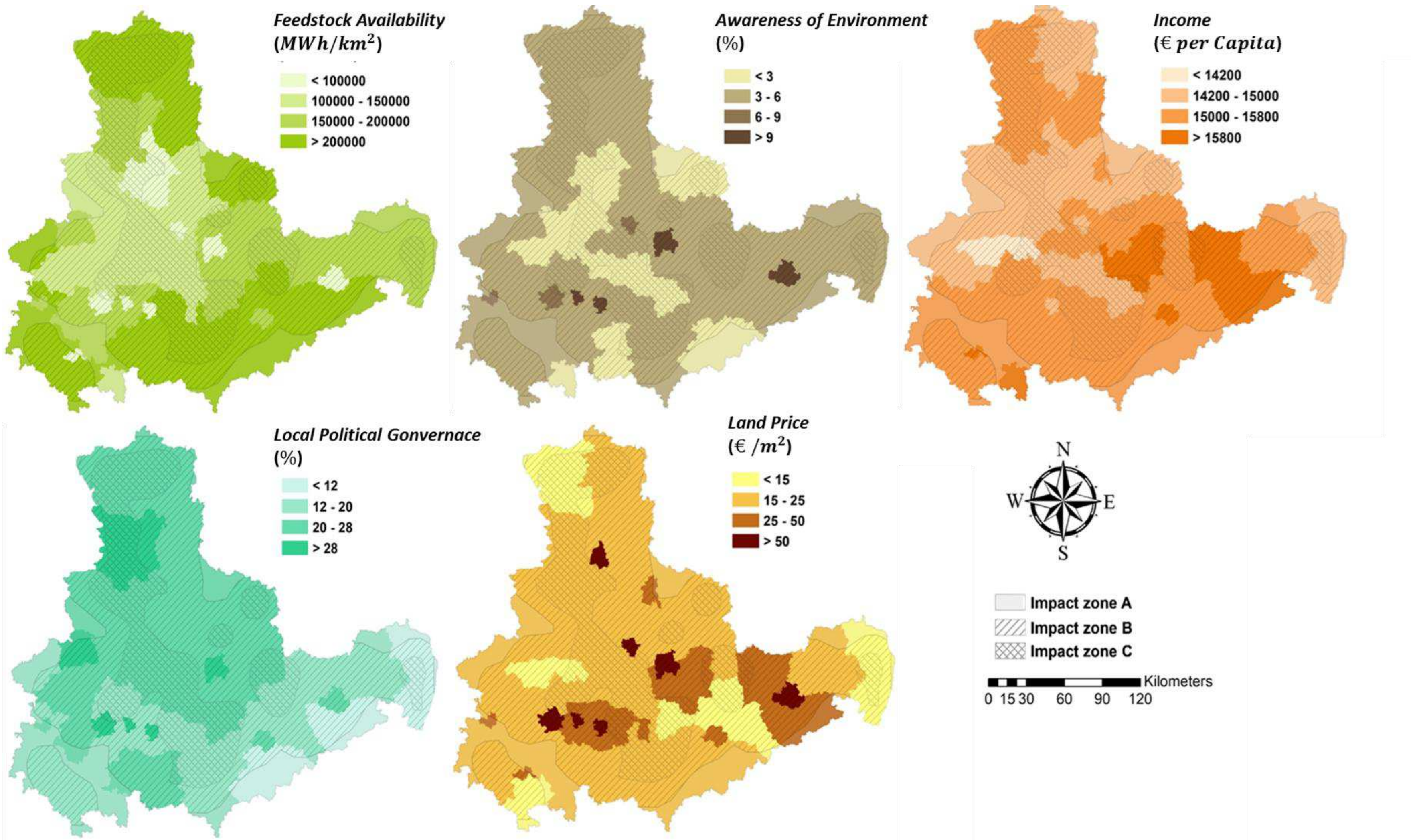
Three biogas production impact zones were identified in the studied area with value ranges of 0 - 3.80 kW/km^2 for impact zone A, 3.80 - 10.00 kW/km^2 for impact zone B, and 10.00 - 18.70 kW/km^2 for impact zone C. If a certain impact zone comprised more than 50% of a county's area, this county was assigned 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. In CG, 12 counties fell under impact zone A, 32 under impact zone B, and 6 under impact zone C. A spatial illustration of the biogas production impact zones is presented in Fig. 4.



Source: EE-Monitor and Germany administrative Area (NUTS3)

Fig. 4 Biogas production impact zones.

We further linked the biogas production impact zones with each factor map. The result is presented in Fig. 5. As shown, there was no clear pattern between feedstock availability and biogas production density. Some high biogas production density areas (impact zone C) were in counties where the technical biogas potential was considerably low. This could be also observed in the income factor. High and medium biogas production density areas (impact zones C and B) heavily overlapped with both high- and low-income counties. In contrast, high and medium biogas production density areas more strongly overlapped with regions with a high awareness for the environment and local political governance, which had both positive effects on the adoption of biogas production and choice in plant size. In the empirical analysis, we found that land price had a negative influence on the construction of biogas plants but no impact on choice of plant size. The spatial analysis illustrated that areas with a high biogas production density were generally located in counties with medium to low land prices.



Source: Regional Statistics Database of Germany

Fig. 5 Results of the spatial analysis on the influences of environmental, social and economic factors on biogas production decisions.

3.2 Influences of the EEG on biogas production decisions and agricultural land use

3.2.1 Results of the empirical analysis

The regression results of Model II.1 and II.2 are summarized in Table 5. As shown in Model II.1, the number of newly established biogas plants increased significantly from the EEG I to III periods and slowed down in the EEG IV amendment period. EEG III had the strongest impact among the four EEG amendments we studied. During the EEG III period, each county had an average of 1.99 more biogas plant units in operation compared to the EEG I period, after controlling for all other effects. Unlike the results of Model II.1, only the EEG dummy variable EEG_{II} in Model II.2 was significant, at a 99% confidence level, indicating that the average size of the biogas plants built during the EEG II period was 24% bigger than those built during the EEG I period, after accounting for all other effects. Apart from this, there was no significant difference in size between the biogas plants constructed under EEG I and under EEG III and IV after controlling for all other effects.

Table 5. Results of the multivariate regression for both Model II.1 and Model II.2.

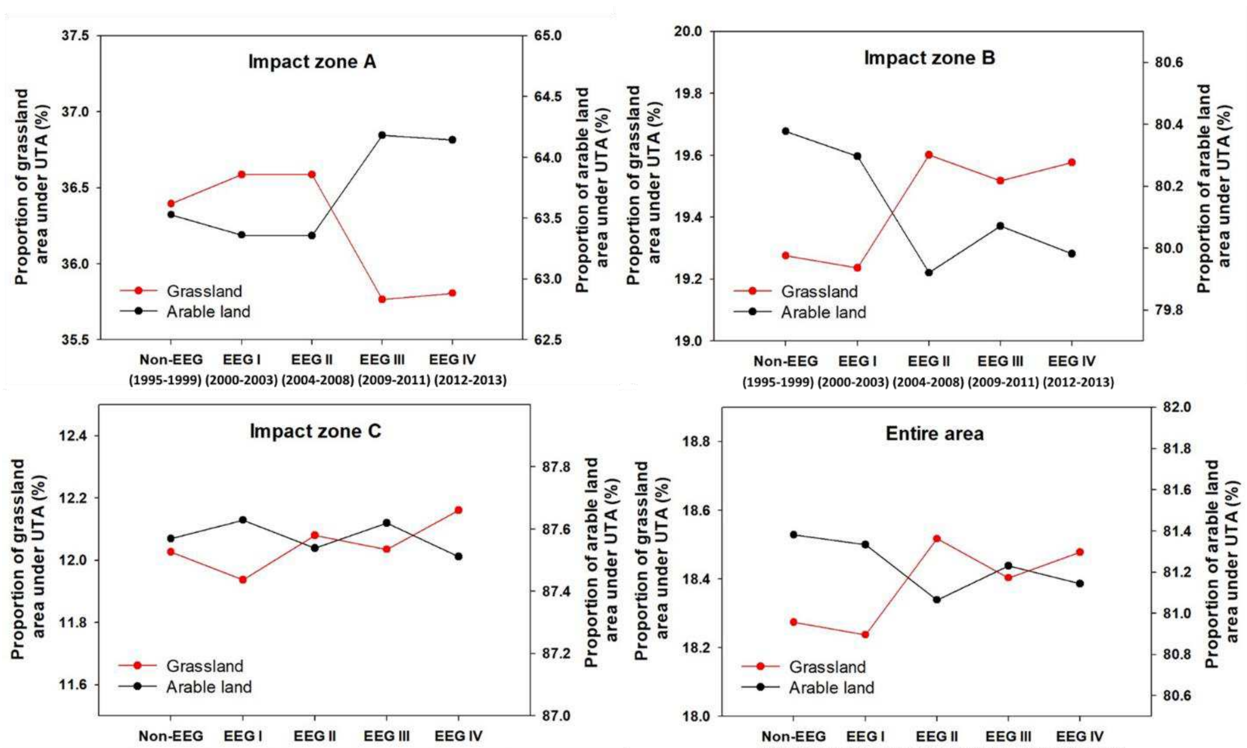
Variables	**Model II.1 (Number of biogas plants *BP*)**		**Model II.2 (Installed capacity *IC*)**	
	Coefficient	**Standard Error**	**Coefficient**	**Standard Error**
Intercept	13.56	16.56	**12.35***	4.96
Environmental-social-economic variables				
ln(BPI)	**0.46****	0.16	**-0.21*****	0.06
ln(AE)	0.14	0.28	**0.19•**	0.11
ln(DI)	-0.20	1.92	-0.30	0.57
ln(GN)	**0.56***	0.27	**0.30*****	0.07
ln(LP)	**-0.55****	0.18	0.00	0.04
$ln(PPAP_t)$	**-3.68****	1.16	-0.47	0.33
Control variables				
City	**-0.93****	0.29	**-0.42***	0.19
EEG dummy variables				
EEG_{II}	**1.40*****	0.26	**0.24****	0.09
EEG_{III}	**1.99*****	0.40	0.05	0.12
EEG_{IV}	**1.44****	0.49	-0.12	0.15
Adjusted R^2	0.25		0.10	
Sample size	700		1016	

Note: “***”,“**”,“*” and “•” denote 99.9%, 99%, 95% and 90% confidence levels respectively.

3.2.2 Results of the spatial analysis

3.2.2.1 Arable land and grassland area changes

From the Non-EEG to the EEG IV period, the area of UTA in CG decreased continuously from 28,954.08 to 28,661.08 km^2. In the same period, the total area of arable land in CG also went down from 23,563.05 to 23,256.86 km^2. In contrast to UTA and arable land, the total area of grassland in CG fluctuated between 5,266.80 and 5,336.91 km^2 with an increase of less than 0.1% from the Non-EEG to the EEG IV period. Changes in the proportion of arable land and grassland under UTA in each impact zone are displayed in Fig. 6. While increasing trends for proportions of grassland in UTA could be observed in medium- and high-density biogas production zones, the proportion of grassland in impact zone A decreased. In terms of the proportion of arable land under UTA, the opposite trends to grassland were observed in all three zones. In general, the proportions of grassland and arable land under UTA in CG showed increasing and decreasing trends from the Non-EEG to the EEG IV periods respectively.



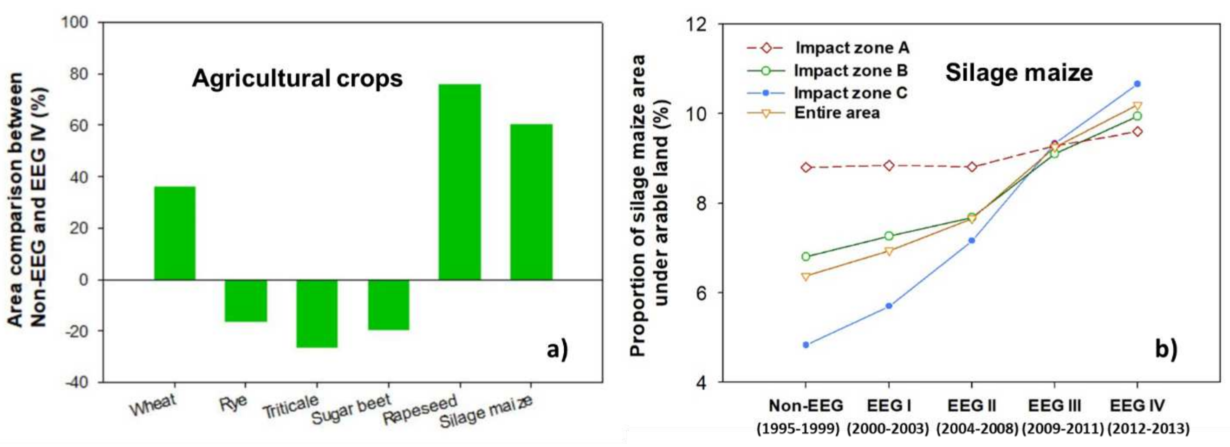
Source: Regional Statistics Database of Germany

Fig. 6 Proportion of arable land and grassland area under UTA in impact zones A, B, C and entire CG area.

3.2.2.2 Maize expansion influenced by biogas plant development

The change analysis for the cultivation areas of major crops showed that the planting areas of the energy crops silage maize and rapeseed increased by 57.85% and 76.49% respectively from the Non-EEG to the EEG IV period. Wheat was cultivated in around 45.79% of the area of major agriculture crops and accounted for the largest proportion of any crop throughout the period under investigation. Compared to the Non-EEG period, the cultivated area of wheat in EEG IV increased by 37.53%, while rye, triticale and sugar beet all declined over the same period. Of these crops, the area for triticale cultivation decreased significantly by 25.74% (see Fig. 7 a).

In CG, the proportion of the area for silage maize cultivation in arable land in CG increased from the Non-EEG to the EEG IV period (see Fig. 7 b). Compared to the proportion of silage maize in the Non-EEG period, the proportions in EEGs I to IV were 8.84%, 20.16%, 45.12% and 59.93% higher respectively. However, the patterns differ when it comes to specific impact zones. In the Non-EEG period, the highest proportion of silage maize was identified in impact zone A, while the proportion of maize cultivation in impact zone C was the lowest. Since then, there have been strong increases in the proportion of silage maize in impact zones B and C, while impact zone A only showed a mild increase. Starting in EEG III, the proportion of silage maize in impact zone C was the highest among all the zones.



Source: Regional Statistics Database of Germany

Fig. 7 Status of a) changes in the area of agricultural crops and b) the percentage of silage maize cultivation on arable land in each impact zone.

4. Discussion

4.1 Influences of environmental, social and economic factors on biogas plant adoption and size

The regression results of Model I.1 and Model I.2 showed that almost all of the environmental, social and economic variables studied correlated significantly with both the adoption and size of biogas plants in CG. The spatial analysis presented in Fig. 5 also supported the empirical results.

The awareness for the environment and the local political governance had the same expected signs in both Model I.1 and I.2, after controlling for the city effect. The positive correlations between these two variables and adoption and size of biogas plants were in line with most of the previous studies [33-38]. The spatial analysis also indicated that, except for the cities, the high and medium biogas production impact zones (impact zones C and B) largely overlapped with regions that had a relatively high environmental awareness and local political governance ratio. In addition, the price of agricultural products was, as expected, negatively correlated with the biogas production decision. This finding could be explained by the argumentation that biogas production constituted an alternative investment for the farmers in order to diversify their sources of income [74,78].

Feedstock availability had a positive sign in Model I.1 and was in line with many previous studies. This indicates that biogas plants were more likely to be built in regions where substrate resources were plentiful [70-73]. The negative sign of this variable in Model I.2 was mainly because a large number of biogas plants in CG were private farm-scale plants [92]. In regions with a high technical biogas potential, biomass could be supplied in the direct vicinity of a farm-scale biogas plant [74]. However, in counties with a low technical biogas potential, a larger biogas plant might be built and supported by several farms as it is not economical to build a biogas plant for each farm, even after considering the cost of feedstock transportation [92]. Since the total regional biogas production volume was the product of the number of biogas plants and average installed plant capacity, regions rich in feedstock might not have high biogas production outputs. This finding was also reflected in the spatial analysis in that a large proportion of high and medium impact zones were in regions where the biomass for biogas production was less plentiful.

As with feedstock availability, the disposable per capita income positively correlated with the decision to operate a biogas plant, but negatively influenced the choice of size. Therefore, as we also observed in the spatial analysis, the figure showed no significant pattern in the relation between biogas production density and income. In Germany, the adoption of biogas production involved a series of investments in time and capital [88,93]. In particular, the construction and installation of private biogas plants were largely achieved with the help of a loan provided by different credit institutions [79]. Therefore, farmers with high disposable income could be granted loans comparably easy and were more likely to operate biogas plants. However, if the income of the farmers was higher than a certain level, they might be reluctant to build a large-scale biogas plant since it required more time to operate. Many scholars argue that the adoption of biogas production has been an alternative investment for many farmers as a way to diversify their income. The income diversification effect of biogas production was not significant for farmers who could earn much more from other sources.

In line with many previous studies, the land price in this study had the expected negative effect on the decision to build a biogas plant but no effect on the choice of plant size. This empirical finding was also reflected in the spatial analysis, which showed that, in particular, impact zone C lay generally in the counties with medium or low land prices. In Germany, investors in biogas production often leased or bought agricultural land for their production [86]. The high rental and purchase price for land would squeeze out the profit from biogas production investments and thus reduce their willingness to start biogas production. However, the choice of biogas plant size was not influenced by the price. Instead it was strongly influenced by other factors such as output prices in accordance with legislation, the availability of raw materials, and ensuing transportation and production costs [23,94].

In general, the strong influence of the price of agriculture products and per capita disposable income pointed to the fact that the income diversification effect of biogas production plays a vital role in biogas production decision making. In the biogas production decision making process, farmers pay more attention to whether the biogas production is profitable after taking the cost of production, such as land price, into account, and whether the profits from biogas production can strongly contribute to income diversification.

4.2 Influence of different EEG amendments on adoption and size of biogas plants

All of the EEGs have the ultimate goal of increasing the contribution of renewable energy to total electricity consumption in Germany [16-20]; however, the impact of each EEG amendment on promoting the adoption of biogas production varied. As reported in other studies, the growth of the biogas sector was much faster in the EEG I to III periods and slowed down during the amendment of the EEG in 2012 [32,95]. This could also be observed in Appendix Fig. A5. After a rapid increase in the cumulative number of biogas plants from EEG I to III in CG, expansion slowed down during the EEG IV period.

The results of Model II.1 confirmed the distinctive results of different EEG amendments from 2000 to 2014. Compared to EEG I, the EEG II and III periods saw an average of 1.40 and 1.99 more units of newly built biogas plants in each county in CG after controlling for all other effects. Expansion during the EEG II period was mainly due to the newly introduced biomass bonus, which, from 2005 and 2006, substantially encouraged biogas production using energy crops [23]. However, since 2007, agricultural biomass prices have risen considerably, which reduced the number of new power plants built in 2007 and 2008. The stronger increase in the number of biogas plants observed with the EEG 2009 amendment was the consequence of an enlarged subsidy scheme, an increase in basic subsidies and the biomass bonus [72].

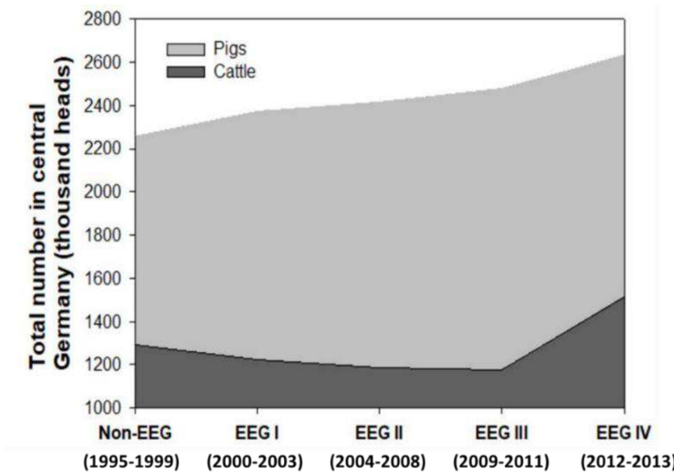
The expansion of biogas plants during the EEG IV period slowed down compared to preceding years. There was an average of 1.44 more units of newly constructed plants in each county in CG during the EEG IV period compared to the EEG I period, which were 0.55 fewer units compared to the EEG III period. The reasons behind this were an altered funding scheme and the introduction of a “maize cap” in the newly amended EEG 2014 [95]. As of 2004, EEG II started to encourage the use of energy crops like silage maize for biogas production [96]. After the implementation of EEG III, the cultivation of silage maize for biogas production increased significantly. Therefore, the “maize cap” was introduced under EEG IV [19]. Starting in 2012, the biogas sector started to be integrated into the German electricity market with fewer subsidies and using new mechanisms like the market and the flexibility premium. As a consequence, EEG IV lowered the growth rates of silage maize cultivation for biogas production and the biogas production industry in Germany [97,98].

In terms of the impact of EEG I to IV on the size of the biogas plants in CG, the regression result of Model II.2 matched the average size of newly constructed biogas plants under each EEG amendment in CG as presented in Appendix Fig. A5. The average installed capacity of the newly constructed plants under EEG II was the highest among all the amendments studied. Under EEG III, the subsidy for small-scale was raised to encourage the adoption of this type of plants. Therefore, it was argued that the plants constructed in the EEG III period should mainly be small-scale plants [23]. Due to the development in technology, a new subsidy category was introduced for 75 kW/h manure-based biogas plants in the next EEG IV period that was the most profitable of all categories [24]. This was to reinforce the support for the development of small-scale biogas plants [99]. In summary, the adoption of small-scale plants was strongly promoted starting under EEG III. However, the empirical results were unable to detect any decrease in the average size of biogas plants constructed in the EEG III and IV periods. There was no significant difference in the average installed capacity of biogas plants between EEG I and EEG III and IV. The reason behind this could be that the choice of plant size was mainly influenced by the operator's own situation and needs, such as feedstock transportation costs, production costs and available working time [23,24,94]. Therefore, our county-level analysis was unable to capture these factors, which was reflected in the low value of *Adjusted* R^2 in Model II.2.

4.3 Maize expansion status in CG

A central topic in the discourse on agricultural biogas production was the question of whether the expansion of biogas production leads to land competition between permanent grassland and silage maize cultivation [100]. Our study found that the proportion of silage maize in the total area of arable land increased rapidly during the EEG period. Starting from EEG III, the proportion of silage maize was the highest in regions where biogas production density was also high. This is consistent with the findings of studies conducted in Schleswig-Holstein and Hesse [75,101]. We also observed that the effect of the "maize cap" introduced under EEG IV played a very limited role in decreasing the growth rate of maize cultivation in CG. However, Vergara and Lakes [98] found a significant slowdown in the silage maize growth rate in the nearby region of Brandenburg during the EEG IV period. One possible reason was the difference in the data used in their analysis. In our study, the data on the silage maize cultivation area was only the aggregated total of the cultivation areas. Vergara and Lakes [98] applied the Integrated Administration and Control System (IACS), which classified the total silage maize cultivation area into different groups according to utilization purposes, e.g. biogas production, crop plants, fodder crops. Therefore, we were unable to conclude whether EEG IV was effective in controlling "mazification of the landscape" in CG.

In terms of the grassland in CG, the total area of permanent grassland slightly increased by 0.1% and the proportion of grassland in UTA remained stable at around 18.41% from the Non-EEG to the EEG IV period. However, other researchers reported different observations in other German states. For instance, Lüker-Jans et al. [101] reported a decrease in the total area of permanent grassland in Hesse during the EEG period. In Lower Saxony and Schleswig-Holstein, reductions in grassland were also observed from 1999 to 2013 [102,103]. According to the EE-Monitor dataset, Lower Saxony and Schleswig-Holstein had the highest biogas production density in Germany, with values of 22.99 and 23.11 kW/km^2 respectively [62,63]. In contrast, the biogas production density of CG was 8.94 kW/km^2. The rapid expansion of biogas plants in Lower Saxony and Schleswig-Holstein might have had a negative influence on the local grassland conservation. The small increase in grassland area in CG observed during the EEG period might be due to the fact that farmers adopted a combination of biogas and livestock production to better diversify their farming investments [88]. This view could be supported by the fact that the numbers of livestock, especially cattle and pigs, gradually rose in CG (see Fig. 7). Furthermore, between 2008 and 2013, the milk quota system was phased out by raising the quota 1% each year. This made dairy farming more and more attractive to farmers [104]. As shown in Appendix Fig. A6, the livestock business in Germany also became more profitable since the prices of dairy products and meat have shown upwards trends in the last two decades. Furthermore, the EU's Common Agricultural Policy (CAP) reform in 2013 regulated "greening" obligations to incentivize farmers to conduct environmentally sound farming practices such as crop diversification and maintaining ecologically rich landscape features [105]. To meet the greening requirement, the percentage of grassland relative to arable land in each district of Germany should not decrease by more than 5% over the 2012 levels. These regulatory forces left scope for an increase in grassland in CG [106].



Source: Regional Statistics Database of Germany

Fig. 7 Number of cattle and pigs on hand in Central Germany from the Non-EEG to EEG IV period.

5. Outlook and implications for future studies

In contrast to previous research that used farm-level data to study the factors that influence the adoption of biogas production in a certain area, this study's approach can be applied to other regions in Germany by updating the input data. The results of this study were able to provide information on the influence of environmental, social and economic factors on biogas plant development, as well as their spatial association through various biogas production density impact zones. This could serve as a starting point for a more detailed farm-level study in the future and can also be validated by a survey-based dataset. Based on the findings of our research that disposable per capita income and agricultural product prices strongly correlated with the biogas production decision, future studies should pay more attention to the income diversification effect of biogas production on the adoption decision. Additionally, our study emphasized the importance of spatial analysis. Due to the regional heterogeneity caused by spatial characteristics, e.g. topographic, soil, climatic, and other social-economic variations, the EEG's impact on different regions in Germany still contains large discrepancies. Therefore, to understand policy effectiveness on a national level, future studies should take into account environmental, social and economic factors, as well as regional spatial-temporal agricultural land use change. We should also note that the maize expansion detected in our study and the change in grassland during the EEG period might also be the result of other policies implemented in the same period, such as the obligation to set aside land and the "greening" obligation of CAP, as well as the milk quota [15,104,105]. Therefore, a future study focusing on the impact of the EEG on the environment should find a suitable research method that could strip all of the effects of other policies. Finally, if models could provide or generate spatial-temporal data on energy crop distribution in the future study, it would be possible to conduct more detailed landscape analyses such as resource optimization and trade-off analysis between the environmental costs and economic gain of adopting biogas plants.

6. Conclusion

The current study integrated empirical analysis with spatial analysis to better understand the impact of environmental, social and economic factors and the EEG amendments on biogas production decisions and the environment. The empirical result of the effects of environmental, social and economic factors on biogas production decisions indicated the importance of the income diversification effect of biogas production for the potential biogas plant operators in CG. By using the event study econometric technique, we found that the EEG was effective in promoting the adoption of biogas production in CG. However, in terms of the choice of plant size, despite there was being a clear encouragement to adopt small-scale biogas plants in EEG III and IV, we did not observe a decrease in the average size of the plants constructed in these two periods. The analysis of agricultural land use change illustrated that the development of biogas production in CG was associated with maize expansion, especially in regions with a high installed capacity for biogas. We also observed that, during the period under investigation, the area of arable land declined while the grassland area increased in CG. Apart from the CAP greening obligations for grassland conservation, the farmers' adoption of a combination of livestock farming and biogas production as a way to have diversified sources of income in CG was also the reason behind this observation.

Abbreviations

EEG: Erneuerbare-Energien-Gesetz; CG: Central Germany; GIS: Geographic Information System; GHG: Greenhouse Gas; FIT: Feed-in Tariff; UTA: Utilized Agricultural Area

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Authors' contributions

XY and YL designed the underlying model, analyzed the literature and interpreted the results. The empirical analysis section was mainly conducted by YL. The spatial analysis section was mainly assessed by XY. The manuscript was written primarily by XY and 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 methods section, the raw data used for the study was collected from many different sources. Most of these are publicly available. The datasets analyzed in the current study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no conflicting interests.

Appendix

Table A1. Remuneration Policy for EEGs I to IV.

Year	Installed Capacity	Remuneration in €-ct/kWh							
		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							

Soruce: EEG-Vergütungssätze (2000 - 2004); Mindestvergütungssätze nach dem neuen Erneuerbare-Energien-Gesetz (EEG). vom 21. Juli 2004; Vergütungssätze und Degressionsbeispiele nach dem neuen Erneuerbare-Energien-Gesetz (EEG). vom 31. Oktober 2008 mit Änderungen vom 11. August 2010; Einspeisevergütung für im Kalenderjahr 2012 neu in Betrieb genommene Eigenerzeugungsanlagen nach dem Erneuerbare-Energien-Gesetz - EEG vom 28.07.2011.

Note: 1. RR: Renewable Resources; 2. M: Manure; 3. LM: Landscaping Material; 4. ER: Emission Reduction; 5. FC I: Feedstock Class I; 6. FC II: Feedstock class II; 7. OW: Organic Waste; 8. this category is specified for the small manure biogas plant.

Table A2. Results of ANOVA for linear model fits test for both Model I and Model II.

Model	Residual DF	RSS	Sum of Square	F	p-Value
Model I: $\boldsymbol{BP = \alpha + ln(BPI) + ln(AE) + ln(DI) + ln(GN) + ln(LP) + ln(PPAP) + City + (EEG) + \varepsilon}$					
I.1	693	2792.90			
II.1	690	2634.80	158.16	13.81	0.00***
Model II: $\boldsymbol{ln(IC) = \alpha + ln(BPI) + ln(AE) + ln(DI) + ln(GN) + ln(LP) + ln(PPAP) + City + EEG + \varepsilon}$					
I.2	1008	447.34			
II.2	1005	436.20	11.14	8.56	0.00***

Note: “***”,“**”,“*” and “” denote 99.9%, 99%, 95% and 90% confidence levels, respectively.

Table A3. Results of variance inflation factor of independent variables for both Model I and II.

Environmental-social-economic Variables	Variance Inflation Factor	Control and EEG Dummy Variables	Variance Inflation Factor
Model I.1: $\boldsymbol{BP = ln(BPI) + ln(AE) + ln(DI) + ln(GN) + ln(LP) + ln(PPAP) + City}$			
ln(BPI)	1.77	*City*	2.88
ln(AE)	3.15	EEG_{II}	-
ln(DI)	3.42	EEG_{III}	-
ln(GN)	1.31	EEG_{IV}	-
ln(LP)	2.30		
ln(PPAP)	2.22		
Model I.2: $\boldsymbol{ln(IC) = ln(BPI) + ln(AE) + ln(DI) + ln(GN) + ln(LP) + ln(PPAP) + City}$			
ln(BPI)	1.16	*City*	1.54
ln(AE)	2.63	EEG_{II}	-
ln(DI)	3.25	EEG_{III}	-
ln(GN)	1.08	EEG_{IV}	-
ln(LP)	1.21		
ln(PPAP)	1.81		
Model II.1: $\boldsymbol{BP = ln(BPI) + ln(AE) + ln(DI) + ln(GN) + ln(LP) + ln(PPAP) + City + EEG}$			
ln(BPI)	1.81	*City*	3.09
ln(AE)	3.74	EEG_{II}	2.89
ln(DI)	6.75	EEG_{III}	5.12
ln(GN)	1.39	EEG_{IV}	5.40
ln(LP)	2.50		
ln(PPAP)	3.19		
Model II.2: $\boldsymbol{ln(IC) = ln(BPI) + ln(AE) + ln(DI) + ln(GN) + ln(LP) + ln(PPAP) + City + EEG}$			
ln(BPI)	1.20	*City*	1.70
ln(AE)	3.14	EEG_{II}	4.34
ln(DI)	5.21	EEG_{III}	8.01
ln(GN)	1.11	EEG_{IV}	5.13
ln(LP)	1.32		
ln(PPAP)	2.73		

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

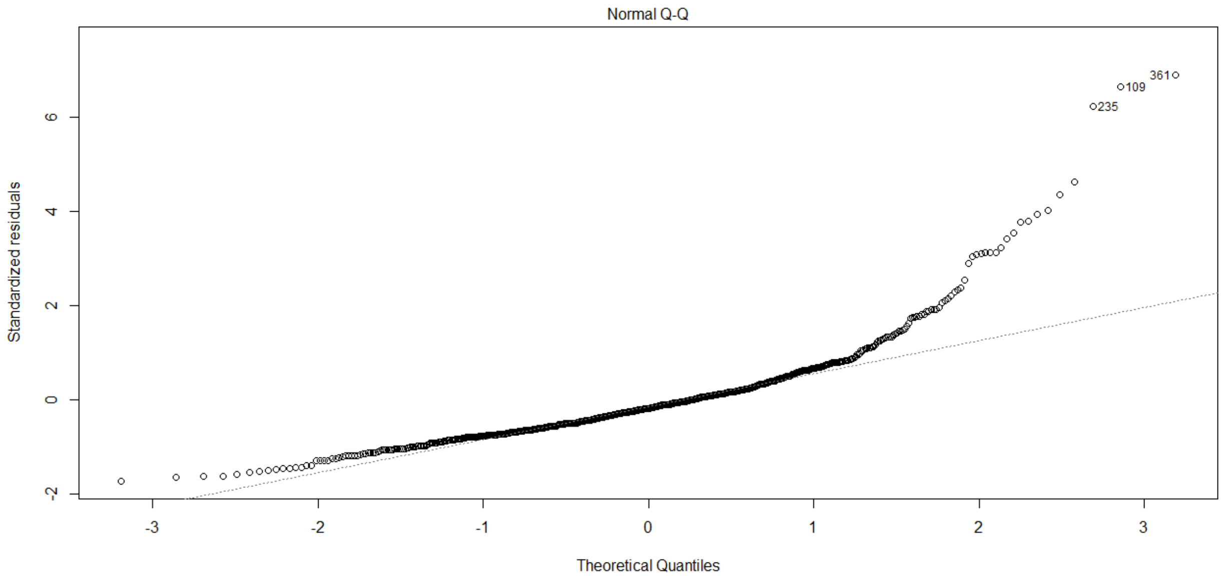


Fig. A1 Quantile-quantile plot of regression residuals of Model I.1.

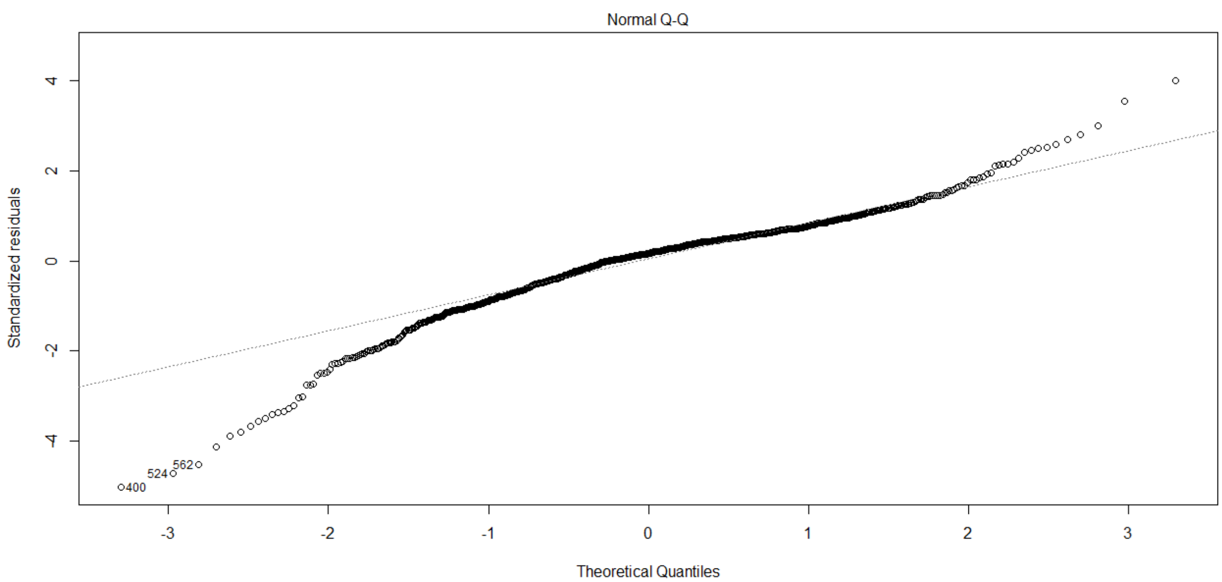


Fig. A2 Quantile-quantile plot of regression residuals of Model I.2.

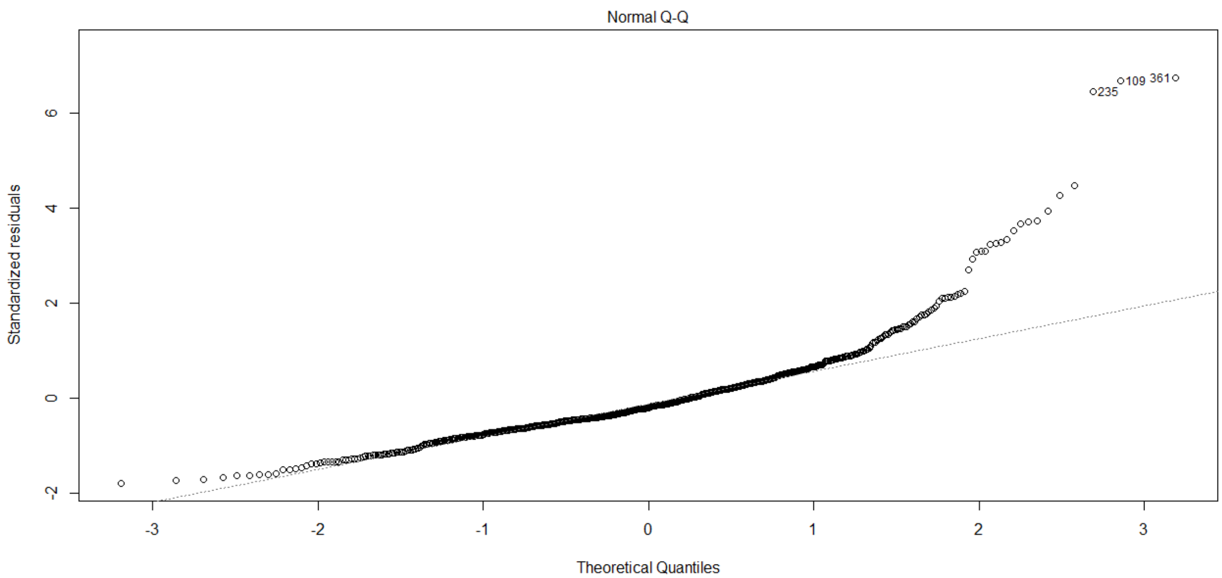


Fig. A3 Quantile-quantile plot of regression residuals of Model II.1.

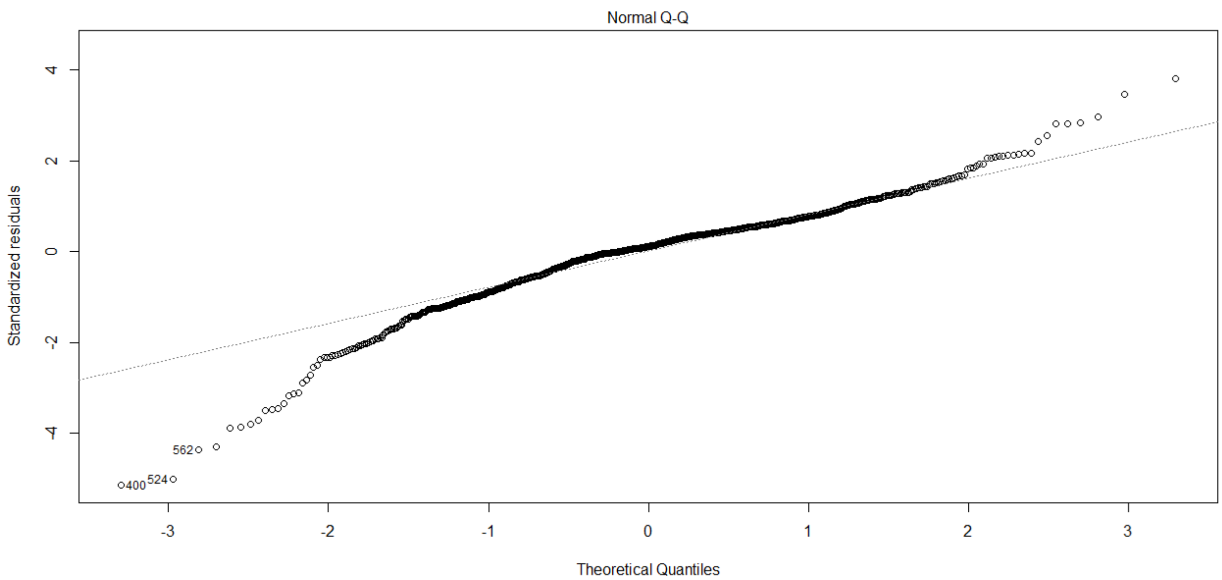
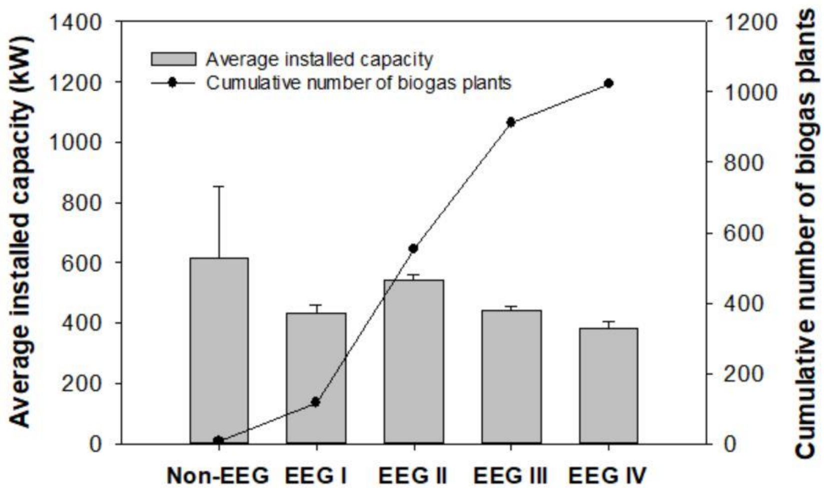
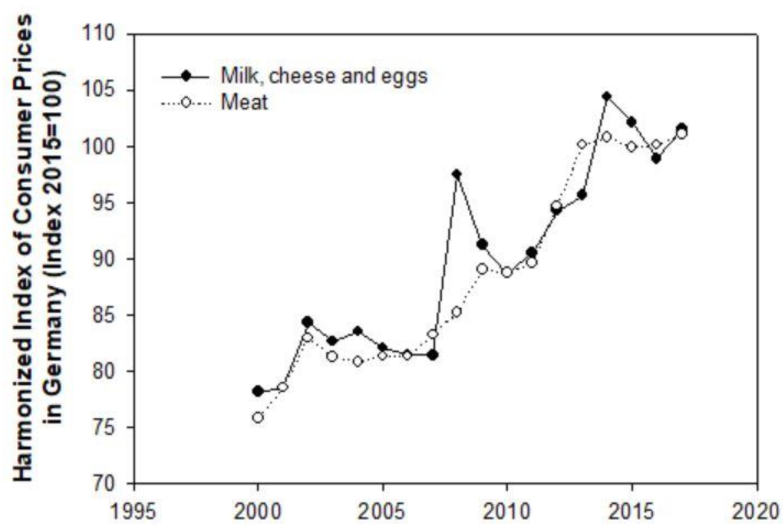


Fig. A4 Quantile-quantile plot of regression residuals of Model II.2.



Source: EE-Monitor

Fig. A5 Cumulative number of biogas plants from the Non-EEG to the EEG IV period and the average installed capacity in each period.



Source: Federal Reserve Bank of St. Louis

Fig. A6 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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Figures

Figure 1

The development phases of the German biogas sector along the timeline of the Renewable Energy Sources Act Source: Thrän et al. (2020)

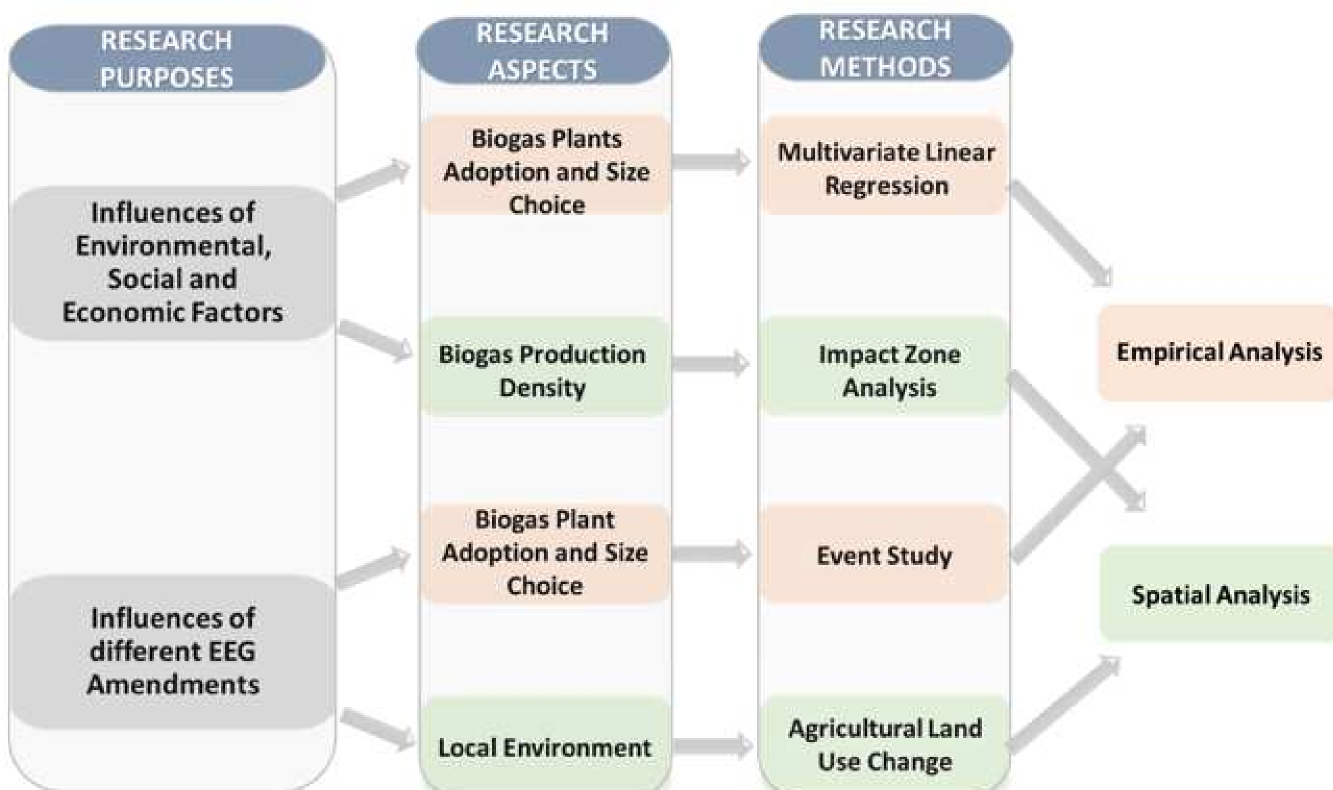
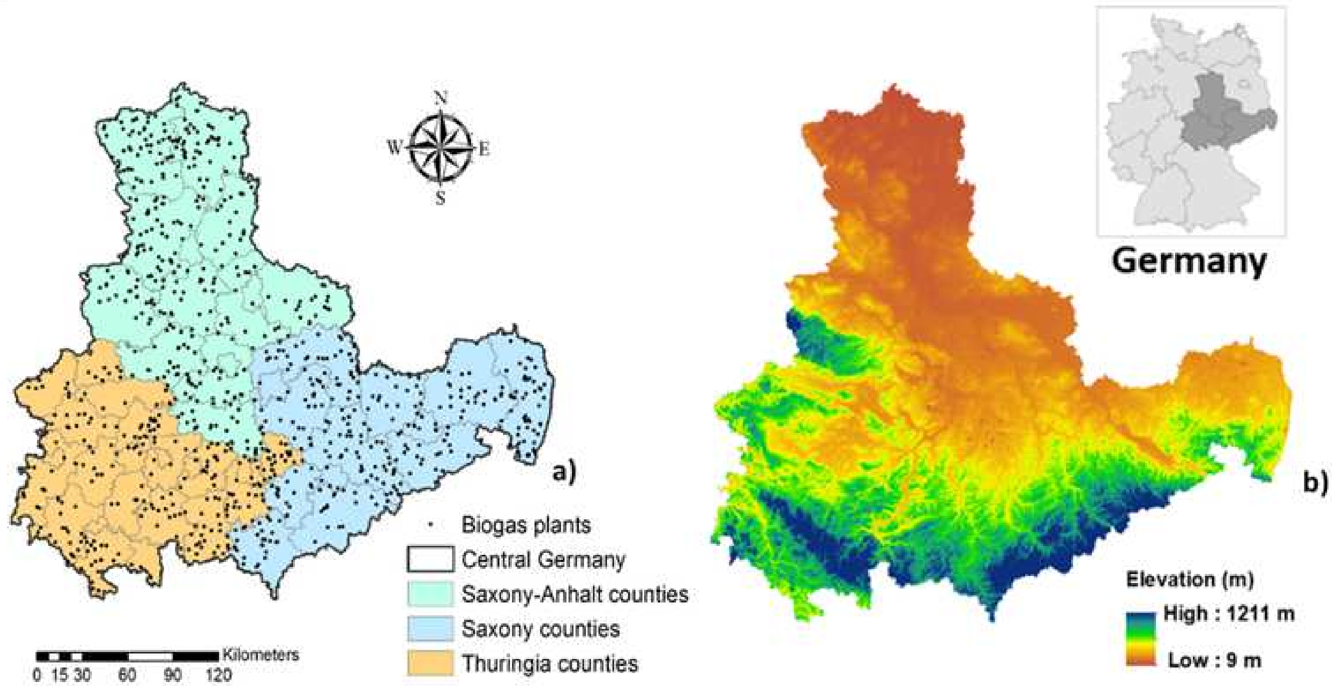


Figure 2

Flowchart of the current study



Source: EE-Monitor, Shuttle Radar Topography Mission (SRTM) and Germany administrative Area (NUTS3)

Figure 3

Maps of Central Germany with a) the distribution of biogas plants overlaid with administrative areas in Central Germany and b) the digital elevation map

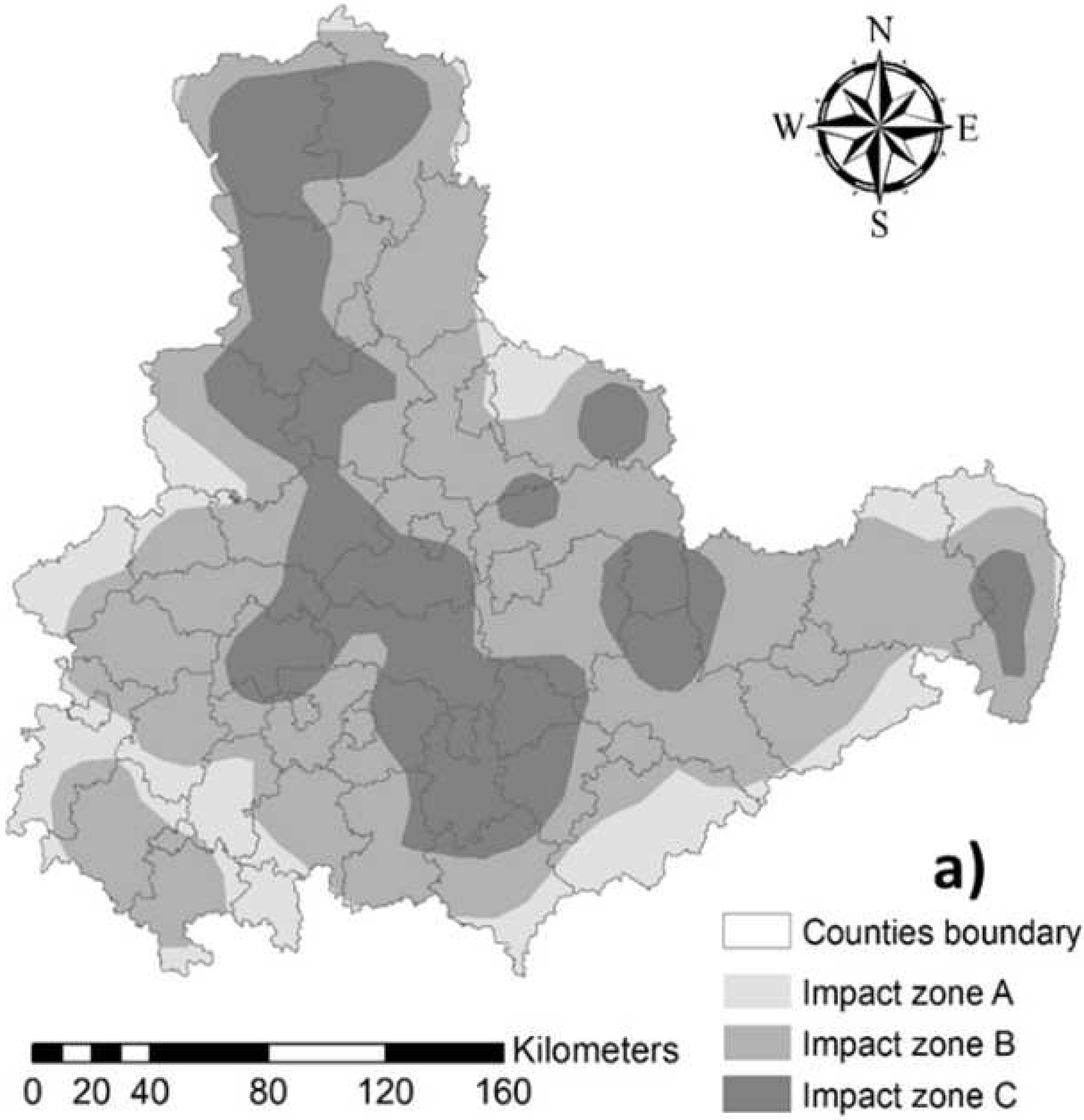
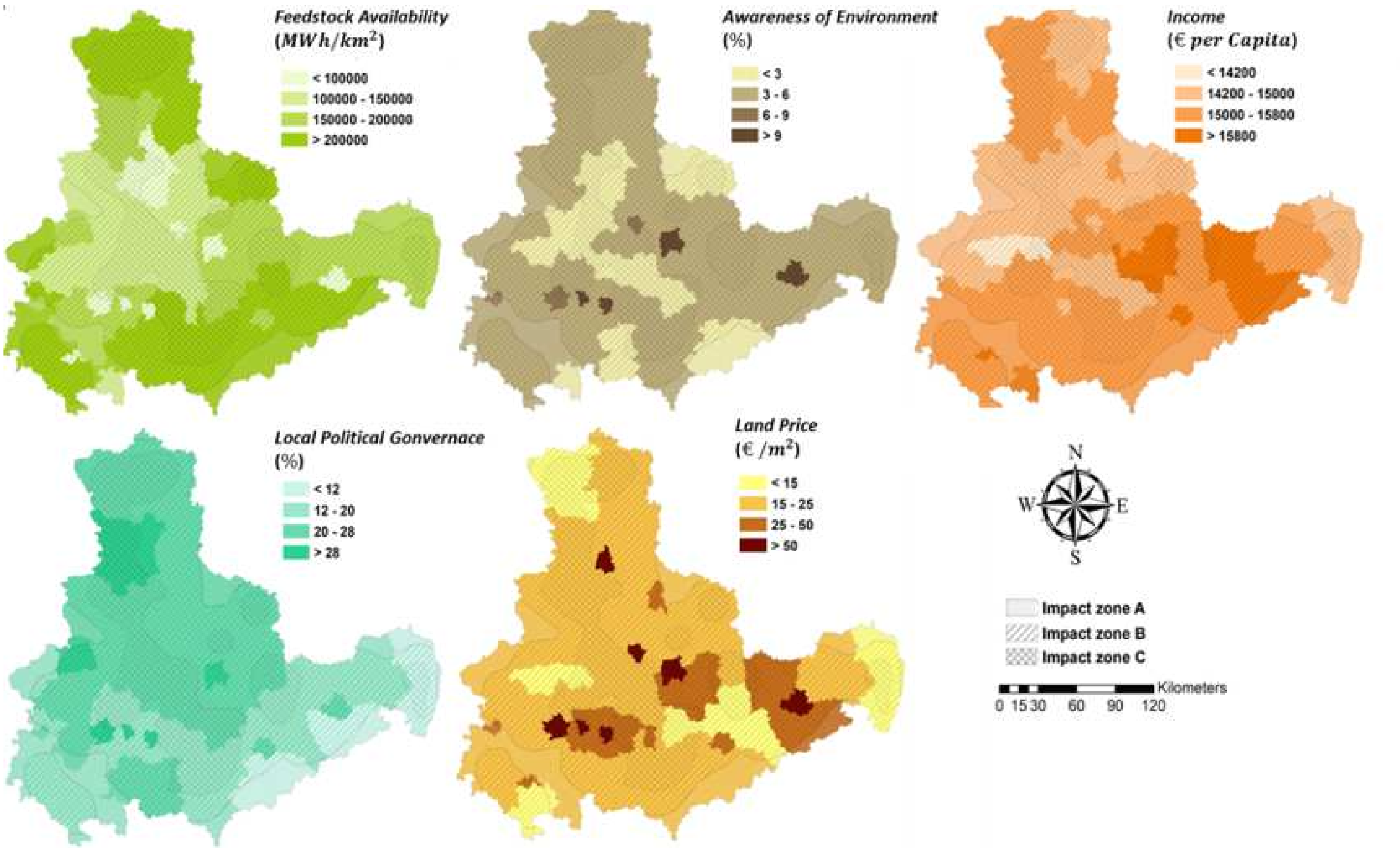


Figure 4

Biogas production impact zones. Source: EE-Monitor and Germany administrative Area (NUTS3)



Source: Regional Statistics Database of Germany

Figure 5

Results of the spatial analysis on the influences of environmental, social and economic factors on biogas production decisions.

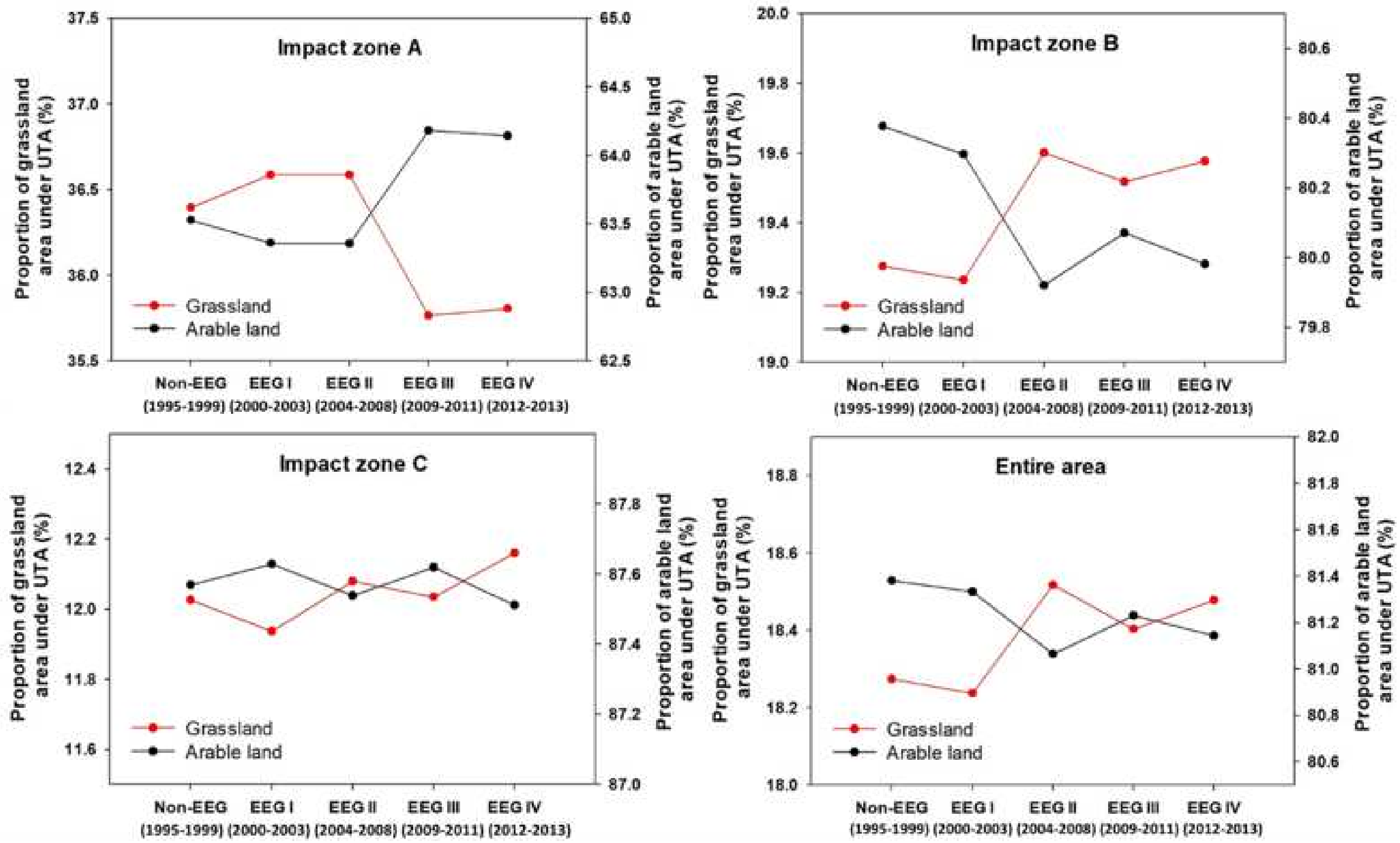


Figure 6

Proportion of arable land and grassland area under UTA in impact zones A, B, C and entire CG area. Source: Regional Statistics Database of Germany

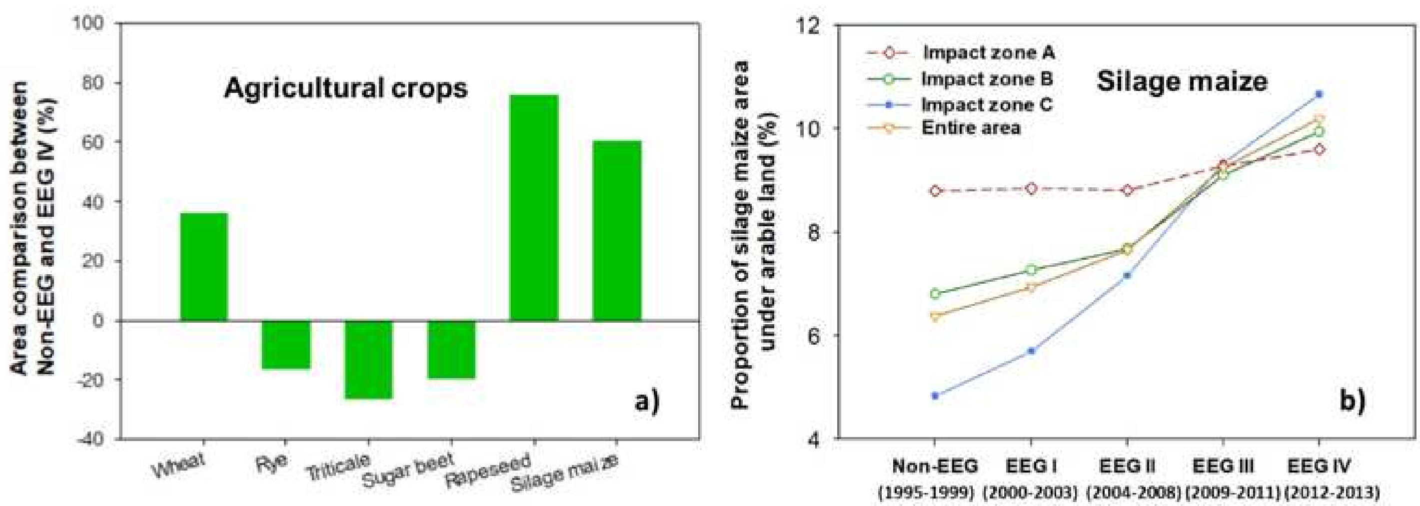
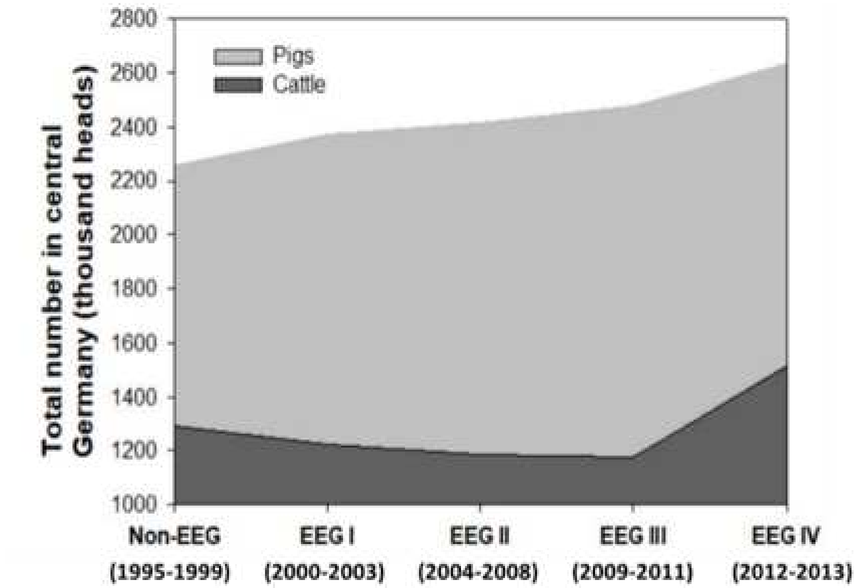


Figure 7

Status of a) changes in the area of agricultural crops and b) the percentage of silage maize cultivation on arable land in each impact zone. Source: Regional Statistics Database of Germany



Source: Regional Statistics Database of Germany

Figure 8

Number of cattle and pigs on hand in Central Germany from the Non-EEG to EEG IV period.