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Modelling Regional Maize Markets for Biogas Production in Germany: The Impact of Different Policy Options on Environment and Transport Emissions

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Abstract

The production of biogas is considered to be a promising candidate for a sustainable energy mix. Accordingly, Germany's Renewable Energy Act (EEG) promotes electricity production from biogas along with other renewable energies. While overall benefits are seen in terms of climate protection and increased employment in rural areas, for example, biogas production (mainly from maize in Germany) also has the potential to create negative environmental effects on a regional scale. This can be caused by the production of monocultures and increasing transport volumes, to cite two prominent examples. To assess environmental effects arising from bioenergy policies, different types of agricultural models have been applied to determine the effects on competition for primary factors. Generally, these models do not however capture the demand side for crops with high transportation costs such as maize.

Based on location theory combined with an analysis of existing location models, a new tool to determine optimal locations and sizes for biogas plants is developed in the course of the thesis, and therewith maize demand curves are derived. The location model ReSI-M (Regionalised Location Information System – Maize, or Regionalisiertes Standortinformationssystem – Mais) allows for the determination of regional demand functions of silage maize as a function of silage maize prices as well as further explanatory factors such as transport costs and economic profitability of different biogas plant types. It simulates demand functions for three different policy scenarios: the EEG 2004, the EEG 2008 including the respective feed-in tariffs, and finally a counterfactual scenario where feed-in tariffs are paid independent of plant size and technology. The later is applied to compare the EEG scenarios with a situation in which the resulting plant structure is theoretically a cost-minimal solution.

Coupling ReSI-M with RAUMIS, a partial supply model which depicts German agriculture based on regionally differentiated processes, adds regional market clearing for a robust impact assessment of biogas production. As a result, policy implications on land use of different policy settings are analysed in this thesis. Furthermore, ReSI-M simulates regionally differing CO_2 emissions from transports per kWh_{el} (kilowatt hour electric), as well as the efficiency of subsidies for the policy scenarios.

The results show that adding maize demand to an assessment of land use changes improves the representation of regional maize markets since regional demand characteristics such as transport costs and availability of inputs are taken into account. Simulation results indicate that under a scenario adopting feed-in tariffs according to the EEG 2004, less land for maize cultivation per kWh$_{el}$ is used and also less transport emissions are caused compared to the EEG 2008 and the counterfactual scenario. Furthermore, results point out differences in regional maize markets under the applied scenarios: under the EEG 2008 scenario, maize production increases in regions with high livestock densities, which therewith further intensifies maize production in regions where the production level is already high. Applying the counterfactual scenario shows that production increases in regions with low transport costs. However, under the EEG 2008 the greatest amount of energy from biogas is produced and most subsidies per produced kWh$_{el}$ are paid. The efficiency of subsidies is best in the counterfactual scenario, in which feed-in tariffs are paid independent of plant size and technology. Against these results, the thesis concludes with policy recommendations and suggestions for further research. The work provides a tool for policymakers to evaluate distinct regional demand levels for maize and its environmental impacts while the work also contributes to an ongoing political debate of the benefits and drawbacks of bioenergy production.

Zusammenfassung

Die Produktion von Biogas wird als vielversprechende Option innerhalb eines nachhaltigen Energiemixes angesehen, und dementsprechend wird in Deutschland die Produktion von Biogas zusammen mit anderen erneuerbaren Energien durch das Erneuerbare-Energien-Gesetz (EEG) gefördert. Während Vorteile für den Klimaschutz und ländliche Entwicklung gesehen werden, birgt die Produktion von Biogas (in Deutschland hauptsächlich auf der Basis von Silomais) die Gefahr, negative Umwelteffekte wie beispielsweise den Anbau von Mais in Monokulturen und steigende Transportaufkommen auf regionaler Ebene zu verursachen. Zur Bewertung von Umwelteffekten, die durch unterschiedliche Bioenergiepolitiken entstehen, wurden verschiedene agrarökonomische Modelle angewandt, um Auswirkungen auf den Wettbewerb von Einsatzfaktoren zu erfassen. Diese Modelle bilden die Nachfrageseite von Pflanzen mit hohen Transportkosten, wie beispielsweise Silomais, jedoch nicht ab.

Basierend auf der Standorttheorie und vor dem Hintergrund bestehender Standortmodelle, wird im Laufe der Dissertation ein neues Modell entwickelt, um Standorte und Größen von Biogasanlagen zu bestimmen und somit deren Maisnachfrage abzuleiten. Das Standortmodell ReSI-M (Regionalsiertes Standortinformationsmodell – Mais) ermöglicht es regionale Nachfragefunktionen für Silomais als eine Funktion von Silomaispreisen und weiteren Erklärungsvariablen wie Transportkosten und wirtschaftliche Profitabilität von verschieden Biogasanlagentypen abzuleiten. Es simuliert Nachfragefunktionen für drei Politikszenarien: das EEG 2004, das EEG 2008 mit entsprechenden Einspeisevergütungen, und außerdem ein fiktives Szenario („counterfactual scenario“), in dem Einspeisevergütungen unabhängig von Anlagengröße und –technologie gezahlt werden. Das letzere Szenario wird angewandt, um die EEG Szenarien mit einer Situation zu vergleichen, in welcher die resultierende Anlagenstruktur theoretisch einer kostenminimalen Lösung entspricht.

Durch das Koppeln von ReSI-M mit RAUMIS, einem partiellen Angebotsmodell, das den deutschen Agrarsektor regional differenziert abbildet, wird eine regionale Markträumung einer Folgenabschätzung der Biogasproduktion hinzugefügt. Somit werden in dieser Dissertation Politikauswirkungen auf Landnutzung und resultierende Umwelteffekte analysiert. So werden mit ReSI-M regional unterschiedliche CO_2

Transportemissionen pro kWh_{el} (Kilowattstunden elektrisch) und die Effizienz von Subventionen für die Politikszenarien simuliert.

Die Ergebnisse zeigen, dass eine Ergänzung der Maisnachfrage innerhalb einer Bewertung von Landnutzungsänderungen, die Abbildung von regionalen Maismärkten verbessert, da regionale Charakteristika auf der Nachfrageseite, wie Transportkosten und die Verfügbarkeit von Einsatzstoffen, berücksichtigt werden. Simulationsergebnisse weisen darauf hin, dass unter dem EEG 2004 Szenario die geringste Landfläche pro kWh_{el} benötigt wird und weniger Transportemissionen im Vergleich zu dem EEG 2008 und dem fiktiven Szenario verursacht werden. Zudem stellen die Ergebnisse Unterschiede der regionalen Maismärkte bei den verschiedenen Szenarien heraus: unter dem EEG 2008 Szenario steigt die Maisproduktion vor allem in Regionen mit einer hohen Viehdichte an und verstärkt somit den Maisanbau in Regionen, wo er für den Futteranbau bereits hoch ist. Die Anwendung des fiktiven Szenarios zeigt, dass sich die Produktion in Regionen mit geringen Transportkosten ausdehnt. Dabei handelt es sich vornehmlich um Ackerbauregionen. Unter dem EEG 2008 wird jedoch die meiste Energiemenge produziert und die meisten Subventionen pro kWh_{el} gezahlt. Die Effizienz der Subventionen ist hingegen im fiktiven Szenario am besten. Vor dem Hintergrund dieser Ergebnisse, schließt diese Dissertation mit Politikempfehlungen und Vorschlägen für weiteren Forschungsbedarf. Die Arbeit stellt ein Instrument für Entscheidungsträger vor, das dabei hilft, unterschiedliche regionale Maismärkte und deren Umwelteffekte zu bewerten und trägt somit zu der aktuellen politischen Debatte über die Vor- und Nachteile der Förderung von Bioenergie bei.

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Abbreviations

a	Year
BBR	Federal Office for Building and Regional Planning
BHHP	Block heat power plant
CFLP	Capacitated Facility Location Problem
CHP	Combined heat and power
CO_2	Carbon dioxide
EU	European Union
EEG	Renewable Energy Source Act
FITs	Feed-in tariffs
GIS	Geographical information system
ha	Hectare
km	Kilometres
km^2	Square kilometres
KTBL	Association for Technology and Structures in Agriculture
kW_{el}	Electric kilo watt
kWh_{el}	Electric kilo watt hours
LCA	Life cycle assessment
MIPM	Mixed-Integer Programming Models
MW_{el}	Mega watt electric
N	Nitrate
Nm^3	Normal cubic metre
NUTS	Nomenclature of Territorial Units for Statistics
P	Phosphate
RAUMIS	Regional Agri-Environmental Information System
ReSI-M	Regionalised Location Information System - Maize
ROI	Return on investments
SOFL	Statistical Offices of the Federation and the Länder
tFW	Tons fresh weight

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1 Introduction

The promotion of bioenergy is driven by different political objectives and motivations. It is considered to be a promising candidate for a sustainable energy mix, with benefits including climate protection, energy self-sufficiency and increased employment in rural areas. However, there might be trade-offs between these advantages and potential drawbacks. These can be seen in an increased cultivation of crops for bioenergy production, competition for land and environmental effects of intensified agriculture. Focusing on biogas production from maize and manure, this thesis aims to identify these trade-offs with respect to various policy options on a quantitative basis. A new simulation tool to model maize demand is presented and coupled with an agricultural sector model to analyse different policy options with respect to environmental effects.

After providing an overview of biogas production, the problem statement is discussed in detail and an overview of the current state of research is provided. The outcomes establish the research questions for the thesis.

1.1 Background and Problem Statement

“We will pass an action plan for climate protection and energy policy that is more concrete than ever before in the history of the European Union. It is a comprehensive complex, which - alongside climate protection and sustainability - includes external energy relations as well as a domestic market, competition and environmental protection” stated the German Federal Chancellor Angela Merkel in an interview with Sueddeutsche Zeitung (KORNELIUS and WINTER 2007). The Assessment Report of the Intergovernmental Panel of Climate Change in 2007 (IPCC 2007) contributed to public awareness of climate change. This awareness was increased by the Stern Review on the economics of climate change (STERN 2007), where impacts of climate change and mitigation strategies are monetised. In 2007, the German Advisory Council on the Environment (SRU) emphasised that climate protection had become the most important topic in environmental policy and the central challenge of the international community. Besides increasing energy efficiency, the substitution of fossil fuels by renewable energies is considered to make a significant contribution to the challenge (SRU 2007, p.1). In this context, bioenergy is said to have a high level of

potential in contributing to an energy-mix with regard to a sustainable energy concept. Based on the European Renewable Energy Road Map, which aims to increase the share of renewable energies for primary energy consumption to 20% by 2020 (EUROPEAN COMMISSION 2007), Germany has subdivided the 20% target into a share of 14% in the heating sector, 17% for fuels and 27% in electricity production (BMU 2007). In relation to the total primary energy production, bioenergy accounted for about 5% in 2009, and is targeted for an increase to 10% in 2010 (BMU 2009, p. 6ff). In addition to electricity from wind, water and solar energy, electricity from renewable energy is produced from biogas, which is mainly based on the fermentation of biomass. Within renewable energies, biomass already has a share of 70% of renewable energies in Germany, and is used for heat, fuel and electricity production. Due to current targets, the use of biomass (but not share) is expected to grow in the future (SRU 2007, p.1).

The most important incentive to increase electricity production from renewable energy in Germany is a German law called the Renewable Energy Sources Act (EEG). The instrument, its history and influence on biogas production in Germany is described in the following section.

1.1.1 Development of the EEG and Biogas Production

The EEG provides producers of electricity from renewable energies with per unit feed-in tariffs (FITs) which are higher than the price paid for electricity from fossil fuels. Thereby the EEG compensates the higher production costs of renewable energies and makes them competitive with electricity from conventional energy sources.

The EEG was created in 1990 and revised in 2004 and 2008 (BGBL, 2004 and 2008). In 1990, the German government set up a law on the incorporation of power from renewable energies into the public power grid (Stromeinspeisungsgesetz SEG) (BGBL 1990). Taking effect in 1991, the SEG for the first time required electricity suppliers to pay producers of renewable energies fixed prices for the energy they generate and allowed them to pass on costs to consumers. The SEG, the predecessor of the Renewable Energy Source Act, was passed in its first version in 2000 (BGBL 2000). It aims *"in the interest of climate and environmental protection to enable a sustainable development of the energy supply and to significantly increase the share of renewable energies for electricity production, in order to at least double the* *share of renewable energies in total energy consumption by 2010 according to the targets of the European Union and the Federal Republic of Germany."* (BGBL. 2000, I S.305). FITs for electricity from biomass are graded corresponding to the plant's capacity (size): up to an installed capacity of 500 kW_{el}, 10.21 Cent per kWh_{el} are paid, while plants up to 5 MW_{el} receive 9.21 Cent per kWh_{el}, and plants larger than 5 MW_{el} obtain 8.70 Cent per kWh_{el}. Tariffs for new plants constructed after January 1st, 2002 are reduced annually by 1% (BGBL. 2000, § 5). Once a biogas plant is built, FITs for electricity are guaranteed for a time period of 20 years. As a result, the installed electrical power capacity increased from 49 MW_{el} in 1999 to 111 MW_{el} in 2001 (see Figure 1). A monitoring report reassured the success of the EEG, concluding that the share of renewable energies for electricity consumption increased from 5.2% in 1998 to 7.5% by the end of 2001 (GERMAN FEDERAL CABINET 2002, p.2).

To further increase energy production from renewable energies, in 2004 the EEG was amended. In addition to the goals of the EEG 2000, the scope of the EEG 2004 was extended to "*reduce macroeconomic costs of the energy supply also by including long-term external effects, to protect nature and the environment, to contribute to avoiding conflicts over fossil energy resources and to develop technologies for energy production from renewable energies."* (BGBL. 2000, § 1 (1)).

FITs are higher in the EEG 2004 and divided into a basic payment per kWh_{el} (Grundvergütung) and additional fees adjusted depending on input, plant size and plant technology. The maximum possible fees are displayed in Table 1, whereas the amount depends on some requirements: The so-called "NaWaRo" (renewable resources) bonus is restricted to electricity that is gained from plants or parts of plants which are produced in agricultural, silvicultural or horticultural farms and manure (for more details on definitions see BGBL. 2004, § 8 (2)). Producers receive a bonus for using heat according to the heat-and-power-generation law. The combined heat and power generation (CHP) bonus also depends on the actual amount of heat used and depends on the plant's electricity efficiency. The efficiency as well as the share of heat used is generally lower in small plants (< 150 kW_{el}), which therefore benefit less from this bonus. The technology bonus is paid if CHP is applied and biomass is transformed by thermo-chemical gasification or dry fermentation, the biogas produced is processed to natural gas level quality or electricity is gained from fuel cells, gas turbines or other applications, which are defined in BGBL.2004, § 8 (4).

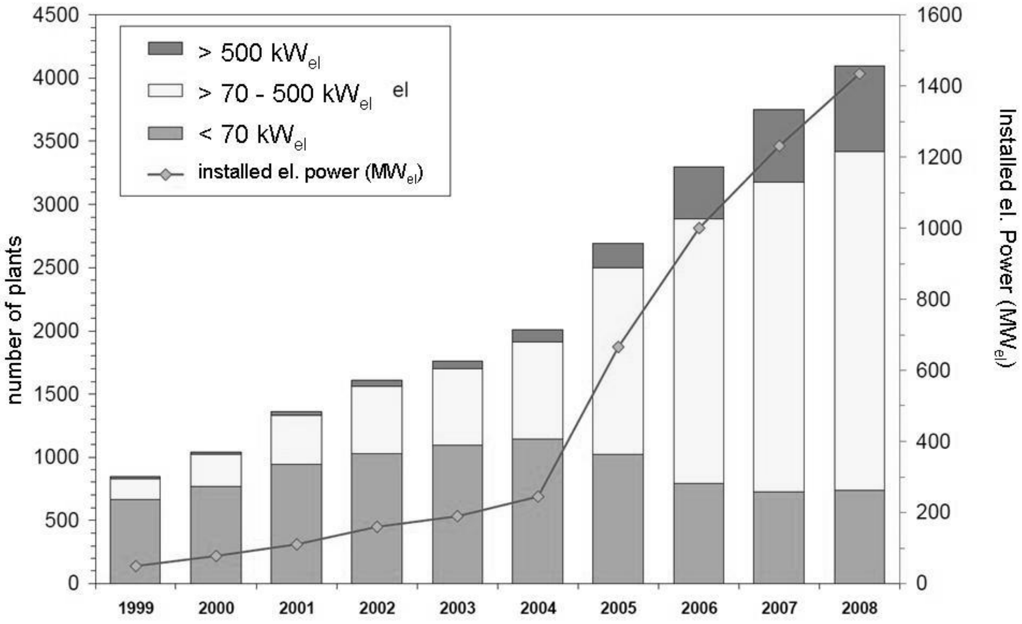
Table 1: Feed- in tariffs for EEG 2004

	$\leq$ **150 kW$_{el}$**	$\leq$**500 kW$_{el}$**	$\leq$ **5 MW$_{el}$**	**5-20 MW$_{el}$**
Basic feed-in tariff	10.67	9.18	8.25	7.79
NaWaRo bonus	6	6	4	0
Manure bonus	0	0	0	0
Bonus CHG*	2	2	2	2
Technology bonus	2	2	2	0
max. possible revenues from EEG (€ cent / kWh$_{el}$)	**20.67**	**19.18**	**16.25**	**9.79**

Source: BGBL.2004 ** CHG = Combined Heat and Power Generation*

As a consequence of the EEG 2004, energy production from biogas increased considerably with the installed electric power increasing from 190 MW$_{el}$ in 2003 to 1450 MW$_{el}$ in 2008 (see Figure 1).

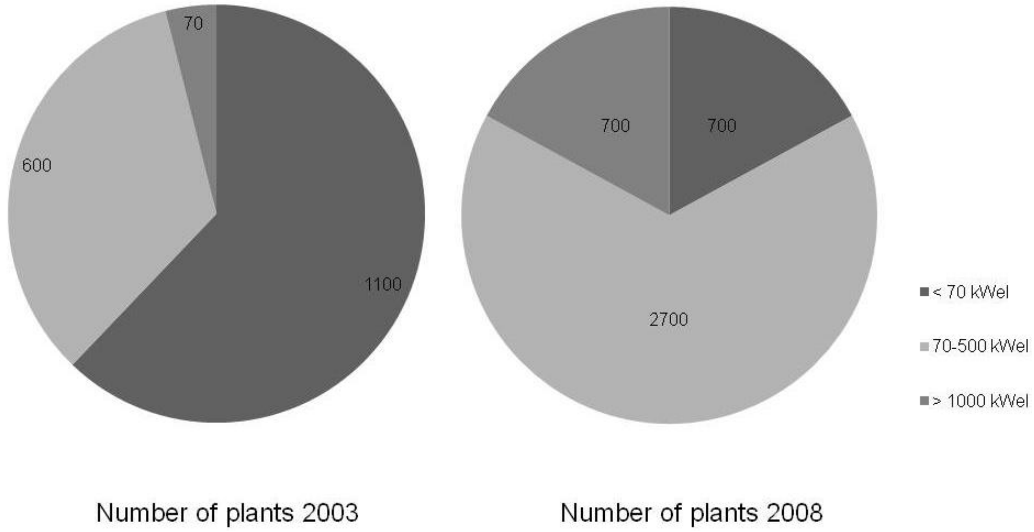
Figure 1: Installed electric power and share of different plant sizes



Source: modified after TRÄHN ET AL. 2009, p.18

Not only have more biogas plants been constructed, but their average plant size has also increased. The technology bonus supported the development of technologies for processing of biogas and feeding it into the natural gas grid, which is only profitable for large scale biogas plants. This development is illustrated in Figure 2. The number of plants with capacities between 70 and 500 kW_{el} increased from 600 to 2700 while their share on the total number of plants also grew from about 33% in 2003 to 64% in 2008 (dark grey field in Figure 2), whereas the number of plants smaller than 70 kW_{el} decreased from 1100 to 700 and the share declined from 62% to 17% in the same period of time (light grey field in Figure 2).

Figure 2: Number of biogas plants of different plant sizes in 2003 and 2008



Source: data from S*CHLOWIN ET AL. 2007b, p. 74*

For the time period from 1999 to 2008 this development is illustrated in Figure 1. Given that medium-sized plants (500 kW_{el}) were favoured by FITs, differentiated according to plant size by the EEG 2004, plant sizes between 70 and 500 kW_{el} in particular were constructed. Starting from a lower base, the number of large scale plants (capacities of more than 500 kW_{el}) increased as well.

The version of the EEG 2004 aims to achieve a 12.5% share of renewable energies for electricity production by 2010 and 20% by 2020. In order to meet the target of a 27% share of renewable energies for electricity production (BMU 2007), the 2020 target was even raised with the EEG 2008, which aims to increase the share of renewable energies for total electricity production to at least 30% by 2020 (BGBL 2008). With rising food prices in 2007/2008 and therefore higher input costs, the EEG was amended in 2008, taking effect in 2009. Due to higher tariffs for the use of CHG, the sum of FITs was increased for all plant sizes. In addition, to provide an incentive to use a larger share of waste materials in order to reduce competition for land, small scale plants using 30% manure receive a special bonus. Comparing Table 1 and Table 2, small-scale plants especially benefit from the amendment if they are able to claim all tariffs paid if all requirements are fulfilled.

Table 2: Feed- in tariffs for EEG 2008

	≤ 150 kW$_{el}$	**≤500 kW$_{el}$**	**≤ 5 MW$_{el}$**	**5-20 MW$_{el}$**
Basic feed-in tariff	11.67	9.18	8.25	7.79
NaWaRo bonus	7	7	4	0
Manure bonus	4	1	0	0
Bonus CHG	3	3	3	3
Technology bonus	2	2	2	0
max. possible revenues from EEG (€ cent / kWh$_{el}$)	**27.67**	**22.68**	**17.25**	**10.79**

Source: BGBL.2008

In an interim report on electricity production from biogas, TRÄHN ET AL. (2009) state that the amendment of the EEG 2008 establishes considerable incentives for a further extension of biogas production, which is focused on plants up to 150 kW$_{el}$, while processing of biogas for introduction into the gas grid is expected to grow (TRÄHN ET AL. 2009, p. 18).

Along with the increase of biogas production, demand for inputs increases as well. It is assumed that in 2009, 530,000 ha have been used for the cultivation of inputs for biogas production (FNR 2009), accounting for approximately 5% of total agricultural land in Germany, or about 1/4 of what the EU subsidises as renewable energy area. To better understand the influence of biogas production on shaping land use, some background on biogas production is provided in the next section.

1.1.2 Background on Biogas Production

Biogas can be produced from a wide variety of input sources. Due to its cost efficiency, the dominating feed-stock observed in reality is maize which is often combined with manure and grain (see e.g. SCHLOWIN ET AL. 2007b). SCHULZE STEINMANN & HOLM-MÜLLER provide an explanation of this. According to the concept of von Thuenen Rings, the profitability of different inputs for biogas production is calculated and it can be shown that despite high transports costs of maize, its land rent (von Thuenen's "Lagerente") is the highest up to a transport distance of 24 km. At longer distances grain is the most profitable input (SCHULTE STEINMANN AND HOLM-MÜLLER 2010, p. 8ff).

Maize (in the following called maize) is cultivated on fields surrounding a biogas plant and the harvest can be stored centrally at the biogas plant or de-centrally on the field. Biogas plants using manure are usually located in the direct vicinity of livestock or dairy farms. Alternatively small amounts of manure are transported to biogas plants to improve their fermentation performance. After fermentation, residue has to be transported back to the field and is used as a substitute for fertiliser. The German regulation on fertiliser (BGBL 2007) restricts the application of farm fertiliser on cropland to 170 kg N/ha (BGBL 2007 DüV § 4), whereas the application of residue from renewable raw materials (NaWaRo) needs to be in line with "good agricultural practices". Therefore, farmers are obliged to measure ammoniacal nitrogen and nitrogen every year and phosphate every sixth year in order to detect available nutrients in soil. Based on these analyses, farmers fertilise as needed (BGBL.2007 §3). If a plant is fed with a certain share of manure the restriction of 170 kg/ha N is only charged in proportion to the manure share.

The biogas produced can be used in different ways. One option is to directly produce electricity and CHG in a block heat power plant (BHPP). CHG is the simultaneous production of power (e.g. electricity) and heat (FNR 2006, p.19). The biogas produced is almost entirely used for the direct production of electricity in motor-BHPP (HOFMANN ET AL. 2005, p.75). For the heat generated (thermal energy), suitable heat sinks (e.g. buildings that require heat) need to be found. Another option is to feed upgraded biogas into natural gas pipelines and transport it to locations with better opportunities to use heat. This increases the energy efficiency, but is only possible for large-scale biogas plants due to high processing costs which can only be off-set if economies of scale are utilised.

Besides potential benefits of biogas production, some negative impacts might arise. Against this background the problem statement for the thesis is discussed in the following section.

1.1.3 Problem Statement

With rising food prices in 2008 and resulting discussions on competition of land for energy or food production and several studies that question positive CO_2 balances of bioenergy and biofuels in particular (e.g. QUIRIN ET AL. 2004, ZAH ET AL. 2007, BANSE ET AL. 2008, AL-RIFFAI ET AL. 2010), the use of biomass for energy production is increasingly criticised. In the case of energy production from biogas, less CO_2 is emitted along the process chain compared to energy produced for the German energy mix[1] (see e.g. life cycle assessments by SCHLOWIN 2006, FRISCHE ET AL. 2007, ZIMMER ET AL. 2008). However, biogas production bears the potential to cause negative environmental effects on a regional scale, including production of monocultures and increasing transport volumes (EEA 2006, p.24ff, SRU 2007, p.2). Cultivating maize for large-scale biogas production in particular might increase transportation from fields to biogas plants, which therefore may cause higher CO_2 emissions due to fuel consumption.

An amendment of the EEG in 2008 aims to increase the share of manure, a waste product from livestock or dairy production to reduce the share of maize as input for biogas production. However, maize production might increase: in areas with a high density of livestock, maize production for feedstock is high, while these areas additionally have problems with high nitrogen surpluses already. The EEG 2008 might cause additional pressure on nutrition surpluses in soil and a higher share of maize production on arable land. Therefore, there is a conflict between the goal of climate protection and negative regional environmental impacts.

As a result, with the different versions of the EEG favouring different plant sizes and technologies, the distinctive design of policy options is of interest. In order to analyse effects of land use change and transport emissions caused by

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[1] In 2008, electricity in Germany was produced from 23.7% lignite coal, 23.3 % nuclear plants, 19.6% hard coal, 13.5% natural gas, 10.5% wind and water energy, and 9.4% others (STATISTISCHES BUNDESAMT 2009)

biogas production, suitable tools need to be applied to simulate policy options. Therefore, it is important to analyse how and where biogas plants will develop in the future, and what environmental effects this will have.

In the following section, the current state of this new field of research is briefly summarised. The outcomes represent research questions which are addressed in this thesis.

1.2 Current State of Research and Resulting Research Objectives

In the past, different types of agricultural models have been applied to capture effects on competition for primary factors, to analyse welfare impacts and assess the environmental externalities arising from bioenergy policies focusing on first generation biofuels (e.g. LAMPE 2007, HERTEL ET AL. 2008, AL-RIFFAI ET AL. 2010). Feedstock demand for first generation biofuels relies on existing marketing channels for cash crops such as cereals or oilseeds, and thus can be integrated into existing economic simulation models for agriculture to assess social, economic and environmental impacts arising from changes in policies or markets.

Land use change caused by biogas production in Germany, is addressed by GÖMANN ET AL. (2007), who analyse changes in maize production and its influence on the cultivation of other crops under the EEG 2004. They assume a unified price for maize in Germany’s NUTS 3 regions (Nomenclature of Territorial Units for Statistics)[2] and calculate an area of 1.5-1.8 mio. ha of maize production for the year 2010, which mainly crowds out grain production (GÖMANN ET AL. 2007, p. 267). These simulations are performed with the Regional Agro-environmental Information System (RAUMIS), which has been developed by HENRICHSMEYER ET AL. (1996). RAUMIS is a partial supply model which displays German agriculture based on a regionally differentiated process analytical approach. The agricultural sector is divided into approximately 40 activities and produce more than 50 products. The model is based on data by official German agricultural statistics, technical input-output coefficients, cost estimates, data from a network of representative farms and various other calculation data and represents 326 so-called “modelling regions” which are derived from the German NUTS 3 regions.

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[2] For a description see: http://ec.europa.eu/eurostat/ramon/nuts/basicnuts_regions_en.html

Independent of each NUTS 3 region, RAUMIS simulates the supply of agricultural products at given prices for agricultural inputs and outputs, production technologies for the different agricultural production processes and agricultural resource endowment. In a non-linear objective function it maximises the product of per unit profit margins of an activity (e.g. production of a certain crop) and the level of each activity (e.g. the amount of the produced crop). In this setting maize for biogas production will compete for land with other crops, and additionally interact with the agricultural production program via organic fertilising and feeding. Accordingly, the supply curves for maize take into account the adjustment of the farming program including opportunity costs.

However, biogas production from agricultural biomass is mainly based on bulky raw products with much higher per unit transport costs and small-scale, localised demand. The latter influences location decisions for biogas plants which are driven to a larger degree by regional differences in transport and production costs of feedstock, especially if there is little spatial variance in other important factors such as output prices, investment costs and other operational costs. Location decisions in turn will drive regional markets for bioenergy feedstock, and interact with the market for cash crops, requiring an integrated assessment of both types of markets.

As far as can be determined within this work, there is currently no tool available to simulate changes in feedstock demand and supply arising from the EEG or variants thereof. Consequently, environmental effects of these changes have not been analysed.

As a result, the research objective is to analyse environmental effects of different policy options by applying an integrated assessment of land use change in Germany. This objective can be broken down into the following key research objectives:

(1) *Analyse regional land use changes caused by various policy settings*. The objective of this part is to simulate regional maize markets and the share of maize cultivation on arable land in order to show effects on land use in regions with different characteristics in Germany caused by various support measures for biogas production.

(2) *Analyse transport emissions for biogas production caused by different policy settings*. This part aims to address CO_2 emissions from the transportation of inputs and outputs from biogas production, which

depends on plant sizes, locations and inputs used. As profitable plant size and location varies with incentives set by policy makers, the objective of this part is to compare policy settings in terms of CO_2emissions.

(3) *Draw conclusions on potential trade-offs resulting from biogas production under different policy scenarios.* The support of biogas production aims to fulfil various targets, e.g. climate protection, nature protection and reducing macroeconomic costs of the energy supply. Potential trade-offs between these targets are elaborated in this part of the thesis.

Therefore, this thesis discusses future development options of biomass and biogas plants as well as resulting environmental effects and contributes to the ongoing political debate of the pros and cons of bioenergy production.

1.3 Structure of the Thesis

In order to address these research objectives, the thesis is divided into two main sections: (A) *The development of a location model in order to derive regional maize demand functions and coupling it with RAUMIS* and (B) *The simulation and analysis of policy instruments which promote biogas production with respect to environmental effects.* An integrated assessment framework is established prior to simulating policy options. Results show regional changes in land use, as well as CO_2 emissions from transportation, which are compared for the policy settings.

Chapter 2 focuses on the theoretical background for the development of a location model. Literature on the choice of location provides the basis to derive a suitable model as well as to establish necessary parameters for the model.

In Chapter 3, based on specific literature on other applications of location models, the requirements of a suitable location model for the problem at hand are elaborated. This in turn sets the framework for the location model ReSI-M, which is described in detail. In this chapter underlying data is presented and the performance of the model is discussed against some sensitivity analysis.

Chapter 4 begins with a description of the applied scenarios for policy assessment and a detailed literature review of the environmental effects of biogas production. To assess land use change and environmental effects caused by different policy options, an integrated modelling framework consisting of ReSI-M and RAUMIS is applied and results are discussed.

The thesis concludes with chapter 5, in which the findings on land use change, transport CO_2 emissions and the efficiency of subsidies paid in different policy settings are summarised. Based on them, policy recommendations are drawn. Finally, the approach of the thesis is discussed and fields for further research are suggested.

2 Theoretical Background to the Location Model

To develop a location model for the problem at hand, a suitable model is derived from existing theory in this section. The necessary parameters to feed the model are identified and the model is then applied for the locating of biogas plants.

Questions about the optimal location, the optimal number and size of processing plants as well as about where the raw material can be acquired have a long history in research. The classical location theory (CHRISTALLER 1933, WEBER 1909, VON THÜNEN 1826) explains location decisions by differences in transport costs of input and outputs. These theories have been criticised for losing their explanatory power due to decreased transport costs. GLAESER AND KOHLHASE (2004) argue, for example, that the cost of moving industrial goods has declined by over 90% in real terms over the twentieth century (GLAESER AND KOHLHASE 2004, p.197). But in the agricultural sector, where perishable products are transported and specialised handling is required, transport costs remain an important cost factor (BUTLER ET AL. 2005). Additionally, the relative importance of transport costs may again increase with rising crude oil prices, duties and environmental regulations (BOYSEN AND SCHRÖDER 2006, p.152).

Location theory deals with two major questions: how does a company's location influence its economic success and what are its impacts on the surrounding area (MAIER AND TÖDTLING 1995, p.21), as companies are open systems connected with their environment in several ways. MAIER AND TÖDTLING (1995) have identified input availability and output markets as key determinants of where to locate facilities. Many of these determinants depend on location and thereby influence the selection of an appropriate location.

Studies on plant or facility location problems are mainly based on the work of WEBER (1909), and first numerical simulation models were developed in the 1960s.

An overview of applications and theory of plant location models is provided in DREZNER AND HAMACHER (2002) and KLOSE AND DEXL (2005), for example. For the modelling of biogas plant size and location to derive demand functions on NUTS 3 level, we look for a model that allows for the explicit inclusion of driving distances, but we do not need to know the exact location of a plant within a region. Furthermore, we require a model in which elastic demand is assumed and transport costs are able to be adjusted depending on the amount of inputs used. The model should run at one stage for one product, we assume that input data is known, and demand allocation does not need to be measured though delivery tours. The characteristics of location models and their classification are displayed in Table 3 and explained in detail in the following section.

Table 3: Classification features of location models

Category	**Characteristics**
1) The shape or topography of a set of potential plants	Homogenous space (continuous location problem)
	Network of given demand and facility locations (discrete location models)
	No metric distances, set of given potential plants (mixed-integer programming models)
2) Capacity constraints	Uncapacitated (no restriction in demand allocation)
	Capacitated (demand restricted, allocation of demand essential)
3) Objectives	Minimise costs (minimise average distances or minimise maximum distances)
	Maximise profit
4) Stages	Single (one hierarchical stage)
	Multiple (flow of goods covering several hierarchical stages)
5) Products	Single (several products can be aggregated to a homogenous product)
	Multiple (heterogeneous)
6) Demand	Elastic (relationship between, e.g., distance and demand has to be explicitly considered
	Inelastic (demand is independent of spatial decisions)
7) Input data	Static (optimise system performance for one representative period)
	Dynamic (data varying over time within a given planning period)
8) Knowledge about input data	Deterministic (input is assumed to be known with certainty
	Probabilistic (input is subject to uncertainty)
9) Demand allocation	Measured in isolation for each pair of supply and demand points
	Measured through delivery tours

Source: Compilation according to KLOSE AND DEXL (2005)

The first category refers to the topography of sets of plants. Depending on the topography, sets of potential locations can be distributed a) continuously in the (solution) space; they can be located on b) certain points of a network; or the c) structure of plants is only implicitly taken into account by using measures such as transport distances without knowing where a plant is constructed.

These three characteristics yield a categorisation of models in the plane (continuous location models), network location models, and discrete location models or Mixed-Integer Programming Models (see e.g. KLOSE AND DEXL 2005, KLOSE 2001, DREZNER AND HAMACHER 2002).

Continuous location problems are characterised by a solution space described by continuous variables where each point in space represents a feasible location (DREZNER AND HAMACHER 2002, p. 37). Continuous location problems minimise the sum of distances between locations and given demand points (KLOSE AND DEXL 2005, p. 5) while distances are measured by a suitable metric (KLOSE 2001, p. 13). Metrics are distance functions which define a distance between elements of a set, whereas a set with a metric is called a metric space. An example is the classical Weber problem, which aims to minimise distances between single plants (which are defined by calculated coordinates in space) and given demand points (KLOSE AND DEXL 2005, p. 6).

Discrete location models or network location models are based on a network of given demand locations and locations of existing or possible facilities. A network can be based, for example, on a road system, and clients to be supplied are based on crossroads. Transports run along the road, whereas distances are measured in the length of the path to which transport costs are proportional. Network location models can be subdivided in terms of distance into “maximum distance models” (equity objective) and “total or average distance models” (DREZNER AND HAMACHER 2002, p. 82).

Mixed-Integer Programming Models (MIPM) start with a given set of potential facilities, and there are no metric distances. A clear distinction of network location models and MIPM is not possible because the former can be stated as discrete optimisation models (KLOSE AND DEXL 2005, p.8). While parameters such as the structure of potential facilities and distance metric are explicitly taken into account by network location models, MIPM use them as exogenous input parameters. Therefore, these models do not consider the exact location (coordinates) of plants, consumers and driving distances, but include transport costs between consumers and plants. MIPM can be divided into uncapacitated and capacitated facility location problems (CFLP) (KLOSE AND DEXL 2005, p. 8ff), which means that a problem can be formulated with or without capacity restrictions (second category in Table 3). In the case of no capacity constraints there are no restrictions in demand allocation, but if capacity constraints of plants need to be taken into account, demand needs to be allocated carefully, as it is necessary to examine whether single-sourcing (goods are provided from one plant) or multiple-sourcing is essential. A CFLP minimises the costs of satisfying the given demand of consumers d_j which are characterised by their location. Thereby it simultaneously determines the shipments x_{ij} from plants y to consumers and the number of plants of a certain size at each possible plant location. The latter are integer variables and turn CFLP into mixed-integer problems.

$$\min\left(\sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} + \sum_{i=1}^{m} f_i y_i \right)$$

$$\begin{array}{lll}
\text{s.t.} & \sum_{j \in j} d_j x_{ij} \le s_i y_i & \text{for all j} \in \text{J} \\
 & \sum_{j \in J} x_{ij} = 1 & \text{for all k} \in \text{K} \\
 & x_{ij} - y_j \ge 0 & \text{for all k} \in \text{K and j} \in \text{J} \\
 & 0 \le x_{ij} \le 1, 0 \le y_i \le 1 & \text{for all k} \in \text{K and j} \in \text{J} \\
 & y_j \in \mathbb{B} &
\end{array}$$

Each facility $i \in I$ has the fixed cost fi. Every customer $j \in J$ has a demand d_j, and c_{ij} is the unit transportation costs from i to j. Due to scarce capacities s_i shipments are limited (cp. KLOSE AND DREXL 2005).

MIPM differ only slightly from network location models, as they can be stated as discrete optimisation models by defining discrete locations of potential plants. The difference is that network location models explicitly consider the structure of the set of potential plants and the distance metric whereas MIPM use input parameters such as transport costs without addressing the origin of these costs (KLOSE AND DREXL 2005, p. 8).

The third category in Table 3 is the objective according to which a problem is solved. The distribution of plants can be optimised by, for example, minimising costs or maximising profit. EISELT AND LAPORTE (1995) discuss possible objective functions in different location-optimisation problems. In order to derive the main categories of objectives, they first distinguish between private and public plants and then classify objectives by “pull objectives”, “push objectives” and “balancing objectives”. Pull objectives are based on the assumption that that the plants are desirable. In contrast, push objectives are assigned to undesired plants such as noisy or dangerous plants from which customers and the public seek to stay as far away as possible. The third category addresses issues such as equity and offers solutions based on the value system of a decision maker. An example would be to locate a school such that all pupils face equal driving distances. Which objective to choose depends on other components of the location problem at hand. EISELT AND LAPORTE (1995, p. 156) discuss the objectives in the case of a central planner and several customers. At inelastic demand, no competition and desirable plants, consumers will use any one of the planner’s plants, most likely the closest. Hence, if the plant covers transport costs, the planner will open as many plants as necessary to minimise the sum of plant and transport costs. If the number of plants is fixed, the objective then is to minimise costs. In the case of elastic demand, the number of plants to construct is a variable and the planner aims to minimise costs. If the number of plants is fixed, the planner might have the objective of maximising the area covered by the plants, whereas he may seek to minimise the area affected by a plant or maximise the distance between the plant and the local population in the case of an undesired plant. Regarding pull objectives, the “minisum objective”, in which the sum of weighted distances is minimised, is a common choice for public and private objectives, as long as cost functions are linear (EISELT AND LAPORTE 1995, p. 156) and arise in profit-maximising contexts: if the profit function consists of revenue (price times demand) minus the variable and fixed costs minus transport costs (per unit transport costs times demand) for any set of fixed prices, revenue and production costs are fixed. Therefore, profit is maximised when transport costs are minimised (dual problem) (EBID.).

This applies to the problem at hand: regional demand for electricity from biomass cannot be considered as inherent; the specific policy program EEG rather defines completely elastic demand at any location. That calls for a modified CLFP which looks at profits rather than costs. Specifically, taking into account that setting up a new biogas plant is an investment decision, we assume the location decisions is based on returns on investment (ROI) over the planning term rather than on absolute profits for a given plant size at a given location. Reviewing plant location problems, REVELLE AND LAPORTE (1996) lead us to formulate the location problem under the ROI objective, where ROI is the net present value of annual returns over the plant's lifetime divided by the initial investment. The annual return is the revenue minus costs of manufacturing distribution (REVELLE AND LAPORTE 1996, p. 866).

Another category is classified according to processing stages. The CFLP previously described depicts the case of only one explicitly modelled processing stage. Multi-stage models deal with the flow of goods covering several hierarchical stages. A stage might consist of an operation such as the procurement of raw material, fabrication of parts, or assembly. After the first stage, the output is used as input for the following stage.

The fifth category deals with characteristics of the products. In the CFLP model it is presumed that a plant produces one product only and a given set of candidate sites for the location of the facility is considered. If more than one product is produced, these models are called multi-product models. They are characterised by products whose effects on the design of the distribution system need to be considered. A linked category is the homogeneity or heterogeneity of products. Demand, costs and capacity for several products are aggregated to a single, homogenous product in single-product models. An example is the production of screws and nails, which are produced differently but at equivalent costs, as the inputs and distribution systems are comparable.

A further category is demand, which in models can be assumed to be elastic or inelastic. Inelastic demand implies that demand is independent from spatial decisions, whereas for elastic demand, the relationship between, for example, distance and demand has to be considered explicitly (KLOSE AND DREXL 2005, p. 5). If demand is elastic, a model which is designed to minimise costs cannot reflect price changes due to higher transport costs. Therefore at elastic demand, cost minimisation has to be replaced by, in this case, profit maximisation (KLOSE AND DREXL 2005, p.5).

The allocation of demand is another category to classify models. Quality of demand allocation is usually measured in isolation for each pair of supply and demand points, which could cause problems with the separate calculation of delivery costs if demand is met through delivery tours.

Data input into models faces uncertainty. As a result, we can assume to possess knowledge of inputs with certainty (deterministic models) or we can presume that input is subject to uncertainty (probabilistic models). A further characteristic of models is static or dynamic behaviour, whereas static models involve one time period and dynamic models include data that varies over time within a given planning horizon.

Against this background on location models, the development of a location model for the problem at hand is described in the following chapter.

3 Development of a Location Model[3]

In this chapter the location model ReSI-M and its performance are explained. Besides exemplarily showing results for demand functions and regional market clearing quantities and prices, this section provides detailed motivation for the chosen method and discusses underlying data and parameters including a sensitivity analysis for key parameters. Furthermore, the modelling results are validated by comparing the resulting plant structure with the plant structure and distribution of existing and simulated energy production in Germany in 2008.

3.1 Problem Setting and Relevant Studies

The objective of the location model is to determine the total feedstock demand *d* for regions *r* at given feedstock demand prices *w*. Total regional demand *d* equals the sum of plant type *t* specific feedstock demand *x* times their location-specific number *n*:

$$(1) \qquad d_r(w) = \sum_t n_{r,t}(w)\, x_t$$

The plant types are characterised by the given size and feedstock mix. The number of plants *n* of a specific type *t* erected at location *r* depends on their operational profits π which are defined as the difference between revenues - output *y* times price *p* -, operational costs *oc* net of feedstock, and feedstock costs. The latter are equal to the given input demand *x* multiplied by the sum of per unit transport costs *tc* and feedstock price *w*.

$$(2) \qquad \pi_{r,t} = y_t p_t - oc_t - x_{r,t}(tc_{r,t} + w)$$

Per unit transport costs *tc* depend on the regional availability of feedstock, which is determined by regionally differing “location factors”. These are feedstock yields as well as the share of arable land on total land, the spatial

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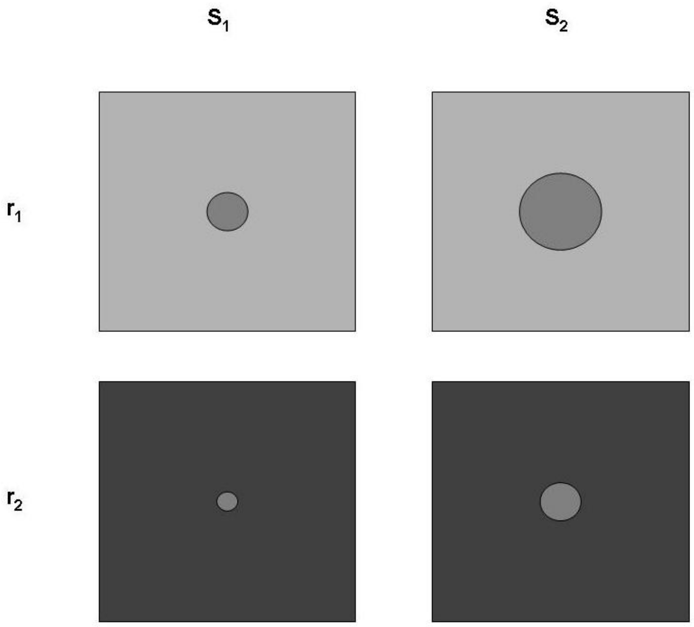
[3] Parts of this chapter were used in the paper: “Modelling regional input markets with numerous processing plants: The case of maize for biogas production in Germany” by DELZEIT, R., BRITZ, W. AND HOLM-MUELLER K. submitted to Environmental Modelling and Software.

distribution of this share and the amount of feedstock that is already used. This spatial distribution determines the homogeneity of a region.

In order to illustrate how location factors impact optimal plant size, Figure 3 shows a hypothetical example with plants of two size classes s_1 and s_2 shown in the columns and two regions r_1 and r_2 in the rows. The intensity of the background colour relates to average feedstock availability of the regions, whereas the circles indicate the necessary harvest areas to feed the plants. Clearly, transport costs *tc* per unit of feedstock demand are higher in r_2 and for plant s_2. Accordingly, profits by plant size may be ranked differently in regions depending on feedstock availability. Equally, differences in regional feedstock prices may have an impact on the ranking.

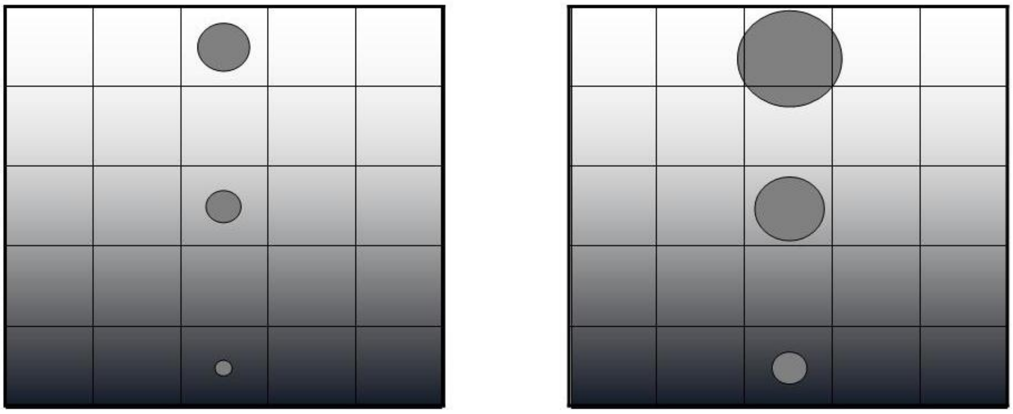
Figure 3: Feedstock availability and related harvesting area



However, as long as some feedstock is left, adding more plants would not change profitability for the different sizes, as the harvest area for each region, size and therefore transport costs are fixed. Total feedstock demand could simply be derived by first determining the most profitable plant size and then calculating the maximal number for that size possible from feedstock supply *s* at given feedstock price *w*. Unused regional feedstock quantities could then be eventually used for smaller sized plants with a lower profit.

For the problem at hand, feedstock demand per plant is small compared to maximal feedstock supply quantities s_r, so that a large number of potential plants must be investigated. Moreover, data suggests that feedstock availability within the regions differs considerably, as shown by the grey gradient in Figure 4. Accordingly, harvest areas vary within regions depending on feedstock density. Investors will now start to erect plants at such locations where feedstock availability is high and consequently transport costs low. Transport costs *tc* become a function of plants already erected. The final problem setting adds complexity to Figure 4 in that several regions are optimised together while allowing plants to acquire feedstock from any of them.

Figure 4: Influence on harvesting area of intraregional feedstock availability



Existing literature (for an overview of methods used in location optimisation, see e.g.: KLOSE 2001, DREZNER AND HAMACHER 2002, KLOSE AND DREXL 2005) does not directly offer a method to solve our problem setting efficiently. Classical solutions to combined location and capacity problems (cp. MELKOTE AND DESKIN 2001, AARDAL 1998) work with a distinct, pre-defined number of locations in space, and are solved as Mixed-Integer Linear Programming Problems in which per unit transport costs are given. BOYSEN AND SCHROEDER (2006) provide a typical example of determining simultaneously optimal sizes and locations of dairies for ~350 regions covering Germany, taking regional milk supply as given. The model is formulated as a Mixed-Integer Linear Programming Problem and solved by combining Genetic Algorithms with Tabu Search. These problems are classified as NP-hard (non-deterministic polynominal time-hard) problems, indicating that the computational efforts increase exponentially with the size of the problem (DOMSCHKE AND DEXEL 2005, p. 125).

MAHLER (1992) provides an analysis for German sugar beet and raw sugar production, simultaneously minimising production costs of sugar beet and sugar for fixed total German sugar output, analysing simultaneously 157 potential locations, different plant sizes and lengths of the harvesting and processing period for the sugar beet.

For the problem at hand these approaches are unsuitable without further modification and extension as they first of all do not deal with a continuous spatial distribution of feedstock availability and its consequences on transport costs, and secondly take either feedstock supply or output demand as given.

Approaches which define an optimal location in a continuous space typically only look at a single or a rather limited amount of potential plants. In his pioneering work in 1963, out of seven potential pear packing plants, STOLLSTEIMER (1963) simultaneously determined which of those plants, characterised by size and location, would be chosen. Extensions of that approach are found in supply chain optimisation, where locations are optimised along the chain, either minimising total chain costs or maximising chain profits (see e.g. ALLEN ET AL. 1998, GRONALT AND RAUCH 2007, HIGGINS AND DAVIES 2005 AND SEARCY ET AL. 2007). These approaches assume a central planning instance to determine an overall optimal industry structure and are therefore not applicable for our example, which deals with many small-scale, private, uncoordinated investment decisions. In addition, these frameworks most likely cannot be solved numerically for the number of possible combinations in our analysis.

In summary, the problem at hand calls for an algorithm that (1) is efficient for a high number of potential plant type-location combinations, i.e. is not NP-hard, (2) does not set the quantities of supply and demand of inputs or of output as given, (3) considers intra-regional distribution of input availability and (4) does not assume a central planner. None of the algorithms used in the aforementioned studies fulfils already conditions (1) – (3), with (4) introducing a different behavioural model.

Therefore, we propose a relatively simple, but efficient solution algorithm to the problem of determining the number and locations of plants at given feedstock prices and maximal feedstock supply, described by the following iteratively repeated steps:

(1) Determine minimum harvest areas for each plant type at given feedstock density to derive type-specific per unit transport costs.

(2) Determine the profits of each plant type and sub-regional location at given per unit transport costs for feedstock. As explained later on, this involves solving a transport cost minimisation problem for each plant type-location combination, as we are dealing with different feedstocks and sub-regions in the analysis.

(3) Determine the plant type-location combination with the highest return on investment (ROI).

(4) Reduce regional feedstock supply according to the selected type and location and determine from this point the current feedstock density.

(5) Repeat this procedure from step 1 until ROI determined in step 3 falls below a predefined interest rate.

Step 2 above is equivalent to a very simple location model: for each plant type, select the sub-region inside the region under investigation where transport costs are minimal, feedstock demand is satisfied and transports do not exceed feedstock supply. The decision rule in (3) could be replaced by alternatives, as discussed above.

The following section describes the model in more detail.

3.2 Overview on the Location Model ReSI-M

The regionalised location model ReSI-M determines the optimal number of plants, their location in sub-regions and their type, characterised by size and feedstock mix at given feedstock prices, in a sequential process. This is done by iteratively maximising the ROI for biogas plants in NUTS 3 regions inside each German NUTS 2 region, characterised by average sizes of ~900 km². Aggregated across plants, total feedstock at different prices for maize (21-53€/tFW) is determined for each NUTS 3 region, which by interpolation allows for regional feedstock demand curves to be derived.

The framework takes into account important regional factors and their interaction determining the optimal type-location combination of biogas plants: output prices depending on scenario settings, input availability and resulting transportation costs, processing costs, and utilisation possibilities for crude biogas and heat.

The number of plants erected *n* of a specific type *t* in a NUTS 3 region *r* are assumed to depend on plants' *ROIs* which are calculated from yearly operational profit π as defined above and total net present value of investment costs *I* divided by the length of the planning horizon *T*:

$$(3) \qquad \text{—}$$

Transport costs per unit *tc* are specific for a certain plant type, its NUTS 3 location r_1 and the NUTS 3 region from which its feedstock is taken, r_2, as well as feedstock demand of already erected plants. As seen in (4), *tc* depend on three terms. The first term α_t covers the costs of un- and uploading of maize. The second term relates to the driving distance *m* from the location region r_1 of the plant to the procurement region r_2, times the transport costs per unit and km β_t, whereas β_t is type-specific since different sized trucks are used. The third and last term captures the intra-regional transport costs for transporting the feedstock from the fields either to the plant or the starting point of interregional transport. It is calculated by assuming that the plant/starting point is placed in the middle of a circle surrounded by plots covered partially with arable land, from which the feedstock is collected, and partially with other land cover. The radius of the circle depends on three parameters: (I) the plant's given input demand for maize *x*, (II) the maize yield on arable land *e* and (III) the share of arable land on land cover *b*. The square root and the constant π stem from the formula[4] to calculate the radius of a circle from its area.

$$(4)\quad tc_{r_1,r_2,t} = \alpha_t + m_{r_1,r_2}\beta_t + \sqrt{\frac{x_t}{\pi\, e_{r_2}\, b_{r_2,cur}}}\beta_t$$

As transport units do not drive to the boundary of the harvesting area for every ride, the mean driving distance (radius), 2/3 r, is used. The mean radius ( ) is derived from:

$$(5)\quad \bar{r} = \frac{1}{|F|}\int_F |x| dA \qquad \text{with } |F| = \pi R^2,\ |x| = r$$

$$(6)\quad \bar{r} = \frac{1}{\pi r^2}\int_0^R r^2 dr 2\pi \qquad \text{with } dA = 2\pi r dr$$

$$(7)\quad \bar{r} = \frac{1}{\pi r^2}\left|\frac{1}{3}r^3\right|_0^R 2\pi = \frac{2}{3}r$$

The share of arable land *b* varies in each region according to uniform distribution from a minimal share b_{min} to a maximal one b_{max}. Collection costs will be minimal where the share is highest, i.e. equal to b_{max}, defining the location inside the region where the first plants will be erected. The maximal share is reached when the maximal available feedstock d_{max} is used. Accordingly, the current share b_{cur} in an iteration can be derived from the already used feedstock d_{cur}, as seen in equation (8).

$$(8)\qquad b_{r_2,cur} = b_{r_2,\max} - \frac{b_{r_2,\max} - b_{r_2,\min}}{d_{r2,\max}} d_{r2,cur}$$

An overview on ReSI-M is provided in Figure 5, showing exogenous and endogenous factors as well as how the simulation tool iteratively solves the location problems (box). Exogenous parameters include yields, per unit transport costs, as well as other operational costs, output prices for the electricity produced, and maize prices. The amount of feedstock which is transported to a biogas plants ($x_{r,s}$) is an endogenous variable. The main results are regional feedstock demands for maize and manure.

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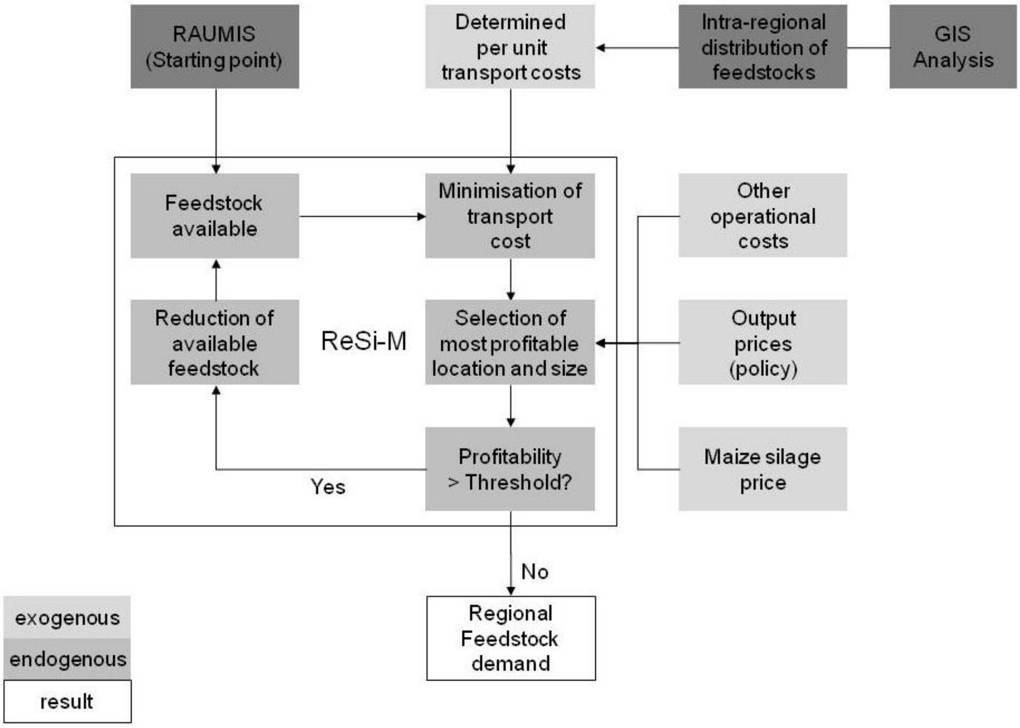
[4] Area enclosed by a circle $A = \pi r^2$

Figure 5: Overview of ReSI-M

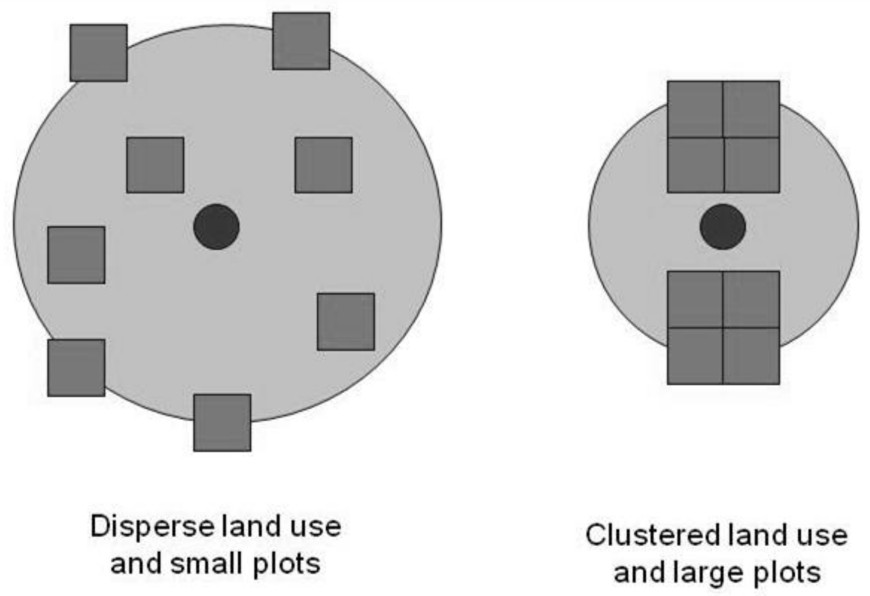


3.3 Assumptions

Given that the EEG guarantees output prices for 20 years after constructing a plant, we take that period as the planning horizon and assume that investments in plants are ranked and realised according to their net present ROI. We distinguish four possible size classes operating with three different manure shares in about 350 administrative NUTS 3 regions inside German NUTS 2 regions. Distinction by size class and manure share is introduced to reflect differences in output prices according to the EEG. Depending on the size of the 35 German NUTS 2 regions and feedstock density, the ROI for several thousand type-location combinations are determined in each region under investigation.

We assume that the transport costs for maize are paid fully by the biogas plant, neglecting eventual transport costs savings by farmers when selling the maize rather then using it for feeding. For transport and storage, a 12% loss is assumed (DÖHLER 2006, p.110). Using data from a Geographic Information System (GIS) on land use, we take different shares of arable land on total land inside the NUTS 3 regions into account so that per unit transport costs increase with rising amounts of used feedstock by already realised plants during the iteration process. Details on the calculation are given in section 3.2. The influence of distribution of arable land is illustrated in Figure 6: on the left hand side plots are distributed disperse, which caused plots to be located isolated. When those plots are harvested, longer distances need to be driven compared to the case at the right hand side, where plots are located in a clustered way.

Figure 6: Influence of distribution of land on field sizes

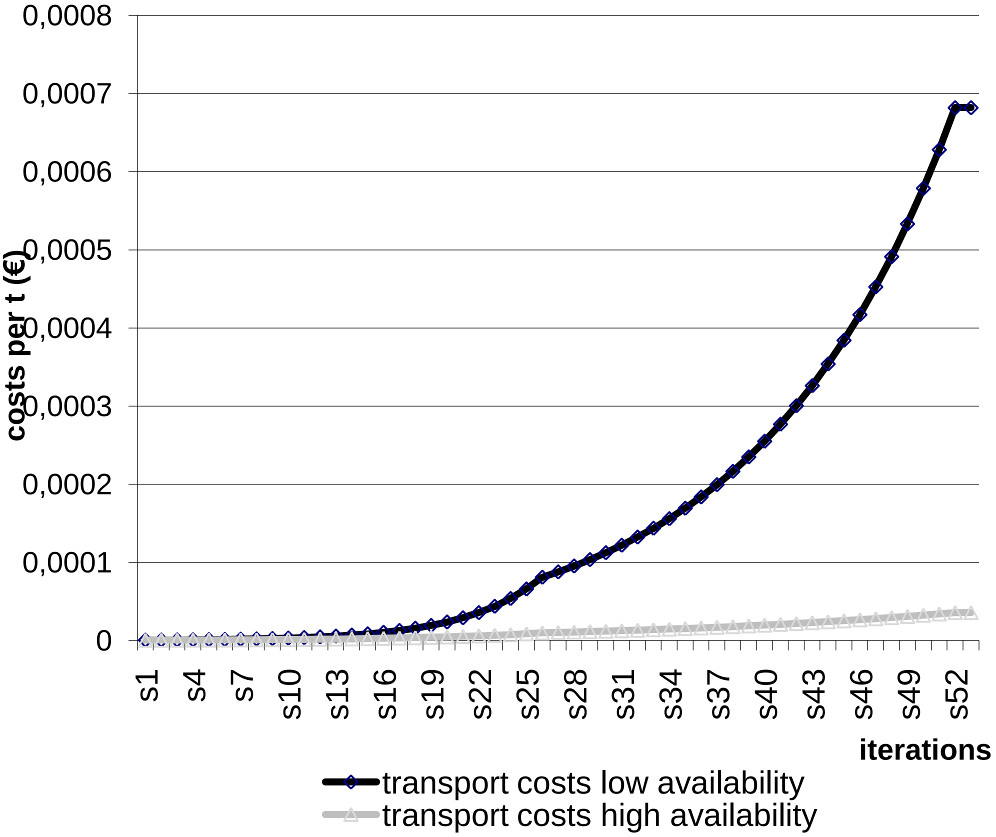


Consequently, we assume that processing plants will first be placed where feed stock availability is high to save transport costs. Consequently, per unit transport costs increase with rising amount of used feedstock by already realised plants during the iteration process.

The market for manure as feedstock operates differently in regions with low and high livestock densities. In some German regions with high stocking densities, farmers are facing costs for manure removal due to the maximum organic fertilising doses. They either have to rent additional land or enter a contract with another farmer to spread their manure. In these regions, we assume that farmers will pay transport costs of manure to the biogas plants. As using manure above a certain share will drive up the guaranteed feed-in price, biogas operators will try to reach this share. We therefore assume that in regions with low stocking densities, transport costs will be fully paid by the biogas plant. As with maize, intra-regional differences in manure availability render per unit transport costs of manure as a function of the amount of manure already used as feedstock for every NUTS 3 region.

As with maize, we use GIS analysis to derive differences in regional stocking densities, and from there, in manure availability to render per unit transport costs of manure as a function of the amount of manure used as feedstock. An example is illustrated in Figure 7. Starting with no transport costs for the first plants constructed, it indicates that costs at a low availability of manure (black line) increase much stronger than in case of a high amount of manure available in a NUTS 3 region.

Figure 7: Transport costs of manure for low and high manure avilability



The crude biogas produced can be used in different ways. The EEG 2004 favours two pathways of usage. The main technology used is based on so-called heat-electricity plants (BHPPs), where electricity is produced with the heat emitted from the engine used locally as a by-product (for details see section 1.1.2). We presume that plants with sizes of 150 and 500 kW_{el} apply this technology. Another pathway is to upgrade crude biogas and induct it into gas pipelines. This allows for production of electricity and heat in a BHPP at another location along the pipeline where heat can be efficiently used. This pathway is only profitable for large-scale plants, which we assume apply this technology. The exact implementation of the different pathways is based on pre-calculations, which determine the most profitable option depending on the plant size and regional availability of gas pipelines and demand for heat for housing.

As we use the year 2004 for our baseline scenario, our calculations are also based on input and output prices prevailing in 2004. We also incorporated the political framework with revenues from the EEG 2004 and can thus compare our results with the current plant structure in Germany (see section 3.8.1).

3.4 Data Source and Processing

Exogenous data to determined π (used in equation (2) and (3)) are taken from literature: data on revenues are defined from electricity prices according to EEG (see Table 1 and Table 22 in section 1.1.1), augmented by heat sales depending on the plant size and degree of combined heat generation.

3.4.1 Production Costs

Production and processing costs for three plant sizes are taken from URBAN ET AL. (2008). The study displays results of a market survey on costs and technologies of biogas upgrading and induction into the gas grid. Underlying assumptions for these costs are described in detail in URBAN ET AL. (2008, p. 84ff). Some crucial assumptions are:

The calculation of capital costs for the biogas plant is static and based on a recovery period of 15 years

- imputed interest rate: 6%
- labour costs are 35€/h
- electricity costs for technical plants are 15ct/kWh_{el}
- 8000 h/a operation hours
- 5250 h/a full load hours of BHPP (block heat power plants)

- electric degree of efficiencies of BHPP: 150 kW_{el} : 33,5%, 500 kW_{el}:37,5% 1000 kW_{el}:39,5%, 2000 kW_{el} :41,7%

These parameters have influence on the amount of annually produced energy in kWh_{el} per year: it is determined by multiplying the plants' capacities (in normal cubic metre (Nm^3)) with the heat of combustion of biogas (kWh_{el}/Nm^3 of biogas), the assumed operating hours and electric degree of efficiency of BHPP.

The study of URBAN ET AL. (2008) does not include data for the size of 150kW_{el}. Thus, we used data from the Association for Technology and Structures in Agriculture (KTBL). As data from the KTBL is categorised differently, only the sums are displayed (ACHILLES 2005, p. 942-944). Assumptions on energy efficiency and maximum operating hours are varied for a sensitivity analysis.

3.4.2 Feedstock Availability

Information from RAUMIS on available manure per NUTS 3 region for the year 2020 is calculated by multiplying the amount of nitrogen secretion of different livestock with a factor of nitrogen content of fluid and solid manure to derive secretion per animal. By multiplying the resulting value with the amount of the respective livestock per region, the amount of solid and fluid manure per type of livestock was calculated. A share of 10% pasture management for cattle was assumed, and subtracted from total amount of manure amount. In addition, it is assumed that development of manure is only profitable at livestocks of more than 30 milk cows or 50 other cattle or 200 picks. Regarding chicken large mass production was presumed. Additionally, RAUMIS provides maize yields at NUTS 3 level.

3.4.3 GIS - Analysis

Geo-referenced data define regional selling possibilities for outputs as well as differences in feedstock availability. Regarding outputs, NUTS 3 regions are classified according to their selling opportunities for heat produced by biogas plants and the possibility of inducting gas into a natural gas pipeline. On the input side, GIS-analysis first excludes urbanised NUTS 3 regions with more than 500/km^2 habitants as possible locations, assuming that zoning laws and low feedstock availability prevent installations of those plants in urbanised areas. This data is provided by the FEDERAL OFFICE FOR BUILDING AND

REGIONAL PLANNING (BBR) and STATISTICAL OFFICES OF THE FEDERATION AND THE LÄNDER (SOFL) (2005).

For the remaining NUTS 3 regions, variances and mean shares of agricultural land are calculated from data provided by LEIP ET AL. (2008), who calibrated data from the European CORINE land cover (CLC) database to national and regional agricultural statistics. Data are available for so-called “Homogenous Spatial Mapping Units” (HSMU) with a resolution of 1x1 km^2 which consider soil, slope, land cover and administrative boundaries as delineation features.

Based on this data, for each NUTS 3 regions, the overall share of arable land on total land area and also the variances of these shares are calculated using the ArcGIS tool box. The data is available for raster cells of one square kilometre, but as raster cells with equal attributes are merged in the data base, they still show variations in size. Thus, the overall share per NUTS 3 region is weighted according to the size of each raster cell. Applying the analysis tool “statistics”, for each German NUTS 3 region, the respective mean shares of arable land on total land as well as their variances are calculated.

Variance and mean for the share of arable land for each NUTS3 region are used to determine the parameters for the Uniform Probability Density Function used in equation (8). This function is defined as:

$$(9) \qquad f(x) = \begin{cases} \frac{1}{b-a} & \text{for } a \leq x \leq b, \\ 0 & \text{for } x < a \text{ or } x > b, \end{cases}$$

where the parameter *a* and *b* denote its maximum and minimum values.

Mean $\bar{x}$ of this function is

$$(10) \qquad \bar{x} = \frac{1}{2}(a+b)$$

and variance of this function is

$$(11) \qquad \sigma = \frac{1}{12}(b-a)^2$$

The calculated shares of arable land on total land is equal to $\bar{x}$. As $\bar{x}$ and σ are gained from the GIS-analysis, we receive *a* and *b*. If we substitute them into the Uniform Probability Density Function we get result in the slop of transport costs (compare section 3.2).

Typical data are found in the following Table 4 for the NUTS 3 regions within the NUTS 2 region “Arnsberg”. Their influence on driving distances is discussed in section 5.1.

Table 4: Exemplary data on land use data

NUTS 3 regions in Arnsberg	Yields (t/ha)*	Mean of share of arable land on total land (%)	Variance of share of arable land on total land
ENQ	61	6	15.1
HSK	63	5.8	4.6
MK	61	4.8	13.8
OE	41	0.9	39.4
SI	65	1.3	0.4
SO	64	34.9	248.2
UNQ	64	28.2	50.4

** from RAUMIS*

3.4.4 Transport Costs per km [5]

Per unit transportation costs per km for maize (α_l β_l, see equations (4) and (5)) are extracted from TOEWS AND KUHLMANN (2007). In this study, three transportation techniques are analysed: a) chaff cutting machine with transport volume of 50.5 cubic meters (m^3), b) chaff cutting machine and tipping trailer with a transport volume of 39 m^3, c) overloading on lorries with a volume of 74 m^3 (TOEWS AND KUHLMANN 2007, p. 36). For the location model it is assumed that plant sizes of 150 and 500 kW_{el} use technique b) where maize is chaff cut on the field and carried by transportation units (haulers of 233 kW) causing costs of 1.5 €/tFW for the first kilometre including up- and unloading and 0.2667 € for each additional kilometre.

Larger plants with 1000 and 2000 kW_{el} are assumed to use technique c) by overloading the chaff cut maize on lorries. The costs for up- and unloading are

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[5] Parts of this section will be used in the paper “Der Einfluss des Standorts und der Anlagengröße auf die Kosten der Gärrestverwertung unter Berücksichtigung möglicher Aufbereitungsverfahren“ by KELLNER,U., DELZEIT. R. UND THIERING, R.

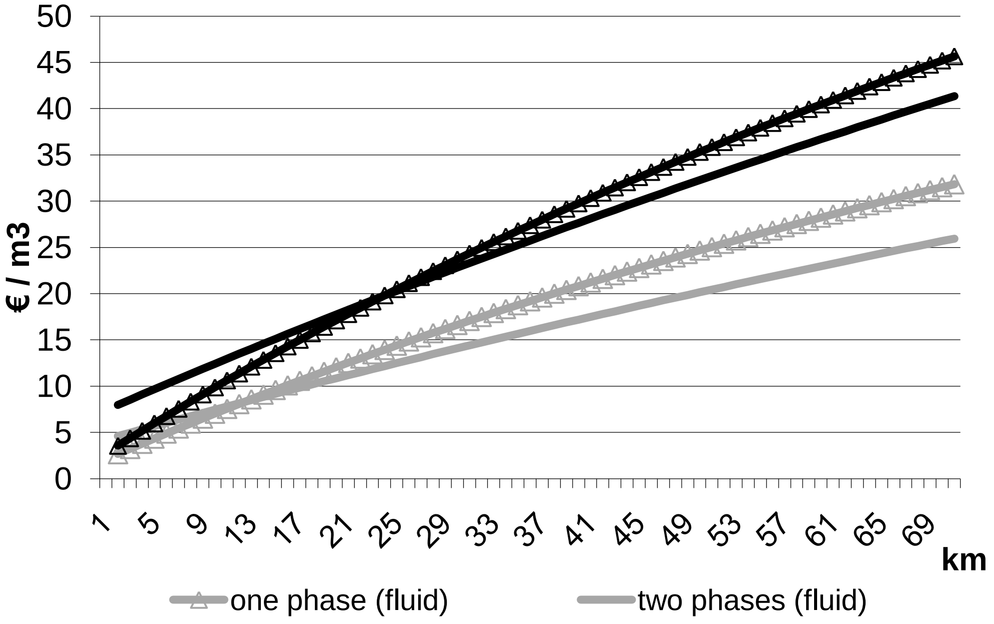
higher with 2.9 € / tFW but are paid off by smaller costs of 0.08333 € per tFW per km (see TOEWS AND KUHLMANN 2007, p.36).

For calculation of per unit transport costs for manure and residues a solid and a liquid phase need to be taken into account. Processing residues basically means to reduce water content. This allows reducing transport costs, but costs for processing arise. Transport and harvesting costs do not only depend on the distance driven, but mainly on time. Another factor, which needs to be considered, is that fast machines usually have a high transport capacity. Hence, when comparing different techniques for application, costs per volume and distance need to be compared.

The application of manure and residues is divided into two techniques: a) transport of residuals and the application itself is conducted by one transport unit, which consist of a tractor and a manure barrel or dung disposer. A second alternative is b) to transport and dispose materials in a separated process. Here, manure can be stored close to the fields or be overloaded from a truck to a manure barrel. We assume that fluid residues have a good flowability and can thus be disposed in the same way as manure, and that the solid phase is comparable to dung.

We calculate transport costs per km for the fluid and solid phase by fixed and variable machinery costs. Charge rates per hour of the machinery association Westfalen-Lippe are applied and the time needed to transport and dispose residues is calculated for each technique. The time for uploading, transport, application and return depends on the distance between fields and plants. Results show that costs in € per tFW increase with field-plant distance, whereas for distances of less than 22 km in case of the solid residues, the transport technique using the same machinery for transport and application (one phase) is cheaper compared to separating transport and application (two phases) (see Figure 8). Costs for transporting the fluid phase per km are lower than transporting solid phase, whereas in case of fluid phase the two-phase-technique becomes more profitable at distances of 12 km.

Figure 8: Costs for application per transport distance of fluid and liquid residues



In order to gain processing costs per m^3 for different processing methods like mechanical or chemical separation we interviewed experts in processing of biogas or owners of biogas plants which process residues. Given that techniques are fairly new and depend on a variety of plant specific factors, interview partners only gave insufficient information regarding processing costs. However, some tendencies could be elaborated: for small-plants, easy and cheap mechanical methods might save transport costs. Systems with a complete processing of residues are not profitable, even for large-scale plants.

Hence, only costs for unprocessed residues are included into ReSI-M, which implies that in particular for large-scale plants, costs for transports of residues might me overestimated. This is especially true as there might be some technological improvements considering that our model time frame is 2020. Today it seems save to say that no more elaborated processing techniques are used on a bigger scale. A detailed discussion on this issue is provided in sections 4.1 on the scenario set up and 5.3 on limitations of the approach.

3.4.5 The Solution Algorithm

The research area of Germany is subdivided into NUTS 2 level regions to which the algorithm is applied. Each NUTS 2 level region encompasses a set of NUTS 3 regions. The breakdown to NUTS 3 matches the regional resolution of RAUMIS. Accordingly, yields and feedstock availability at given prices can be taken directly from RAUMIS, and market clearing prices and quantities for each NUTS 3 region can be calculated by intersecting maize supply curves from RAUMIS with maize demand curves from ReSI-M.

To find the optimal number of plants at a certain size and location, we apply an iterative approach (see Figure 5) as discussed above. During iterations, minimal total transport costs for each location-plant type combination are determined based on solving a simple transport cost minimisation model at the given regional maize and manure availability (see equations (3), (4) and (5)). Assuming a maize price at the field level, the transport costs along with other given data then allow us to define the ROI for each location-type combination.

From all possible locations and plant types, the combination with the highest ROI is chosen in any iteration. The iteration process continues as long as a type-location combination exists whose ROI exceeds an assumed minimum interest rate. Given the simulation tool’s structure, it would also be possible to define other threshold criteria such as absolute profits to stop the iteration process.

Another advantage stems from the design of the iteration procedure: It forces profits to decrease over iterations as feedstock availability decreases and consequently per unit transport costs increase. Accordingly, any location size class combination with a ROI below the threshold in a given iteration will never be realised in any follow-up iteration. That allows for a rapid reduction of many type-location combinations during iterations, speeding up the process further.

NUTS 2 administrative units are solved independently of each other in parallel in a computing grid, each problem simultaneously optimising all NUTS 3 regions in the respective NUTS 2 unit. The speed increase by solving for blocks of NUTS 3 regions instead of simultaneously for all of Germany does however come along with a loss of accuracy as transport flows across NUTS 2 regions are excluded in the first place.

3.5 IT Aspects

In applying our model, the algorithm was implemented in GAMS (ROSENTHAL 2010) with CONPT (DRUD 1992) used as the LP solver. Given the very small size of the LPs to solve – each one minimises for one given plant and location transport costs for two feedstocks from a handful of regions – most likely any other LP solvers might be used instead. Equally, given the simplicity of the sequential algorithm, alternative implementation in other programming languages should be easily feasible.

Each transport cost minimisation problem, calculation of ROI per type-location combination and selection of the most profitable location-size class requires very little computing power in the range of milliseconds. Additionally, the transport cost models for different location and types can be solved in parallel during each iteration. That explains why the sequential process is by far faster even for moderately sized problems compared to a simultaneous solution. Total processing time can be taken as a solid indication of the performance of the algorithm: To solve the 35 NUTS 2 regions for Germany for nine different price levels, the algorithm needs about four hours on an eight core machine, simulating in total approximately 100,000 erected plants, requiring an analysis of many more possible type-location combinations. As mentioned above, the NUTS 2 regions are solved in parallel and not simultaneously.

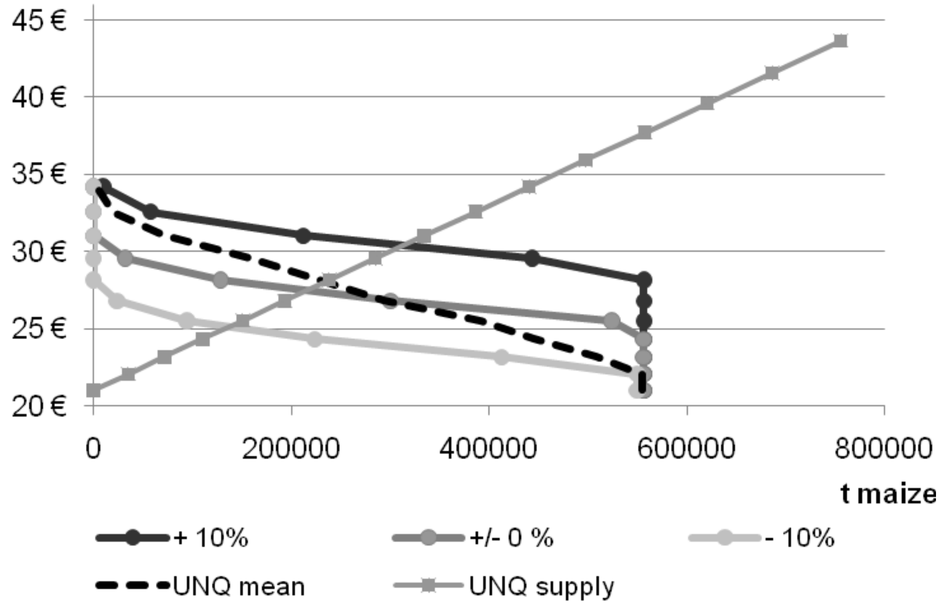
The sequential process allows for some flexibility in that, for example, different decision rules about the most desirable type-location combination in each iteration can be implemented and tested. In our applications, we also use the possibility to update parameters, specifically the share of arable land impacting collection costs and made them depend on previous iterations as the solution processes continued. Such an update would introduce nonlinearities into a simultaneous solution process, which would increase solution time further, as it would require solving large-scale Mixed-Integer NLP problems.

3.6 Incorporation of Uncertainties about Energy Efficiency

Data from existing plants suggests that energy efficiency can differ substantially from the mean energy efficiency levels reported in literature (see section 3.4). Energy efficiency is directly linked to feedstock costs per unit of output and is therefore a main driver for the ROI of plants. ROI in turn is the main driver for regional demand: at given feedstock prices, ROI stems from the number, type and location of plants which have an ROI above the assumed break-even interest rate. Therefore, demand is crucially dependent on assumptions about energy efficiency. Even small changes in energy efficiency could have a major impact on derived demand curves and simulated market equilibriums. To deal with the uncertainty of mean energy efficiency we calculate three demand functions, one for the mean efficiency level from literature and two for efficiency levels that are calculated by either reducing or increasing mean energy efficiency by 10%.

As we do not know the exact efficiency level, for every given price we compute demand as the average of the resulting three demand functions (see Figure 9 with an example of the NUTS 3 region Unna (UNQ)). Assuming a higher efficiency level (+10%, solid black line) increases demand for all analysed price levels until feedstock is exhausted, while lowering the number of plants necessary and thereby also total costs. A lower efficiency level (-10%, light grey line) has the opposite effect.

Figure 9: Example for a sensitivity analysis of energy efficiency



The reader should note how steep the curve behaves at the lower and upper end, indicating a highly nonlinear response to changes in efficiency at the tail of each relevant price change. These nonlinearities explain why the dotted line, which represents the average quantity demanded at each price from the three demand functions, differs considerably from the dark grey line showing the demand at mean efficiency. We took this average demand function to derive market clearing quantities and prices as we consider it not very likely that all investors assume the same mean efficiency, leading to almost rectangular demand curves at certain price levels. Accordingly, using the averaged demand curve should provide a more realistic picture.

3.7 Simulating Market Clearing

In order to perform an impact analysis, market clearing prices and quantities are derived by intersecting the regional demand functions from ReSI-M with supply functions for maize from RAUMIS. RAUMIS consists of independent regional Quadratic Programming Models for German NUTS 3 regions, which simulate the supply of agricultural products at given prices for agricultural inputs and outputs, production technologies for the different agricultural production processes and agricultural resource endowment. Each NUTS 3 region is treated as a fictitious "region-farm" that maximises agricultural income. Overspecialisation resulting from aggregation bias is reduced by a quadratic cost function depending on the production mix (for details on RAUMIS see HENRICHSMEYER ET AL. 1996, GÖMANN ET AL. 2007). Simulations using RAUMIS provided supply of maize net of maize for regional feedstuff for prices ranging from 20€/tFW to 53€/tFW, providing a secure range around the typical average maize prices of 30 €/tFW including transports used in other studies (cp. URBAN ET AL. 2008, HOFMANN ET AL. 2005). Prices of all other inputs and outputs and the agricultural policy framework were taken from the 2004 baseline of RAUMIS (GÖMANN ET AL. 2007). In RAUMIS, maize competes for land with other crops, acts as a substitute for other animal feedstocks and, when sold, provides residues from biogas production as an organic fertiliser. Accordingly, the supply curves for maize derived from RAUMIS take into account production and opportunity costs, relating for example to competition for land between the different crop activities, as well as feeding and fertiliser substitution values.

The simulated price/quantity combinations over the relevant price range suggest linear marginal cost curves, which can be explained by the combination of linear constraints and a quadratic cost function (see HECKELEI 2002). The points on the regional demand curve from ReSI-M suggest a far more non-linear behaviour, which prompted us to use a second order point approximation to find its intersection with the supply curve. This point defines market clearing prices and quantities.

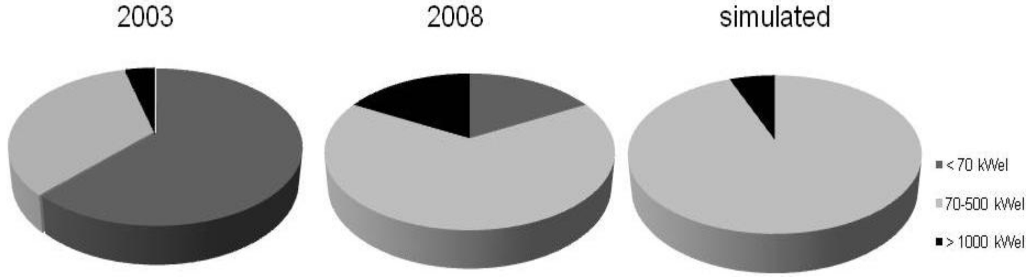
3.8 Model Performance

In this section we discuss selected results to present major findings both from data processing and simulations. We first compare the resulting plant structure with the plant structure in Germany in 2008 and also the distribution of biogas production across German states. Then, we illustrate how regional feedstock availability impacts transport distances, and in turn how it affects the optimal number and types of plants. Next, we compare regional demand curves resulting from the location optimisation and link them with supply from RAUMIS to derive market clearing prices and quantities. Finally, we analyse the sensitivity of results for the parameter “manure availability”.

3.8.1 Comparison of Model Results with Observations

The first modelling exercise simulates the number and sizes of plants which are constructed under the EEG 2004. Mainly medium-sized 500kW$_{el}$ plants are constructed with some share of large-scale plants (6%). Data on the current plant structure in Germany is not very detailed, but allows for a rough comparison with the modelling results. Within an evaluation of the EEG, TRÄHN ET AL. (2009) collect information on plant numbers for a range of plant sizes. Namely, plants smaller than 70 kW$_{el}$ make up 17%, plants with a capacity of 70-500kW$_{el}$ had a share of 65%, and plants larger than 500 kW$_{el}$ contribute to the total number of plants with 17%. An interesting feature is seen in the growth rates compared to 2003, when the EEG 2004 had not yet taken effect. The number of plants smaller than 70kW$_{el}$ decrease by 36%, whereas number of plants with capacities of 70-500 kW$_{el}$ more than quadrupled and, starting from a lower base, plants larger than 500 kW$_{el}$ increase tenfold (cp. Figure 10). Therefore, our modelling results seem to capture the development under the 2004 EEG quite well.

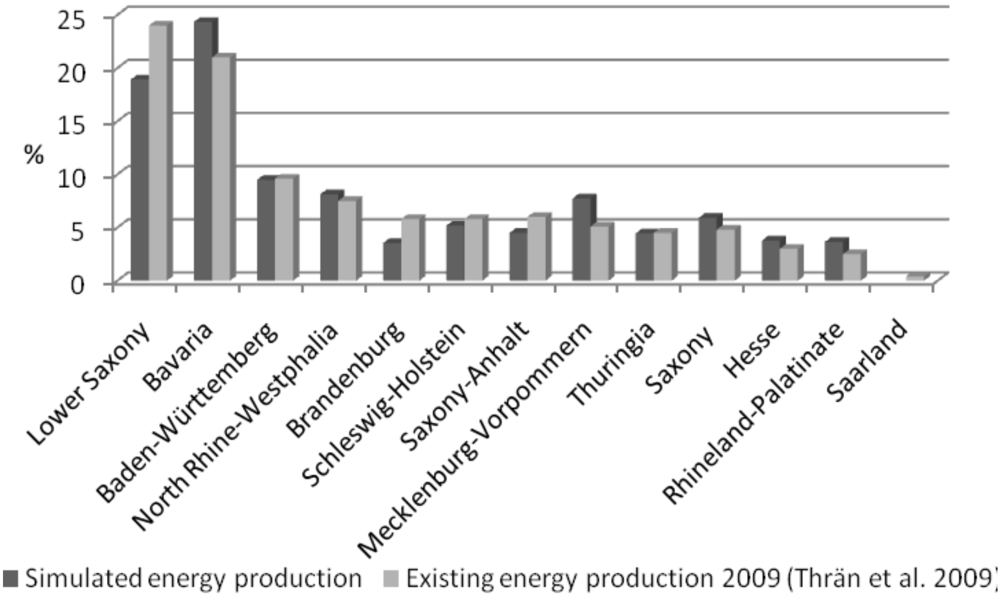
Figure 10: Plant sizes in 2003, 2008 and simulations



Source: TRÄHN ET AL. 2009, SCHLOWIN ET AL. 2007, own simulations

Besides the plant structure, the distribution of plants within Germany is important to evaluate the performance of the simulation tool. In Figure 11 we compare the reported shares of energy production (see Trähn et al. 2009, p. 20) across 13 German states (city-states Hamburg, Bremen and Berlin are excluded) with the simulated shares in the modelling exercise. The shares of the modelling exercise comprise shares of existing plants, whose input demand has been subtracted from the available inputs for the simulated plants. The distribution of simulated energy production seems to represent the energy production of existing plants quite well.

Figure 11: Distribution of existing and simulated energy production by state in Germany



3.8.2 Influence of Necessary Feedstock Harvesting Areas on Location Choice

To explain how regional differences impact the number and type of plants simulated, we compare three German NUTS 3 regions differing in feedstock availability characteristics. Siegen (SI) is characterised by both moderate maize yields and a low mean and variance for the share of arable on total land (see Table 4), which implies low feedstock availability and rather homogenous conditions for biogas locations. Soest (SO) and Unna (UNQ) show comparatively high yields combined with a high share of arable land, thereby high mean feedstock availability. However, the variance of arable land shares in SO is almost five times higher than in UNQ.

We first take a look at harvesting areas necessary for different plant sizes at those locations in each region where the arable crop land share is highest (see Table 5), namely at the minimum of the uniform distribution (see section 3.2). The four plant sizes have a predefined feedstock demand, and besides the maximal feedstock density, the necessary harvesting radii around a plant depend on the square root of demand (cp. equation (4) and Table 5). It can easily be seen that the lower feedstock availability in SI results in much higher harvesting radii. The differences between SO and UNQ reflect the fact that SO has slightly higher yields and shows a less homogenous distribution of the arable land crop share, so that the arable land share and thus the feedstock density in the starting point is higher. We can also see that with the growth of plant size, the increase in the necessary area is much higher in SI than in the other two regions. This means that transport costs rise steeply with greater plant size in SI even for the best available location. We find the lowest increase in harvesting area for SO.

Table 5: Harvesting radii (in km) in different NUTS 3 regions

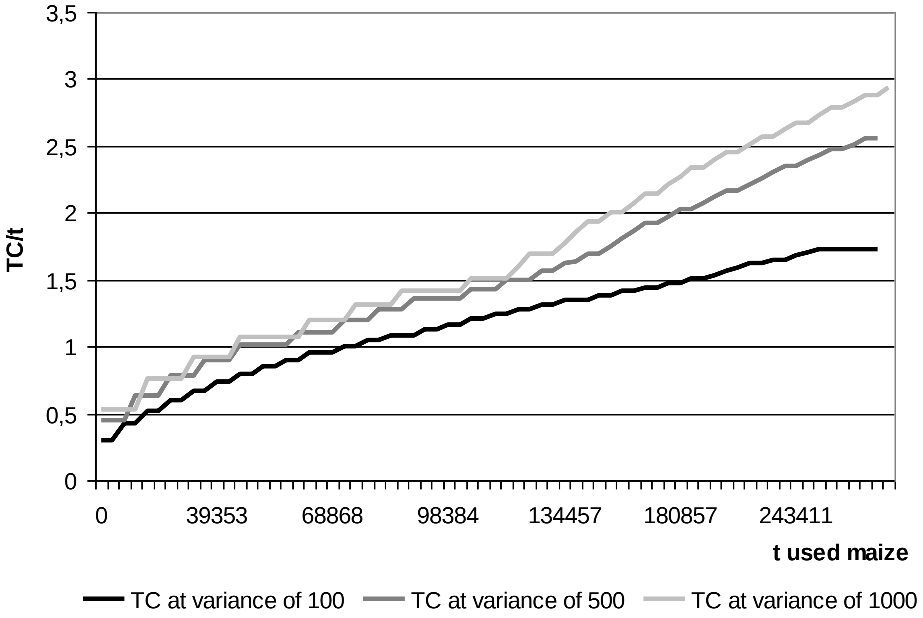
	150 kW$_{el}$	**500 kW$_{el}$**	**1000 kW$_{el}$**	**2000 kW$_{el}$**
SI	3.45	6.3	8.91	12.56
SO	0.67	1.23	1.74	2.46
UNQ	0.75	1.37	1.94	2.74

As has been explained in section 3.2 radii increase with the amount of feedstock used by already erected plants (see equation (4)), since we assume that the most advantageous areas will be used first. The resulting plant structure is therefore a result of initial transport cost - at the maximum density - and its changes from iteration to iteration, which depends on how fast the density changes as a function of demand (see equation (8)).

Medium-sized 500 kW$_{el}$ plants with a 90% maize feedstock share dominate in all NUTS 3 regions, favoured by higher feed-in tariffs for small-scale plants with a minimum 10% manure share. Only in SO are some 2000 kW$_{el}$ units with a 99% maize feedstock share constructed at low price levels for maize and after a high number of iterations, i.e. when the small-scale plants have used up most of the available manure.

Finding large-scale plants in SO is the outcome of somewhat lower harvesting radii in SO combined with a low variance in arable land shares, which cause transport costs to rise relatively slowly from one iteration to the next (see equation (8) in section 3.2. Figure 12 shows how different variances impact changes in transport costs per t of maize during the iterative solving process. Homogeneous land distribution (low variance, black line) lets per unit transport costs for maize rise moderately with demand quantities, whereas the increase of transport costs is strongest (light grey line) for the highest variance plotted. This implies that in regions with identical mean arable land shares but a more homogenous distribution of land, i.e. a lower variance, the first plants built in the solving process face higher per unit transport costs compared to regions with a higher variance, whereas lower transport costs increase during iterations.

Figure 12: Influence of homogeneity on tc per t



Compared to medium-scale plants, the ROI of large-scale biogas plants is less affected by transport costs. Large-scale plants show economies of scale, i.e. lower operational costs and a higher energy efficiency per investment cost and therefore lower feedstock demand per invested Euro, but also receive lower feed-in prices under the EEG. At a low sum of feedstock and per unit transport costs, i.e. the initial situation with no plants erected, the output price effect dominates. In other words, medium-scale plants show a higher ROI and are erected first. If the collecting radius increases as locations with high feedstock availability are already occupied, the relative cost increase for medium-scale plants is higher. First, they use smaller trucks so that per unit and km transport costs are higher compared to large-scale plants, and secondly, they require more feedstock per unit produced. As a result, after a large amount of feedstock is used by newly erected plants, the ROIs of 2000 kW_{el} plants exceed that of 500 kW_{el} plants.

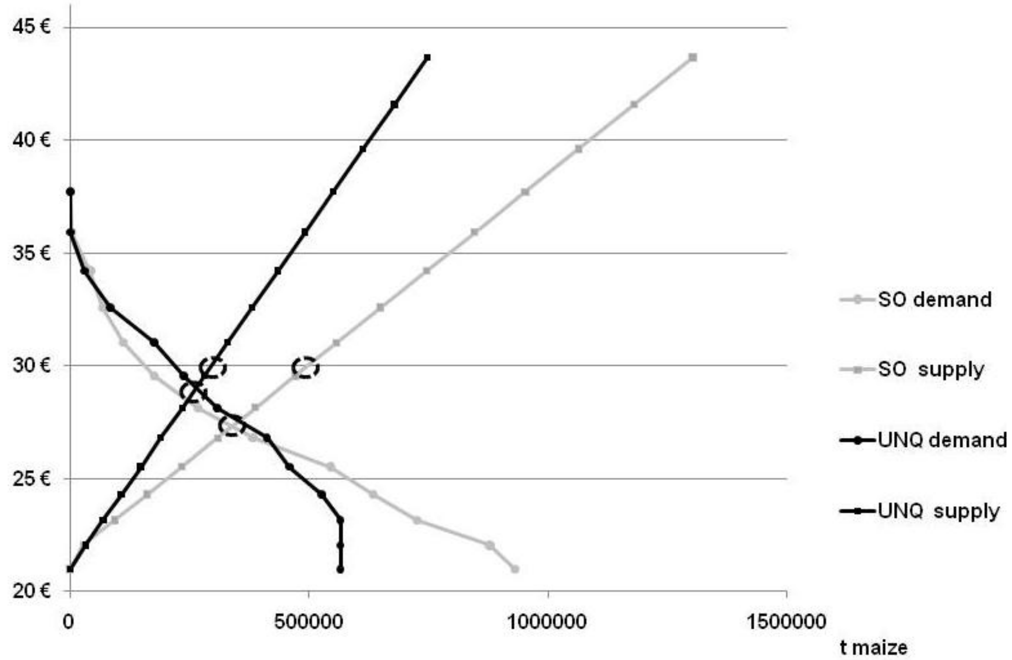
3.8.3 Market Clearing Prices and Quantities

Coupling maize demand at different prices from ReSI-M with maize supply curves from RAUMIS allows for a determination of market clearing prices and quantities (see section 3.7). We will use the NUTS 3 regions introduced above to again illustrate the reasons for different regional outcomes.

Figure 13 reports maize markets for SO and UNQ. As can be seen, both in SO and UNQ, the first plants, which are based on high manure shares and face low transport costs, are profitable even at rather high feedstock prices. For UNQ we simulate a higher market clearing price (at the intersection of the black lines), caused by a steeper supply curve, stemming from RAUMIS, and a demand curve lying above the SO curve for the relevant quantities stemming from ReSI-M.

Compared to UNQ the grey demand curve for SO drops faster until approximately 30€/tFW, as the variance for the arable land share is higher. Thus, only few plants can be erected at locations with high feedstock availability in their vicinity and per unit transport costs will therefore increase rapidly as plants have to be erected at locations where feedstock availability is low. However, with the flatter grey supply curve for SO and therefore also greater maximal feedstock available, the demand curve extends further compared to the UNQ. Market clearing prices in SO – see the intersection of the grey supply and demand curves for SO - are thereby lower and quantities higher compared to the intersection of the black ones for UNQ.

Figure 13: Maize markets in SO and UNQ



As previously mentioned, many studies assume a break-even price for maize of 30€/tFW for biogas plants (cp. URBAN ET AL. 2008, HOFMANN ET AL. 2005). The two upper circles in Figure 13 illustrate maize supply at 30€/tFW for the two NUTS 3 regions. Our analysis suggests considerably lower market clearing prices and quantities and consequently lower impacts of the legislation on farm income or the environment, for example. Indeed, for SO, our analysis suggests roughly half of the market size compared to the 30€/tFW assumption (see Figure 13).

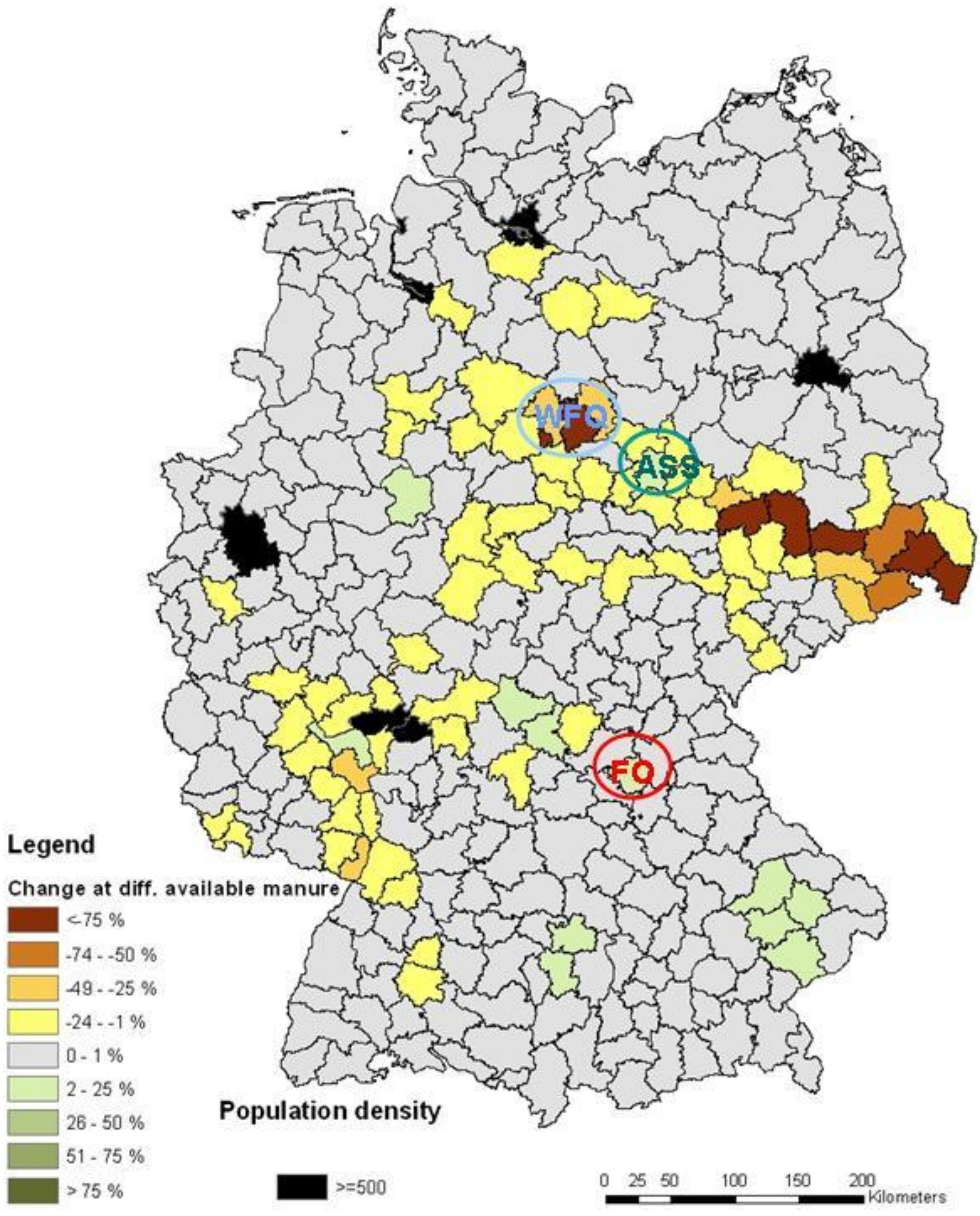
3.8.4 Sensitivity of Data on Available Manure

As mentioned in the data section, the calculation of manure availabilities is based on some assumptions. With the EEG 2008 favouring plants using 30% of manure, the availability of manure is an important factor, which calls for a sensitivity analysis of the parameter manure. Thus, compared to the approach described in the data section 3.4 (we call the resulting amount of manure “initial data”) a different way to calculate manure availability is applied (called “alternative date”).

Based on data from 2003, available manure for biogas production is calculated from data on livestock from the Regional Statistics of Germany

“Regionaldatenbank Deutschland” (STATISTISCHE ÄMTER DES BUNDES UND DER LÄNDER 2009). To convert livestock into manure availability, a conversion index was taken from STATISTISCHES BUNDESAMT (1991) and NIEDERSÄCHSISCHES MINISTERIUM FÜR DEN LÄNDLICHEN RAUM, ERNÄHRUNG, LANDWIRTSCHAFT UND VERBRAUCHERSCHUTZ (2006). This calculation estimates the total available manure. As we assume that only fluid manure is fed to the plants, fluid manure shares are taken from RAUMIS to derive total available fluid manure. Figure 14 displays resulting changes in maize production by comparing manure availability with the initial data with manure availability from calculations using livestock (alternative data).

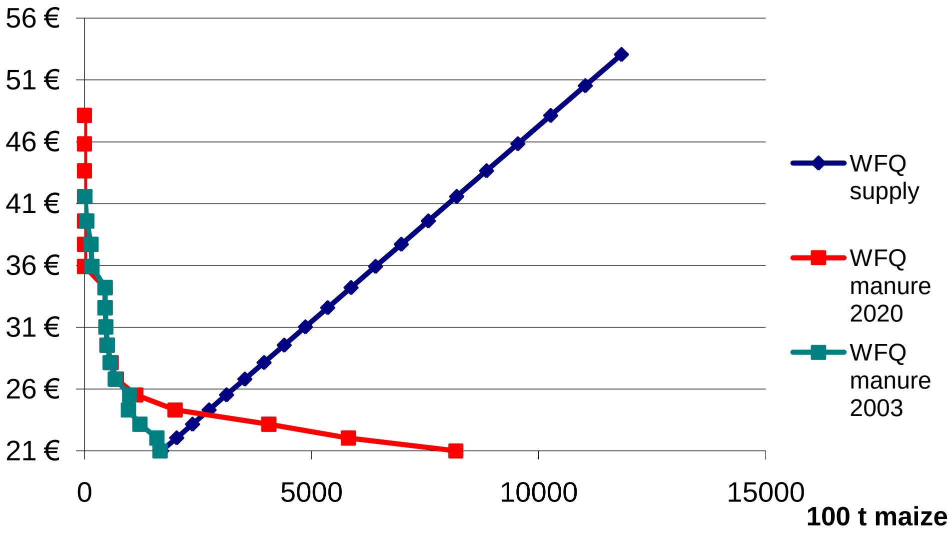
Figure 14: Change in maize production at different manure availability



Data: RAUMIS and ReSI-M simulations, population density from BBR and SOFL (2005)

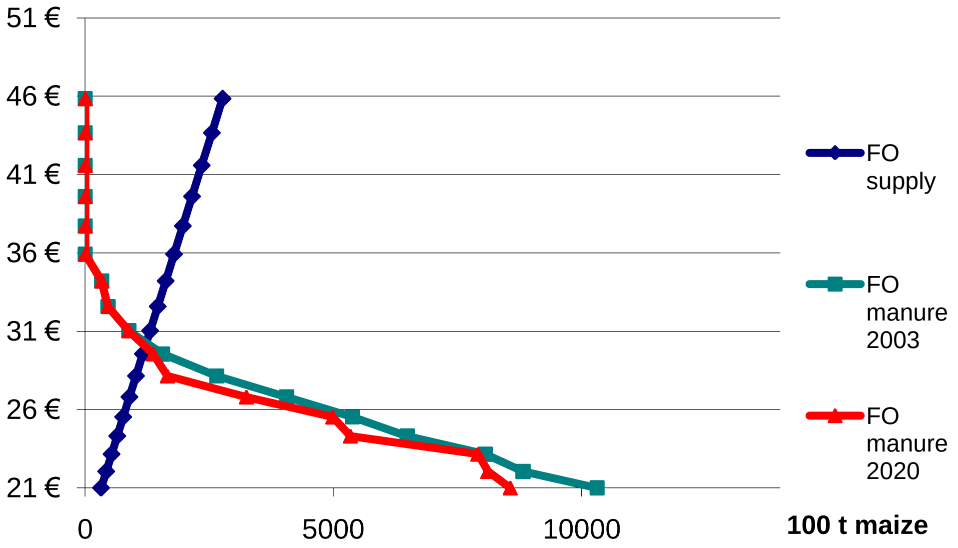
Manure availability according to the initial data is higher than the one applying the alternative data in a number of NUTS 3 region. The NUTS 3 region Wolfenbüttel (WFQ) (marked light blue in Figure 15) provides an example for a NUTS 3 region where manure availability according to the alternative data on manure is only half the availability taking the amount of the initial data. This decrease in manure availability causes maize production to drop from 261.602 t to zero (see red line for maize demand with the initial manure availability and blue line for maize demand with the alternative amount of manure in Figure 15). The reasons for this effect are different increases of costs for manure transport (cp. Figure 7). In the first iteration, costs for manure are lower the more manure is available and they increase with the amount of manure used for each constructed plant during the iteration process. Thus, in case of a low availability of manure, transport costs for manure increase stronger, and maize production is not competitive against other crops in NUTS 3 regions with a low availability of manure.

Figure 15: Maize market in WFQ



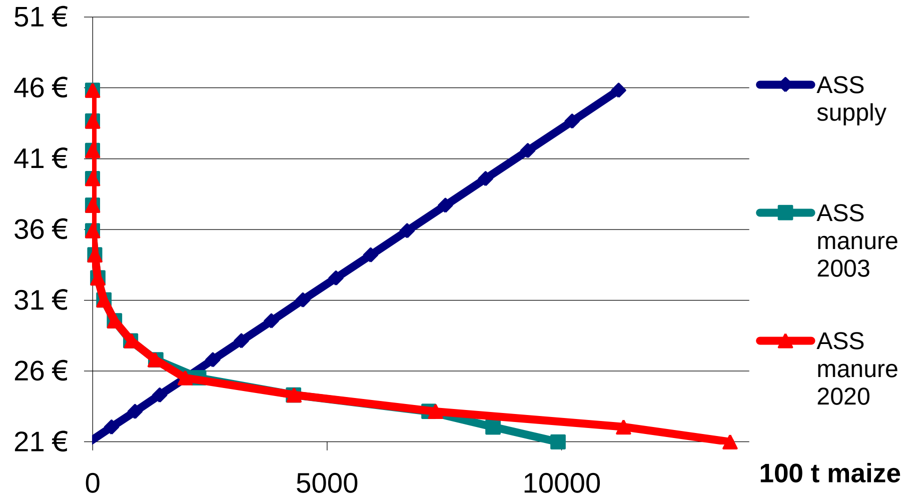
In Forchheim (FO), manure availability is 35% higher in the alternative manure data, causing maize production to increase by 2% (see Figure 16). A reason for this small increase is a low energy content of manure: with 1 ton of maize about 1074 kW_{el} can be produced, whereas one t of manure from cattle only generates 165 kW_{el}.

Figure 16: Maize market in FO



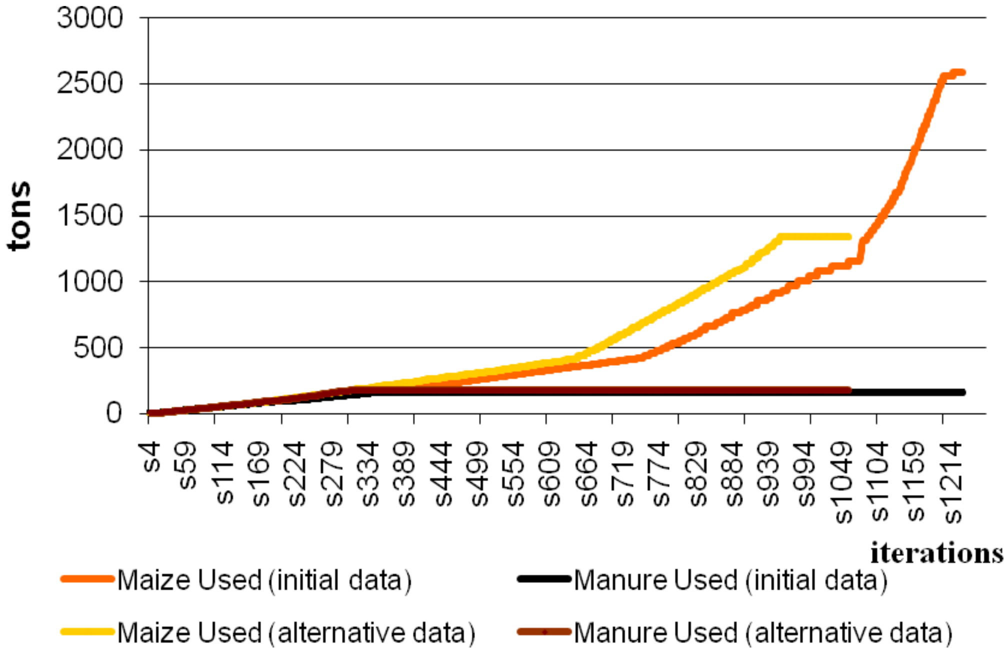
However, in some NUTS 3 regions contra intuitive effects can be observed: in Aschersleben-Staßfurter-Landkreis (ASS), in spite of 65% less available manure in case of the alternative data compared to initial data, maize production increases by 6%. Figure 17 illustrates that maize demand applying the alternative amount of manure starts with a lower maize quantity at a price of 21€/tFW (tons fresh weight), but it drops less steeply than demand at the initial data on manure availability.

Figure 17: Maize market in ASS



This effect can be explained by “maize exports” into neighbouring NUTS 3 regions. As illustrated in Figure 18, only slightly more manure is used at the alternative amount of manure (brown line). The amounts of manure and maize are displayed in relation to their energy content. Thus, we see that until iteration 330 plants are fed with manure and maize, both taken from ASS. The higher use of maize in relation to manure at higher iterations shows that maize is used at plants in neighbouring NUTS 3 regions, where manure availability is higher. As when applying the alternative data less manure is available in ASS but in total more manure is accessible in neighbouring NUTS 3 regions, with the alternative data more maize is demanded than in the situation with the initial manure data despite of less available manure.

Figure 18: Used Maize and Manure in ASS at manure in 2003 and 2020 by energy content



Given this tool to model land-use change for a good with high transport costs, model results can be used to assess environmental impacts of different policy settings.

In summary, the developed location models allows for a high flexibility in decision rules to determine optimal projects as well as to treat both input and output quantities as endogenous. Furthermore, the iterative solving process allows for parameters changes based on results from previous iterations. Another advantage is that in spite of a high number of potential plants, the location problem is not turned into a NP-hard problem. In addition, the model allows to account for intraregional distribution of land which lets unit transport cost increase with the number of already erected plants. Finally, some crucial assumptions on parameters have been identified which need to be considered when analysing model results. Model results are used in the following section to assess environmental effects of biogas production.

4 Assessment of Environmental Effects of Biogas Production

The EEG defines goals to be met with the use of renewable energies: „*The purpose of this Act is to facilitate a sustainable development of energy supply, particularly for the sake of protecting our climate and the environment, to reduce the costs of energy supply to the national economy, also by incorporating external long-term effects, to conserve fossil fuels and to promote the further development of technologies for the generation of electricity from renewable energy sources”* (BGBL 2008).

Based on these objectives, this chapter aims to analyse their performance for the biogas sector. Therefore, we set up four scenarios, which are described in the following section. In section 4.2, the assessment of environmental effects for biogas production is embedded into the current state of environmental research and effects are analysed by means of the scenarios deduced. Costs of biogas production for society are addressed by means of subsidies paid in different scenarios. The determination of scenarios is explained in the following section.

4.1 Scenario Determination

To analyse the effects of this legislation in Germany three scenarios are introduced:

(1) In a *reference scenario,* land use without including regional maize demand is simulated with RAUMIS and is based on the policy framework in 2004 with the target year 2020. Instead of respecting regionally different maize demand, a fixed maize price in each region is assumed. This scenario is relevant when comparing changes in land use. As ReSI-M is not applied, no statements on CO_2 emissions on transportation can be made.

(2) The scenario *“EEG 2004”* includes simulations from ReSI-M as well as simulations of the supply functions by RAUMIS with the resulting supply functions of the target year 2020. ReSI-M assumes that biogas plants receive FITs according to the EEG 2004 and respects the demand for feedstock of existing plants. Plants are constructed with a planning period of 20 years (see section 1.1), and the plant structure in 2020 in this scenario is therefore assumed to display the plant structure resulting from the EEG 2004. As the EEG 2008 took effect in January

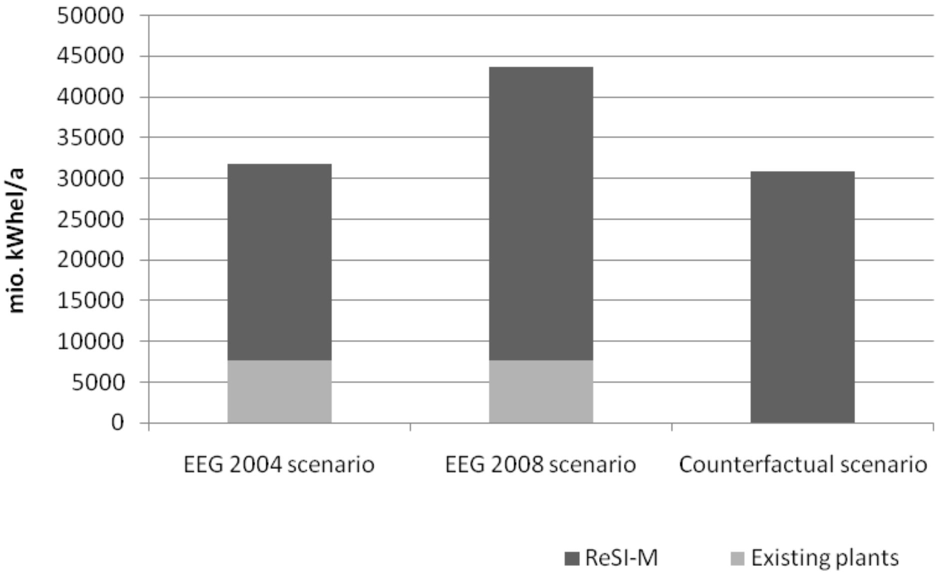
2009, the structure of existing plants is still mainly based on the EEG 2004. As a result, it is assumed that the policy framework of 2004 for both models allows for a comparison of the resulting plant structure with the current observable plant structure. Our modelling results can therefore be validated by comparing the plant structure with and without respecting input demand of existing plants.

(3) To evaluate the support of small-scale plants using manure and its effects on land use change and the environment, the *EEG 2008* contributes a scenario. As a result, this scenario allows for the simulation of the effects of the new legislation.

(4) In a *counterfactual scenario*, all plant sizes receive the same output price per kWh_{el} and there are no extra subsidies for using specific inputs or particular techniques. A subsidy rate of 16.3 $cent/kWh_{el}$ is chosen to result in approximately equal amounts of energy produced compared to the scenario “EEG 2004” in order to make results comparable. In the counterfactual scenario there are no existing biogas plants – all plants are built from scratch. This scenario is chosen to compare the “reality” with a situation in which, theoretically, the resulting plant structure is a cost-minimal solution, due to a lack of influence over plant size and technology by policy intervention. However, potential external effects such as environmental effects due to large scale plants or higher CO_2 emissions might influence cost efficiency. This is analysed in the following section.

Resulting annual energy production for the different scenarios is displayed in Figure 19.

Figure 19: Annual energy production



4.2 Analysis of Environmental Effects

4.2.1 Problem Setting and Relevant Studies

In 2004, the German Advisory Council on the Environment (SRU) noted that *“the agricultural sector in Germany is essentially one of the main sources of harm to soil water, species and biotopes, which means there is in any case an urgent need for action to reduce agricultural impacts on the environment”* (GAY ET AL. 2004, Item 225). However, there is a contrary development with the fast growing cultivation of energy crops. In its report on “Climate Change Mitigation by Biomass”, the SRU declares that with the massive development of bioenergy, risks for soil, water and biodiversity rise (SRU 2007, p. 2), and they assign the expansion of environmentally hazardous crops such as maize as a serious factor to harm the environment (SRU 2007, p. 43). As stated in the introduction, maize has the highest input share for biogas production in Germany. For this crop, the European Environmental Agency (EEA) ascribes a high risk for soil erosion, nutrition leaching, ground and surface water contamination with pesticides and a medium to high risk of water withdrawal, impacts on farmland biodiversity and diversity of crop types, soil compaction and water use (EEA 2006, p. 24).

The EEG 2004 induced large expansions of maize production and, in the context of rising crop prices and the food crisis in 2007, was amended in 2008 to favour medium-scale plants using more than a 30% input share of manure. As a result, the revised legislation in 2008 aims to use a waste material from livestock and dairy production in order to decrease the competition for land for food versus energy production. In addition, small-scale plants are expected to reduce transportation and have a better resulting climate balance. Nevertheless, manure-based small-scale plants receive a bonus if a 30% share of manure is reached, which implies that there is a risk of increasing maize production in areas in which maize production is already high. With manure having very high transport costs, these plants are expected to be constructed in regions that have a high feedstock density and therefore abundant manure availability. However, in these regions fodder maize production is already cultivated with a high share on arable land. Therefore, the promotion of small-scale biogas plants might lead to additional competition for land in these regions. A change in land use which might cause other crops to be cultivated might change characteristics of soil, water and the diversity of ecosystems. Since the EEG aims to protect the climate, making the analysis of CO_2 emissions for different plant sizes and technologies another important issue.

This calls for an assessment of environmental effects caused by different policy settings. Environmental effects of biogas production are analysed in academic literature with respect to land use change, emissions with acid and eutrophication impacts, greenhouse gas emissions and the use of fossil fuel inputs. In addition, biogas production might cause other environmental effects such as water use and soil erosion, but sufficient data in various studies is only available for the aforementioned impacts (see e.g. SCHLOWIN ET AL. 2006, RAMESOL ET AL. 2006, FRISCHE ET AL. 2007). An overview of the current state of research for the impact categories land use change and greenhouse gas emissions is provided in the following sections.

4.2.1.1 Land Use Change

Land-use change is a complex, dynamic process that links together natural and human systems. It has direct impacts on soil, water and the atmosphere (MEYER AND TURNER, 1994) and is thus directly related to many environmental issues.

Statistical data on land used for the cultivation of biomass for biogas production is not fully available. Furthermore, the sector has been growing quickly without being organised in a coordinated way. So far there is no consistent and current data on biogas plants (PÖLKING ET AL. 2006, p. 23).

The German Federal Agency for Agriculture and Food (BLE) collects data on set-aside land appropriated for the growth of energy crops (49.036 ha in 2006) and areas for which farmers have received an energy premium (151.534 ha in 2006) (written information from BLE 2006, in: SCHLOWIN ET AL. 2007b, p. 87). The share of maize accounts for 75.6% of the energy crops on set-aside land and 79.4% of the area with an energy premium. However, based on existing plants and the common input shares, the Leipzig Institute for Energy estimates the area of crops for biogas production at 400,000-500,000 ha (SCHLOWIN ET AL. 2007b, p 87). In the study, the share of maize is estimated to take up 80% of this area (SCHLOWIN ET AL. 2007b, p. 67), resulting in 320,000-400,000 ha of maize cultivation.

In an analysis of the macroeconomic effects of cultivating and using renewable resources, NUSSER ET AL. (2007) simulate a potential supply of 198.9 mio t maize, produced on 3.2 mio. ha of land in 2020 (NUSSER ET AL. 2007, p. 115). By conducting an expert consultation, they derived a demand of 0.35 mio. t in 2004 and 9.83 mio. t maize for biogas production in 2020 (NUSSER ET AL. 2007, p. 85). Assuming average yields of 45t/ha, these figures would result in 87,500 ha in 2004 and 218,444 ha in 2020 which, when compared to the numbers of the BLE and SCHLOWIN ET AL. (2007b), appears to be an underrepresentation.

Applying RAUMIS, GÖMANN ET AL. (2007) address shifts in land use caused by the EEG 2004. They assumed a unified maize price of 24€/tFW and calculated an area of 1.5-1.8 mio. ha of maize production for the year 2010, which primarily crowds out grain production (GÖMANN ET AL. 2007, p. 267). The problem with this study is that differences in regional maize demand due to infrastructure (possibility of gas induction, heat use) and transport costs are not taken into account, while maize prices might vary by region and cause regional differences in demand. As a result, one average maize price cannot be used. The modelling of land use for different policy settings should be improved by taking regional demand into account. Moreover, land use change is correlated with the following environmental effects and should be analysed accordingly.

4.2.1.2 Greenhouse Gas Emissions

A prominent method to capture greenhouse gas emissions is lifecycle assessment (LCA). LCA is a *“method to capture and assess impacts of human activities on the environment, and to derive potential for optimisation*“ (ZAH ET AL. 2007, p. 6). An LCA deals with positive and negative environmental effects which emerge during the lifecycle of a product. Thereby, impacts “from the cradle to the grave” are considered and included in the analysis, including - besides the actual production - materials used for the production of inputs, by-products and materials/energy for waste application. This allows for a comparison of products which provide the same utility. In the case of agricultural production systems, HAYASHI ET AL. (2005) characterise LCA into two categories: LCA studies for production processes (their system boundaries are defined as the cradle-to-gate type) and comparative LCA, which examines several agricultural production systems (HAYASHI ET AL. 2005, p. 98).

In an LCA, ZAH ET AL. (2007) analyse the performance of different biofuels with respect to greenhouse gas emissions and environmental effects in comparison to fossil fuels. The analysis also includes biogas for the substitution of natural gas for transportation/automobiles. They compare different inputs of biogas production: manure from agriculture, biowaste, digestion of whey, digestion of sewage sludge, or the methanation of wood. For our analysis, data on manure from agriculture is of interest. Data is taken from a biogas plant with a capacity of 300 m^3 that uses manure from 30 livestock units (cows) and 20 pigs. In addition, 20% biowaste is used. An assumption is that the manure input is a by-product of raising animals, and is therefore not part of the system to be investigated. Therefore, only those emissions caused in addition to those from undigested manure are considered. The study compares two scenarios: biogas production from manure with and without covering residue storage.

Results show that in the scenario without covering storage, 0.07 kg CO_2 per mega joule (~252 g CO_2/kWh_{el}) are emitted – three fourths emerge during methanation while one fourth emerges from cleaning and CO_2 separation. The majority is caused by biogenous methane emissions. In an optimised process (covering residue storage), the same amount of emissions is caused by cleaning and separation, but emissions are negative and are therefore abated (-0.03 kg CO_2 per mega joule) at methanation. Compared to the scenario without covering, less biogenous methane is emitted, and NO_2 emissions are abated (ZAH ET AL. 2007, p.22ff).

However, this study does not include maize as an input. Since in Germany maize is cultivated, particularly for biogas production, it is necessary to consider its emissions from cultivation and during transportation from the field to the plant when analysing its greenhouse gas emissions.

Studies on greenhouse gas emissions of biogas production from manure and maize using lifecycle assessments have been conducted by, for example, SCHLOWIN ET AL. (2006), FRITSCHE ET AL. 2007, BACHMAIER AND GRONAUER (2007), ZIMMER ET AL. (2008) AND BACHMAIER ET AL. (2009) all based on the GEMIS model and data by the Öko-Institut (http://www.oeko-institut.de/service/gemis/en/index.htm). Results show differences in emissions per kWh_{el} for crop production, operating the plant and to a large extent in direct methane emissions. These differences are caused by assumptions on input shares, abatement of emissions in livestock production, yields, transport distances, the amount of maize lost in storage and transport, different internal energy uses, energy efficiencies, types of fossil energy input, the share of combined heat and power generation, consideration of savings in CO_2 equivalents/ per kWh_{el} for the use of by-products, and last but not least, methane slack. This variety of possibilities for assumptions chosen explains the following differences in results of greenhouse gas emissions in the studies.

SCHLOWIN ET AL. (2006) calculates values of -140 up to 40 g CO_2-equivalent per kWh_{el} for plant sizes and types between 51 and 768 kW_{el} and makes different assumptions on inputs, their shares and residence time in a fermenter (SCHLOWIN ET AL., 2006 p. 46).

FRISCHE ET AL. (2007) investigate three types of biogas plants, resulting in emissions of CO_2-equivalents between -409 to -414 g per kWh_{el}, if savings for the use of the heat by-product are considered (FRITSCHE ET AL. 2007, p. 7). Taking these savings out of the calculation, emissions add up to 243 to 471 g per kWh_{el} (EBID., p. 9).

BACHMEIER AND GRONAUER (2007) analyse four plant types differing in input and heat use, as well as in the storage of residues. Results vary between -143 and 160 g CO_2 per kWh_{el} (savings are included).

Another study is performed by ZIMMER ET AL. (2008), in which CO_2 emissions for three plant sizes with different inputs and technologies are compared:

- 150 kW_{el} plant (100% pick manure, 30% of heat usage),
- 500 kW_{el} plant (ca. 7% pick manure with and without heat use, 30% of heat usage), and
- 1000 kW_{el} plant (direct induction of gas into the gas pipeline, 30% of heat usage).

This study also included “credits” for savings in CO_2-equivalents/ per kWh_{el} for by-products of biogas production. These credits refer to the abatement of direct emissions in manure use (ZIMMER ET AL. 2008, p. 11). The highest emission levels (242 g CO_2-equivalents/kWh_{el} (including credits)) are caused by 500 kW_{el} plants that do not use heat. With emissions of -610 g CO_2 equivalents/kWh_{el} (including credits) the 150 kW_{el} plant shows the lowest emissions level for CO_2-equivalents and also the lowest abatement costs (ZIMMER ET AL. 2008, p.35ff).

BACHMAIER ET AL. (2009) show the large sensitivity of assumptions: based on a reference plant emitting 16 g CO_2-equivalent/kWh_{el} and using manure from cattle instead of chickens, emissions increase almost 13 times. When not using manure, emissions increase up to 254 g CO_2-equivalent/kWh_{el} and to 370 g CO_2-equivalent/kWh_{el} if heat is not used (23 times higher than the reference plant). Not covering the storage of residues adds another 74 g CO_2-equivalent/kWh_{el}.

As a result, depending on assumptions made in the LCA, greenhouse gas emissions calculated in the studies addressed here range from -610 g to 471g CO_2-equivalents/kWh_{el}. Note that the production of electricity from brown coal results in 1,450-1,477g CO_2-equivalents/kWh_{el} if savings are not included and 729 to 1,153 g CO_2-equivalents/kWh_{el} if savings are included (FRISCHE ET AL. 2007, p. 7-9). Therefore, even if the most disadvantageous assumptions for biogas production are applied, its CO_2 equivalent emissions are lower than those of coal production.

Ecological effects of large-scale versus small-scale biogas production have been analysed by SCHLOWIN ET AL. (2007a). In this study, the production of 20

MW_{el} by 40 $500kW_{el}$ plants (biogas plant parks) built on one location[6] is compared with 40 single plants of the same size on different locations. The authors point out several advantages of biogas plant parks, such as higher energy efficiencies, less odour emissions, a better use of residues. At the same time, the study identifies bottlenecks, such as longer transport distances and higher internal power requirements (SCHLOWIN ET AL. 2007a, pp.23-25). Taking ZIMMER ET AL. (2008) as an example, transport emissions make up 6-10.5% of total emissions for 500 kW_{el} plants and 10.5% for 1000 kW_{el} plants, based on fixed transport distances and fixed yields per ha which are presumed in the study.

This review of literature on land use change and CO_2 emissions shows that the assessment of environmental effects has different dimensions. On the one hand, biogas production might change land use, which influences regional impacts on the environment; on the other hand, biogas production has product specific impacts. The latter dimension deals with effects along a process chain, which are caused by a product. A question in this case would be, for example, which effects are caused by one kWh_{el} power from biogas compared to one kWh_{el} power from coal plants or from the overall German energy mix. These effects can be investigated by a LCA.

The problem of an LCA is that it omits alternative land uses. As a result, changes in land use cannot be taken into account. These changes and resulting differences in environmental effects emerge if the product at hand is produced with a certain crop and competes for land with other products realised with other crops, while the use of the product also has an impact on other crops. This implies that if one product associated with specific environmental impacts (such as the need for fertiliser) crowds out another product with presumably other impacts on the environment, the overall impact on the environment might be positive or negative. An example is the production of maize for biogas, which might crowd out wheat cultivation for food production, which in turn might displace other land uses. In the case of agricultural products, these effects cannot be captured by an LCA but by agricultural sector models. They add a spatial dimension to the analysis of

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[6] Under the EEG 2004, 500 kW_{el} plants were most profitable. Investors built 40 of those plants to receive subsidies for each plant, with taking advantage of economies of scale in biogas and residues processing.

environmental effects and are capable of including indirect effects in the assessment. This is done by comparing a reference situation with a different situation caused by a policy change or where another product is more competitive. However, these models often do not take emissions caused by inputs such as fertilisers into account, as they lack detail in product-specific emissions.

Therefore, an integration of detailed information of product-specific environmental indicators from an LCA into agricultural sector models would be the best instrument to analyse different policy settings for biogas production. This is outside the scope of this work, but we will use information from an LCA on greenhouse gas emissions and supplement it with transport data for maize and residue from our models to determine total greenhouse gas emissions of biogas production.

4.2.2 Resulting Research Questions

To summarise the literature on environmental effects of biogas production, product-specific environmental effects have been addressed, but a spatial analysis of environmental effects is lacking. Therefore, modelling land use change with an appropriate modelling framework is necessary, which would allow for an analysis of further environmental effects of land use change in the future, such as nutrition balances. In addition, as transport distances and therefore transport emissions change with yields and land distribution, these variations can be analysed and their impact on the total performance of biogas with respect to greenhouse gas emissions can be addressed.

With the amendment of the EEG in 2008, different plant sizes are favoured compared to the EEG 2004, which has led to different plant size-specific effects. With a set of scenarios at hand, different policy options are analysed. Results on land use change, transport emissions and subsidies are presented in the following sections.

4.2.3 Land Use Change Caused by Biogas Production

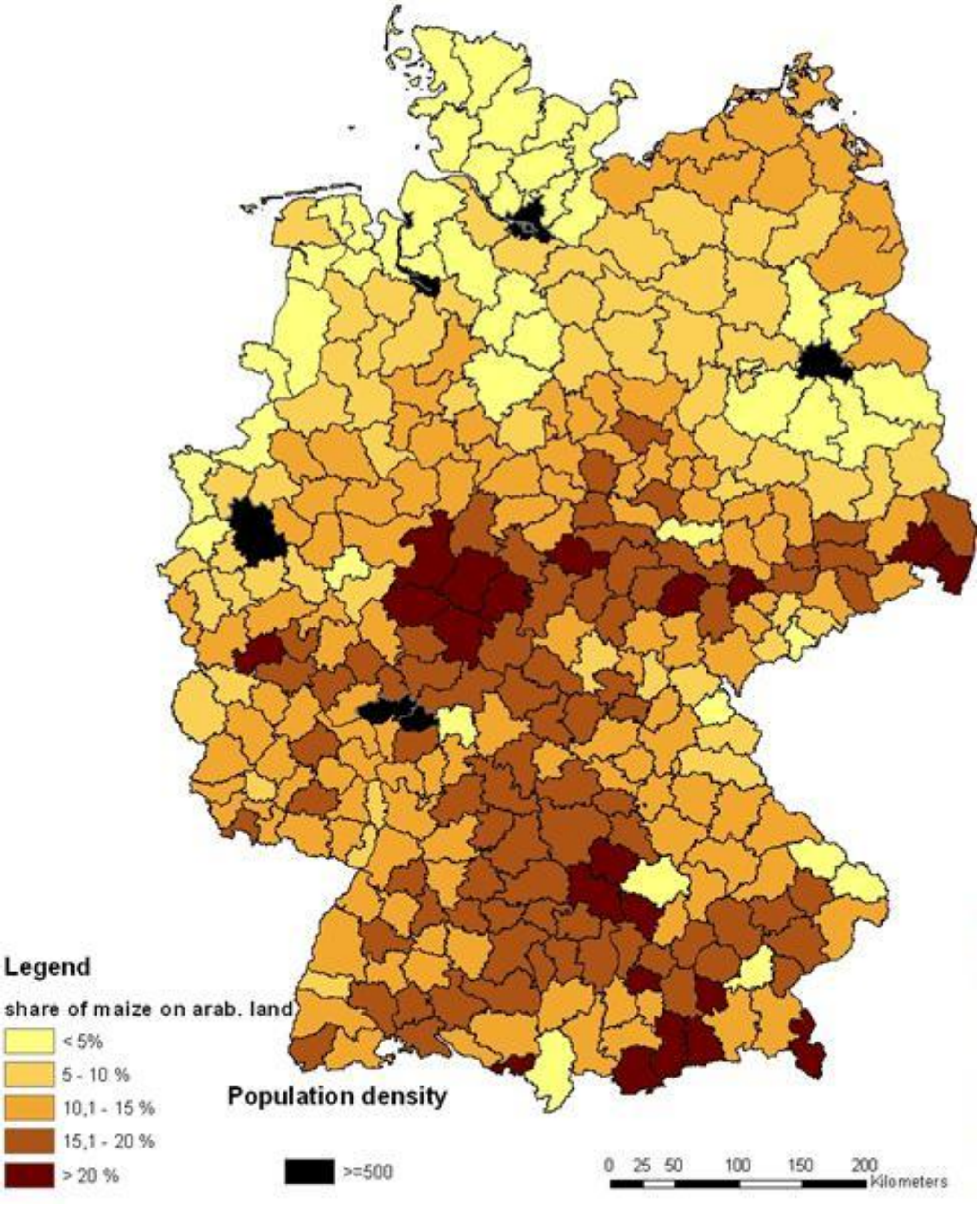
Applying ReSI-M for the EEG 2004, EEG 2008, and the counterfactual scenario and coupling it with RAUMIS allows for the calculation of market clearing quantities and prices for each German NUTS 3 region. These market clearing quantities, the regional maize production yield under the respective scenarios, is expressed in the area needed for maize cultivation (in ha).

Agricultural land changes considerable between regions in Germany. Therefore, to make the area used for maize production regionally comparable, it is related to the total arable land in a region and changes are displayed in “share of maize production on arable land” in percent.

4.2.3.1 Maize Production at Reference Scenario and EEG 2004

In the reference scenario, maize production is simulated applying RAUMIS with a fixed maize price of 30€/tFW for all NUTS 3 regions. Share of maize production on arable land (see Figure 20) is high in crop production areas such as Southern Lower Saxony to Saxony (central-eastern Germany), Soester Boerde and Cologne-Aachen Bay (western Germany), Kraichau (southwestern Germany), Mecklenburg-Vorpommern (northeastern Germany) and the centre of Bavaria (southern Germany). The total area for maize production amounts to approximately 1.4 mio ha in the reference scenario.

Figure 20: Share of maize production on arable land (RAUMIS at price of 30€/tFW)

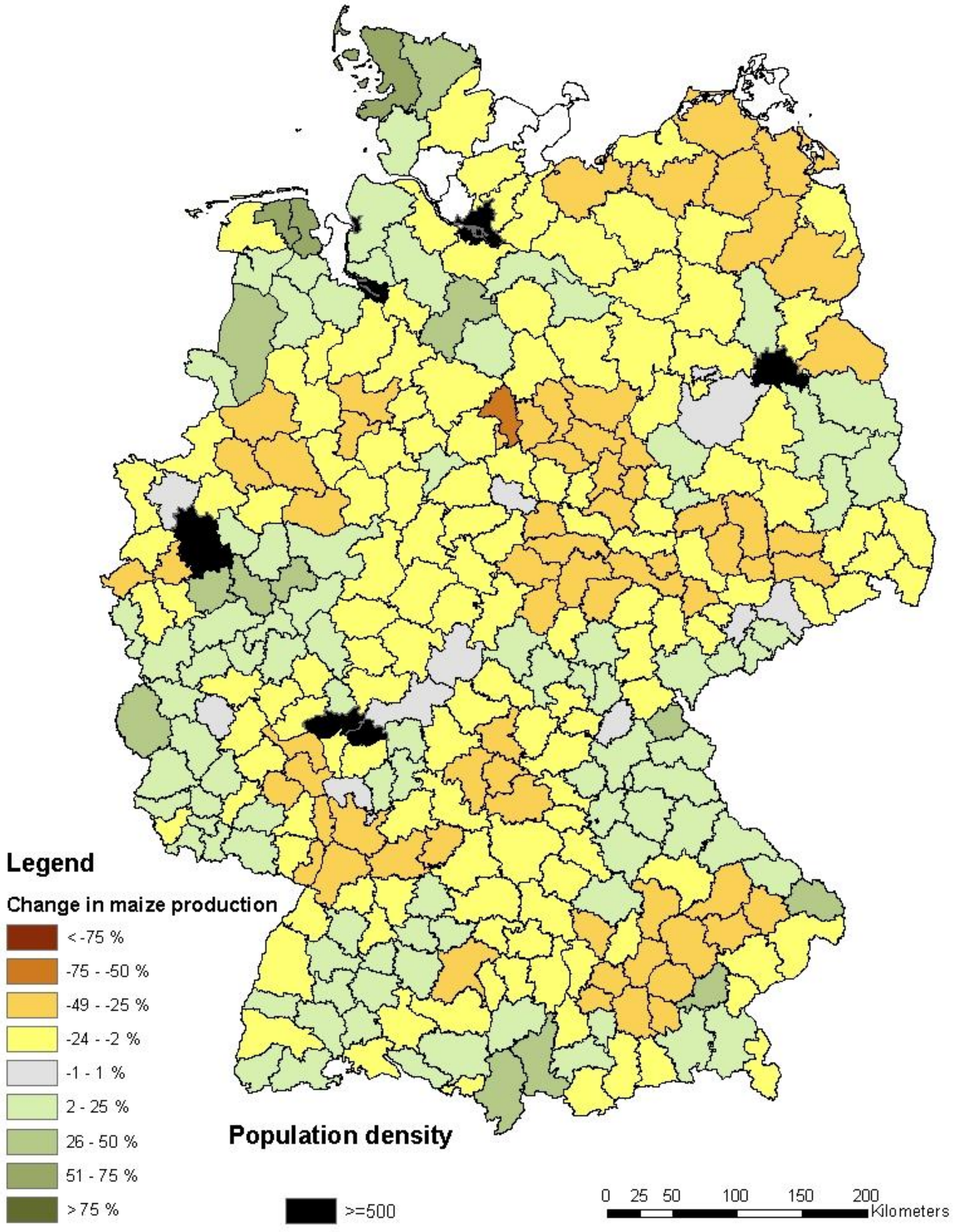


Data: RAUMIS simulations; population density from BBR and SOFL (2005)

Resulting changes of maize production (in %) for all German NUTS 3 regions when coupling the models are illustrated in Figure 21. Maize prices are not fixed but result from intersecting maize supply (RAUMIS) and maize demand

(ReSI-M). Results show that if we link the models in the majority of the counties, ReSI-M has a limiting impact on results of maize production (all orange/yellow shaded counties). In some counties, equilibrium prices and quantities are higher in the coupled system (green shaded counties). Explanations are the number of existing plants and the availability of manure in relation to the availability of maize in these counties. As a result, including regionally varied maize demand causes different results of land use compared to a fixed maize price across all regions. Even if a lower fixed maize price was chosen, regional characteristics could not be addressed and therefore, it is important to include them when assessing land use change.

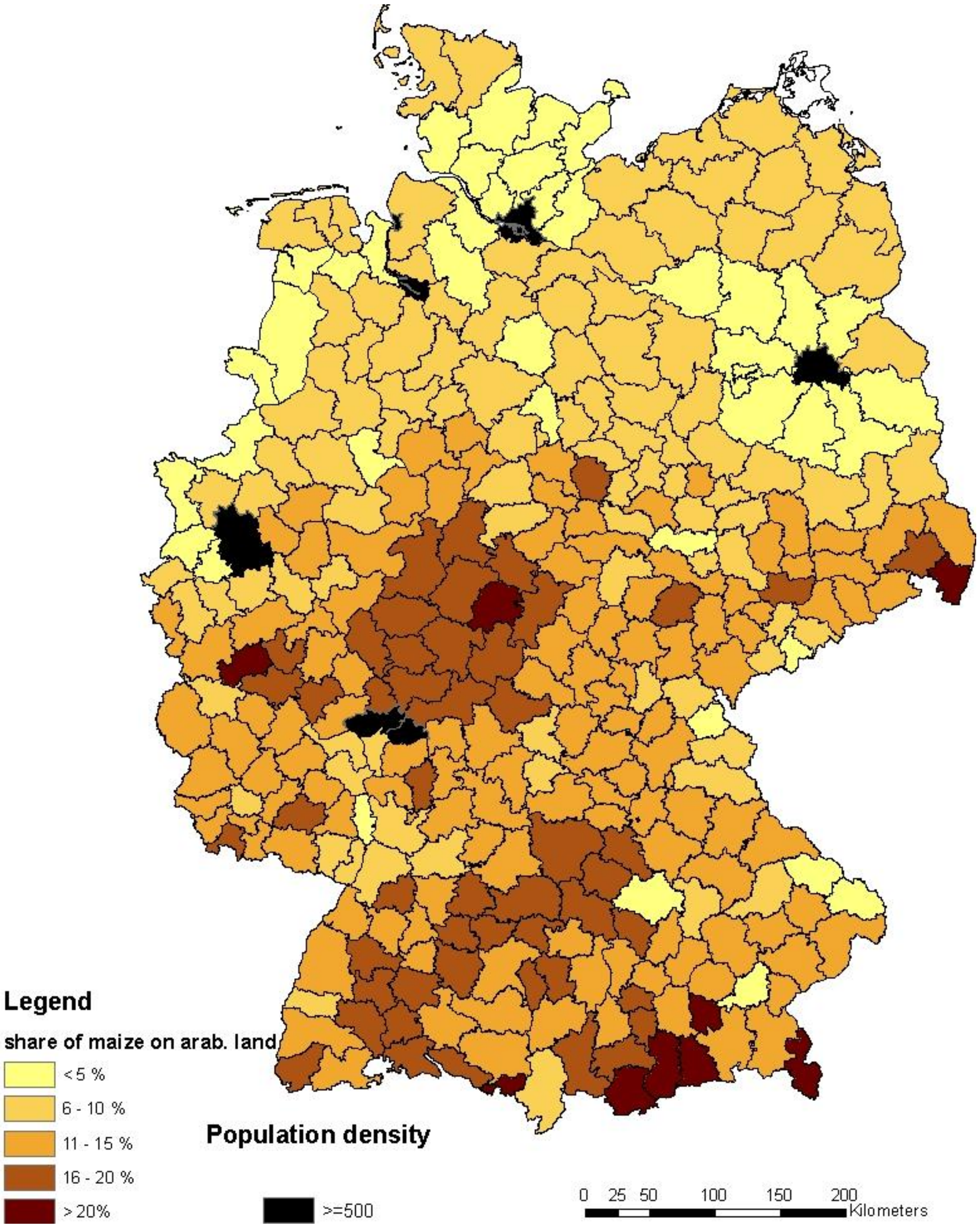
Figure 21 Change in land-use when coupling models



Data: RAUMIS and ReSI-M simulations; population density from BBR and SOFL (2005)

The resulting regional shares of maize production on arable land are illustrated in Figure 22. In the EEG 2004 scenario, regions with a high share of maize production are located in large parts of Hesse and Middle Franconia. In some counties in Upper Bavaria (southern Germany), the area used for agricultural production is very small, and therefore the share of maize production is proportionally high. These counties are shaded dark in Figure 22.

Figure 22: Share of maize production on arable land at EEG 2004 scenario

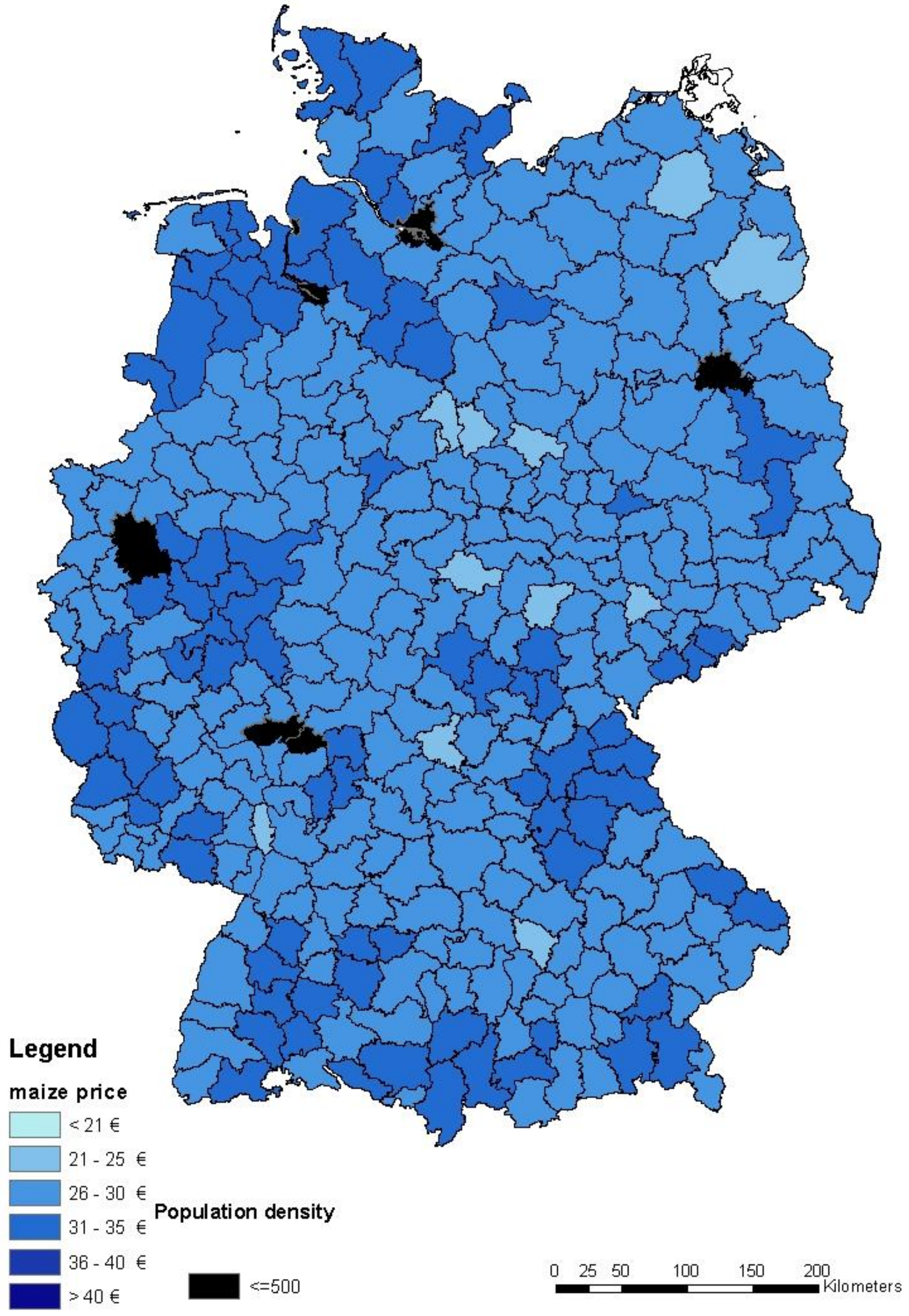


Data: RAUMIS and ReSI-M simulation, population density BBR and SOFL (2005)

Regions with little livestock and dairy production delivering small amounts of manure as well as regions dominated by vegetable and crop production show a low share of maize production for biogas (yellow shaded regions) in Schleswig-Holstein (northern Germany) and Brandenburg (eastern Germany). To summarise maize production areas in Germany, in the EEG 2004 scenario 1,081,489 ha are cultivated with maize for biogas production. These numbers are based on a maize supply potential for the year 2020 simulated by RAUMIS (see section 1.2). Regarding maize demand we assume that an investor exhibits profit maximising behaviour and has realised all of his projects (no adjustment time of investments, see chapter 2). Therefore, coupling the models limits maize production compared to the reference scenario by about 300,000 ha.

Prices for maize under the EEG 2004 vary between 21 €/tFW in counties scattered throughout Germany and 35€/tFW in counties in northwestern Germany, Soester Boerde and some counties in Bavaria (see Figure 23). The average maize price under the EEG 2004 scenario is approximately 28€/tFW and therefore below the assumed fixed price of 30€/tFM in the reference scenario.

Figure 23: Regional market clearing prices at EEG 2004 scenario

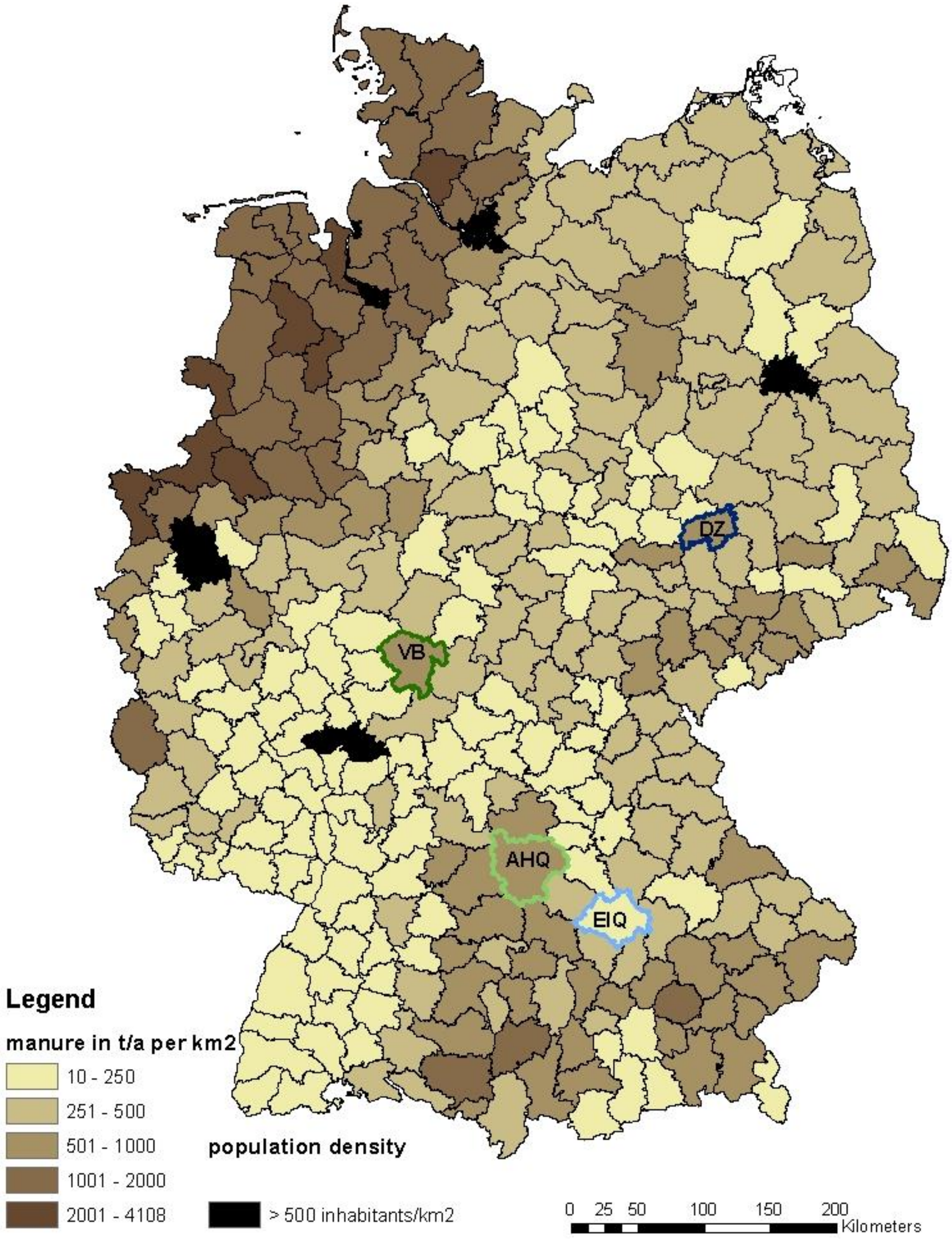


Data: RAUMIS and ReSI-M simulation, population density BBR and SOFL (2005)

What causes these regional differences of price and quantities in maize markets? To answer this question, we need to consider differences in the maize supply in addition to demand. Regarding the demand side, as explained in section 3, location factors “availability of inputs” and “transport costs” (distance) influence regional differences in maize demand.

Availability of manure is high in northwestern Germany, where agriculture is dominated by livestock production (see Figure 24). Manure production is also high in some regions in Bavaria, where there is a large amount of dairy production.

Figure 24: Manure availability by NUTS 3 region in t/a per km^2



Data: RAUMIS simulation, population density BBR and SOFL (2005)

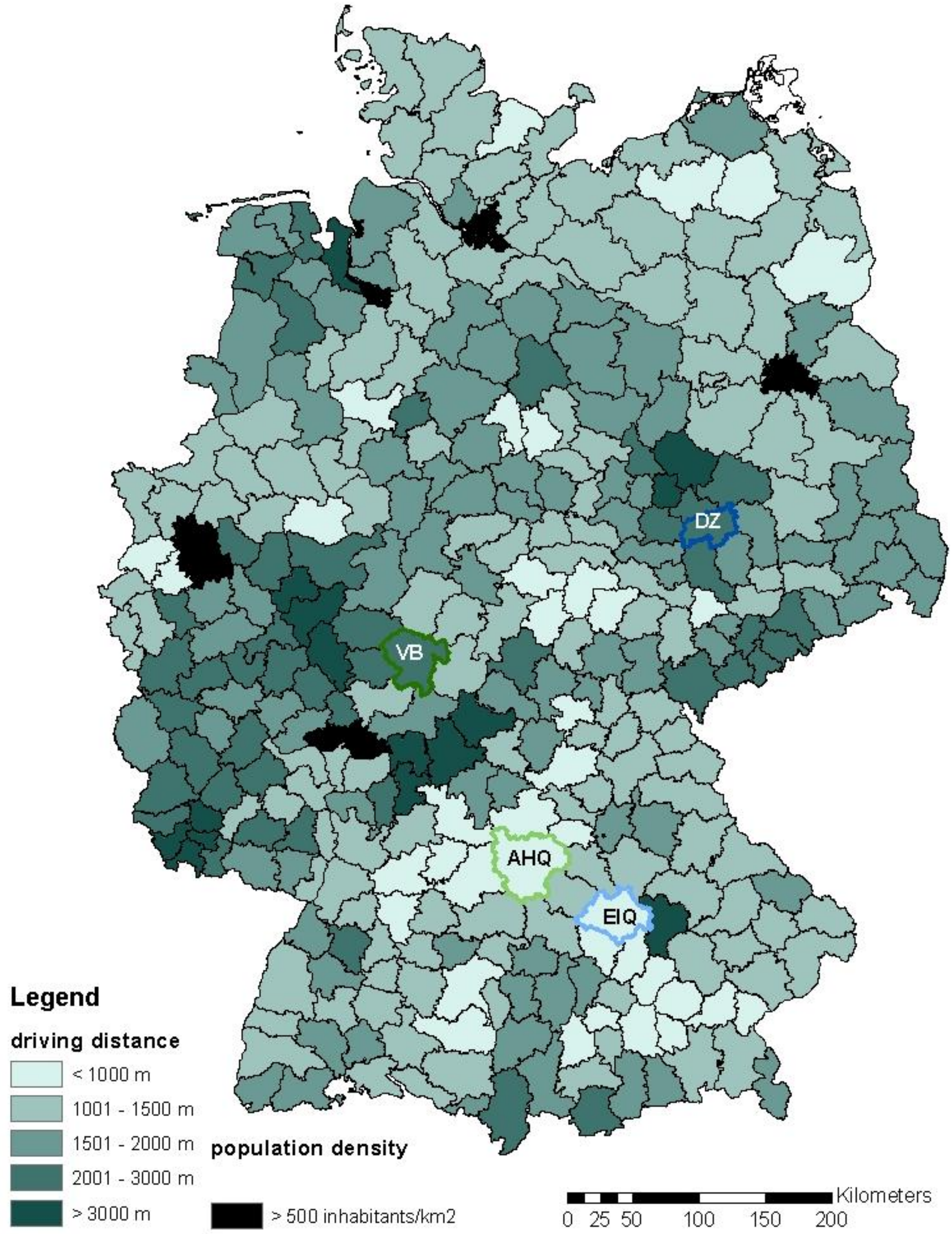
In addition to the absolute production of manure, the relationship between manure and maize availability is also relevant as one of the two inputs might restrict biogas production in a region. In the third row in Table 6 this ratio is displayed and we see that in Ingoldstadt (EIQ) and Vogelsbergkreis (VB), manure availability restricts biogas production. In ReSI-M we assume certain shares of manure which biogas plants use as input. Taking the shares of 30% manure and 70% maize as an example, in Table 6 the ratio regarding these input shares is illustrated. In addition to EIQ and VB, manure also limits biogas production in Delitzsch (DZ). At the same time, in regions where manure availability is high in relation to maize production, maize might become scarce causing prices to increase.

Table 6: Available inputs and ratio

	AHQ	DZ	EIQ	VB
manure (t/a)	1.27 mio	0.33 mio	0.24 mio	0.65 mio
maize (t/a)	5.39 mio	2.78 mio	3.8 mio	2.1 mio
ratio maize: manure	1 : 0.2	1 : 0.1	1 : 0.06	1 : 0.3
ratio: maize: manure with input shares	1 : 0.55	1 : 0.38	1 : 0.14	1 : 0.7

Another location factor is transport costs. Figure 25 displays the calculated driving distances in Germany for a plant size of 500kW$_{el}$. Note that this distance is assumed to rise with increasing numbers of plants constructed during the simulation process (cp. section 3.2). Differences in driving distances result from regionally differing yields, which are high in NUTS 3 regions in southern Germany and central Germany, as well as from differences in the homogeneity of land use, which is high in northern and north-eastern Germany.

Figure 25: Driving distances in German NUTS 3 regions



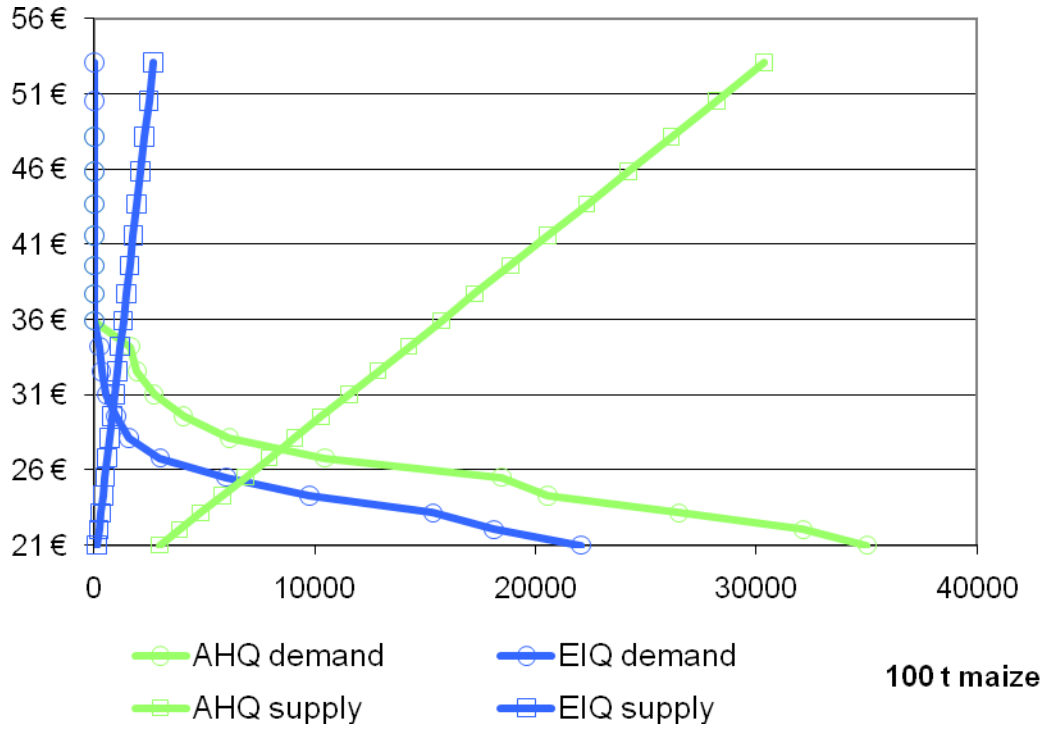
Data: ReSI-M simulation, population density BBR and SOFL (2005)

If we compare driving distances with the share of maize production on arable land (see Figure 22), there are some counties where only small amounts (and shares) of maize are produced at long transport distances. Greater transport distances and therefore high transport costs are a logical cause for low maize production. However, there are some regions where maize production is high despite high transport costs. In order to illustrate the impacts of location factors and the shape of supply functions on regional maize production, four counties (highlighted in Figure 24 and Figure 25) serve as examples.

In the counties Vogelbergkreis (VB) and Ansbach (AHQ), the share of maize production is high, marked in dark and bright green in the figures. A low share of maize production in Delitzsch (DZ) and Ingoldstadt (EIQ) is indicated with dark and bright blue. The colour brightness displays the length of transport distances: counties EIQ and AHQ are surrounded by a bright colour and have low transport distances, whereas distances are high in dark coloured VB and DZ.

Plausible examples are maize markets in AHQ with low transport distances and a high share of maize production and DZ with high transports costs and (as a result) a low share of maize production (see Figure 26). Due to transport costs, the demand function in DZ is a little steeper than in AHQ, while the supply curve is steeper as well, causing a lower equilibrium quantity in DZ.

Figure 26: Comparison of maize markets in AHQ, DZ and EIQ

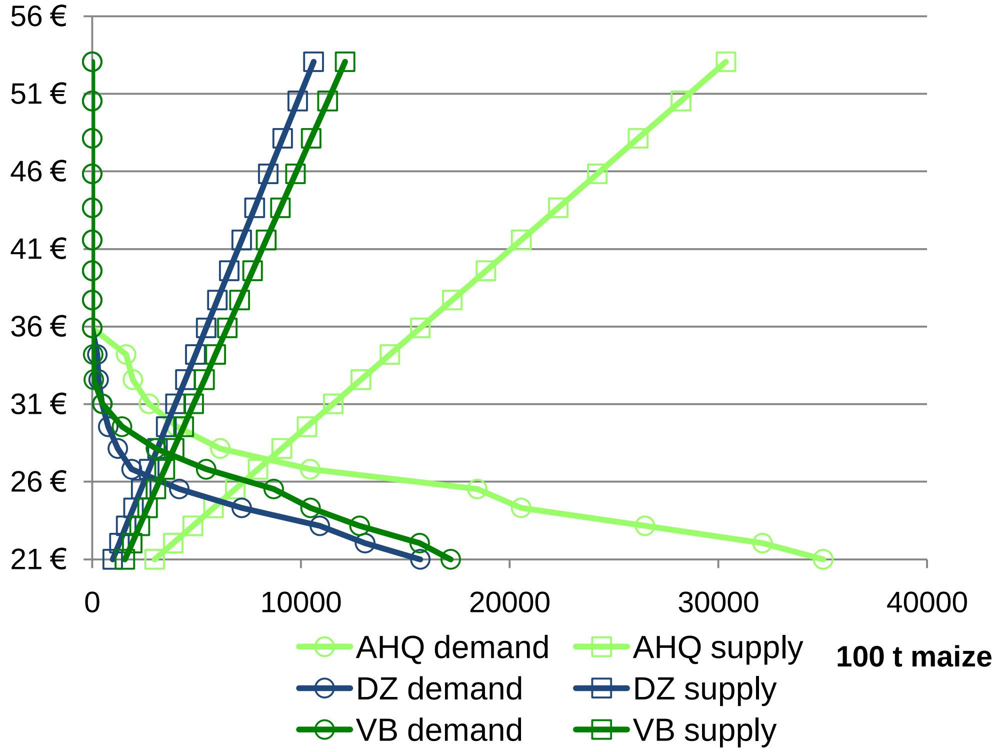


However, there are NUTS 3 regions where maize production is low despite low average transport costs. An example is EIQ. Comparing the two NUTS 3 regions with low transport costs, AHQ and EIQ, the availability of maize is high in both regions (cp. Table 6) and transport costs are therefore low. However, demand at the low price of 21€/tFW maize is lower in EIQ than in AHQ. The modelling results show a share of maize on arable land that is only 2% in EIQ but 15% in AHQ. An explanation is the **steeper supply curve** in EIQ, which causes a higher price for a given quantity or lower maize production for a given price.

Another counterintuitive case is VB, where transport distances and share of maize production are high. Comparing it to AHQ, equilibrium prices are quite similar, whereas absolute maize production in AHQ is almost double as high (see Figure 27 and Figure 23). The maize markets differ with respect to the supply and the demand side. On the supply side (by RAUMIS), the price elasticity is higher in AHQ, which means that if the price for maize changes, the quantity change is relatively high and other crops or activities are more competitive. Maize demand is influenced by a higher amount of available maize in AHQ, which results in **lower transport distances**. At a price of 21€/tFW in AHQ almost 3.5 mio tons of maize are in demand, whereas the crop remains in demand until a price of 35€/tFW. By contrast, in VB the availability of maize is lower and transport costs for maize are therefore higher. However, the availability of manure is higher, which decreases costs for manure accessibility. The influence on the cost of manure is described in detail in 3.8.1 and explains why maize demand is comparatively high in VB despite high transport costs.

In DZ transport costs of maize are as high as in VB and the inclination of supply curves is a little steeper in DR, but as demand in VB declines slower with rising maize price, the equilibrium price is higher (see Figure 27). This is mainly caused by the **availability of manure** (also compare Table 6**)**, which restricts biogas production in DZ and causes fewer costs for exploring manure in VB.

Figure 27: Comparing maize markets in AHQ, DZ and VR



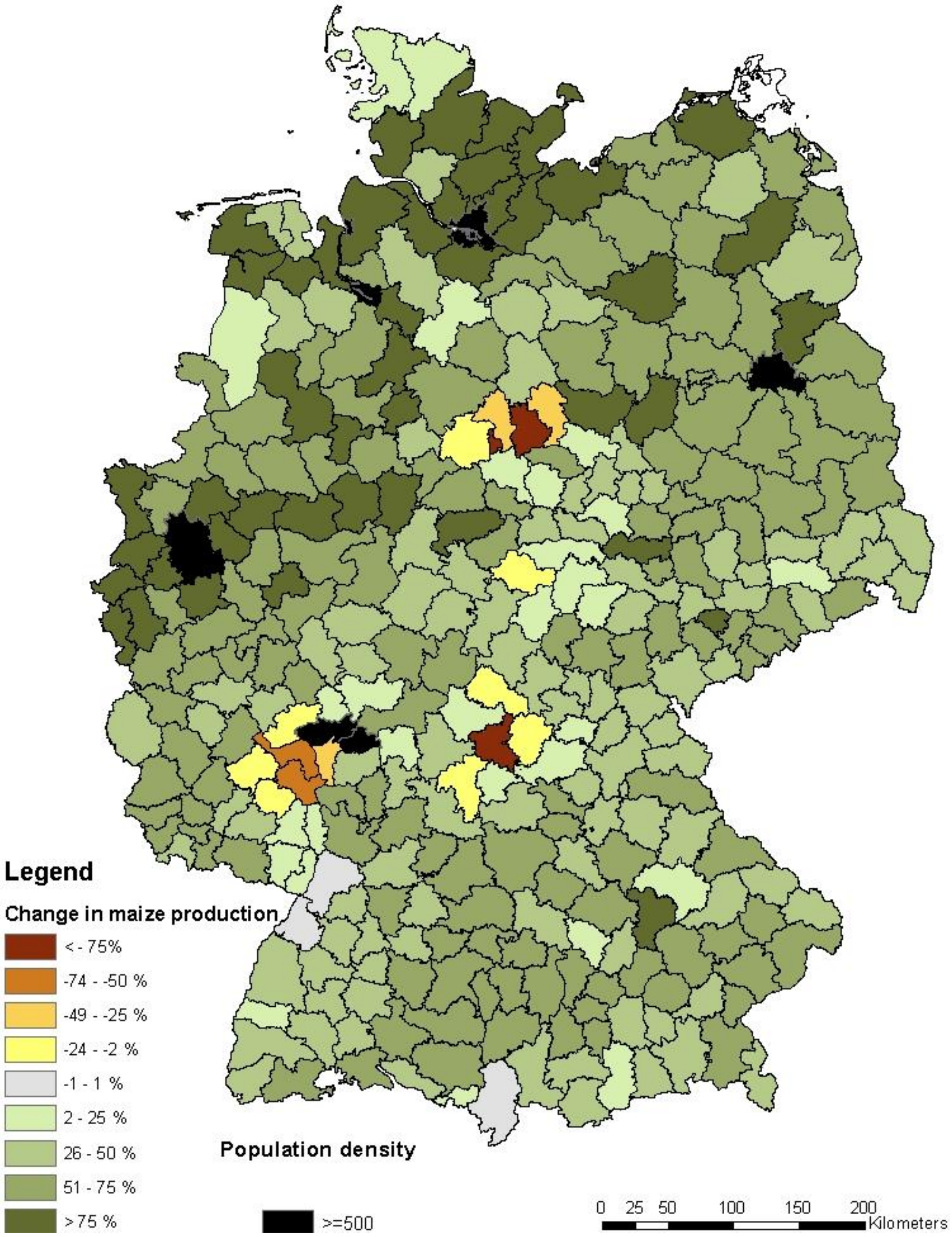
Therefore, in addition to manure availability and exports to neighbouring NUTS 3 regions (cp. section 3.8) three factors and their interactions influence regional maize markets: transport distances, available maize (determining number of possible plants and therewith number of iterations in the solving process), and the shape of the supply function from RAUMIS on the supply side.

The location factor "manure availability" is of special interest in the case of the EEG 2008 scenario, as here a certain share of manure input is rewarded with a special bonus in the law (see section 1.1.2). Its implications on maize production are analysed in the following section by comparing land use change under the EEG 2004 and 2008.

4.2.3.2 Maize production under the EEG 2008

Results for the EEG 2008 scenario show that in the majority of NUTS 3 regions maize production increases considerably under the EEG 2008 scenario compared to the EEG 2004 scenario (green shaded areas in Figure 28).

Figure 28: Change in maize production under EEG 2008 scenario

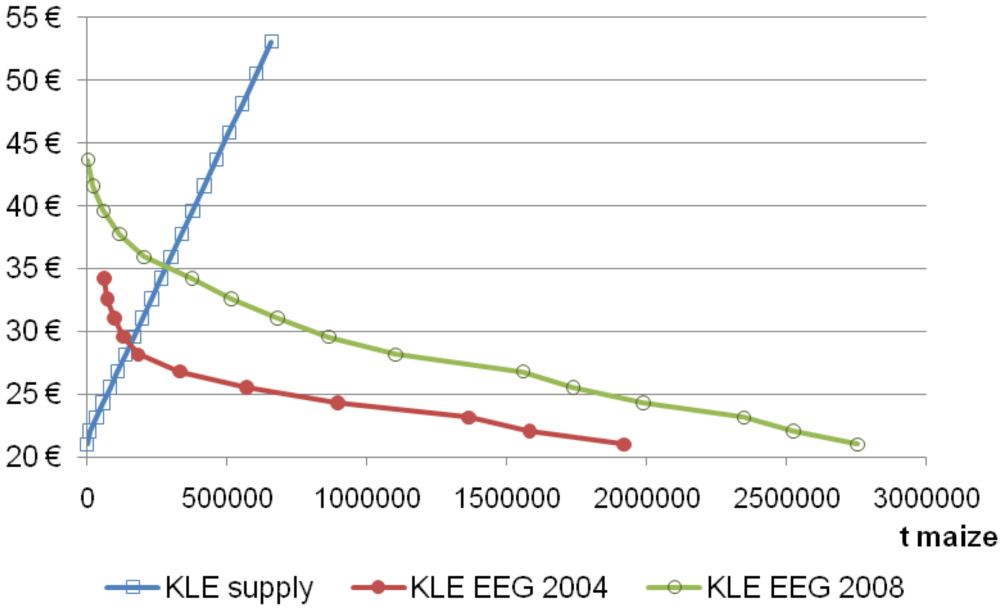


Data: RAUMIS and ReSI-M simulation, population density BBR and SOFL (2005)

The increase is especially high in regions with a high availability of manure (see manure availability in Figure 24). An example is displayed in Figure 29 and shows a higher demand under the EEG 2008, which causes the equilibrium maize price and quantity in Kleve (located in northwestern

Germany) to increase from 29 to 35€/tFW and 153,544 to 281,966 tFW maize respectively.

Figure 29: Maize market in Kleve (KLE) under EEG 2004 and EEG 2008 scenario



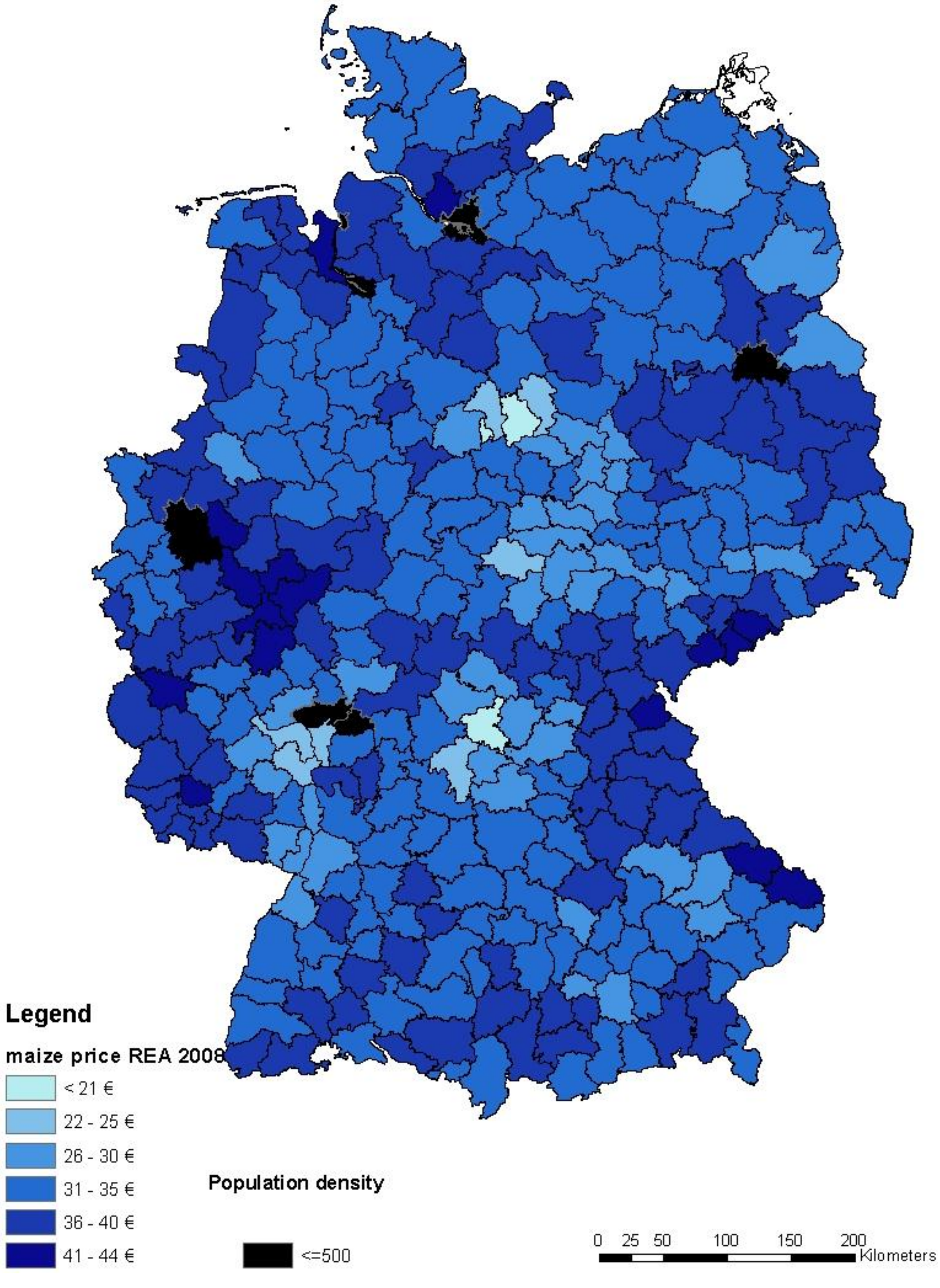
A detailed analysis of data shows that in regions with low manure availability some maize is “exported” into neighbouring NUTS 3 regions, but these exports do not compensate for a decrease in biogas production and therefore maize demand within a NUTS 3 region with low manure availability. Given, that small-scale plants using a share of 30% of manure receive an additional bonus in the EEG 2008, the plants are very profitable and high prices can be paid. This implies that economies of scale in the biogas production by large-scale plants diseconomies are not able to offset the combined effects of decreasing per unit subsidies and higher per kWh_{el} transportation costs when transport distances increase.

Maize production decreases in areas such as central Germany and the Rhein-hesse region (yellow to brown shaded regions). Here, manure availability is low compared to maize availability. Despite the fact that small-scale plants are also constructed in regions with low manure availability, less maize is demanded compared to the baseline scenario due to restrictions in manure accessibility.

The effect on maize prices is illustrated in Figure 30. At the EEG 2008 scenario, prices increase in all counties except for regions marked light blue.

In these regions, lower prices are paid due to manure availability and other crops are more compatible. In the other counties, when competing with other crops, maize is the most profitable option and production is therefore high. In total, farmers receive a higher income from maize cropping in the EEG 2008 scenario.

Figure 30: Regional market clearing prices at EEG 2008



Data: RAUMIS and ReSI-M simulation, population density BBR and SOFL (2005)

For total maize production under the EEG 2008 more land is used for maize production (1,699,206 ha) than in the reference and the EEG 2004 scenario.

In addition to the effect of an absolute land use change, the land use per produced kWh_{el} is an important criterion to assess for different policy options. Approximately 8% more land is needed per kWh_{el} produced under the EEG 2008 compared to the EEG 2004 scenario. This result is counterintuitive, as more manure is used in plants constructed under the EEG 2008 scenario, but we can explain this by, first of all, the low energy content of manure and, secondly, low energy efficiency of small-scale plants:

Energy content of manure is more than six times lower than the energy content of maize. Therefore, an increase in the share of manure as input for biogas production does not lead to the same amount of decrease in maize input. The plant structure changes from mainly $500kW_{el}$ plants using 10% manure under the EEG 2004 to $150kW_{el}$ plants using 30% of manure as input under the EEG 2008. However, when applying a share of 30% manure, the manure share of total biogas production is only 7%. As a result, the different plant structure demands only 6% less maize per kWh_{el} whereas manure input increases from 10 to 30%.

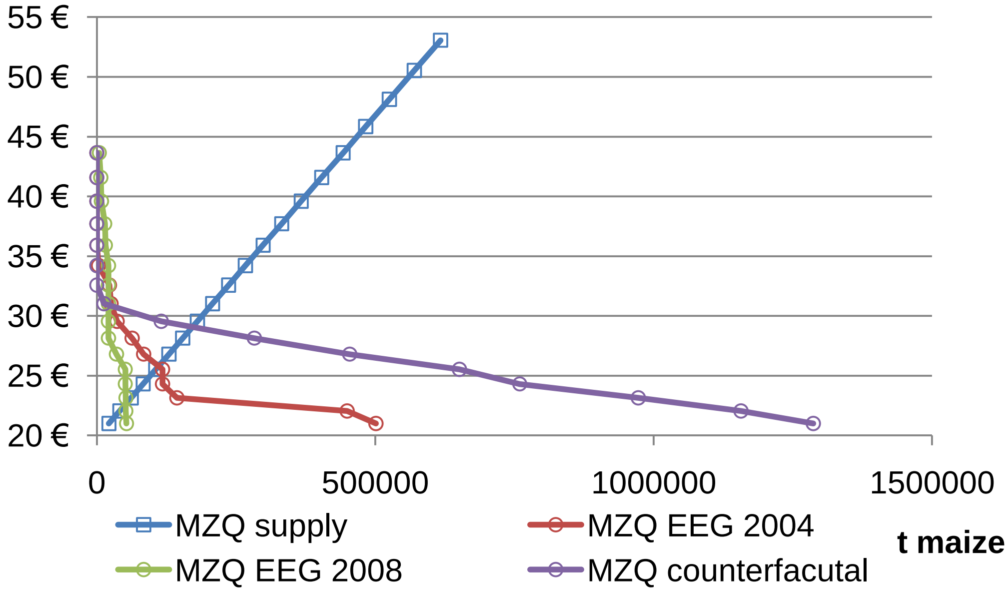
The second reason relates to the electrical efficiency of different plant sizes. Electrical efficiency of small-scale plants is assumed to be only 33.5% compared to 37.5 % for 500 kW_{el} plants and 41.7% for 2000 kW_{el} plants (see section 3.4.1). Therefore, 500 kW_{el} plants are about 12% more energy efficient and 2000 kW_{el} plants are even 24% more energy efficient than $150kW_{el}$ plants. With some share of large-scale plants using 1% of manure constructed in the 2004 scenario, the plant structure causes about 8% more demand per kWh_{el} for land in the EEG 2008 scenario compared to the EEG 2004 scenario.

4.2.3.3 Maize Production at Counterfactual Scenario

In this section we compare land use for maize production under the EEG 2004 and 2008 with the one for the counterfactual scenario (production of approximately the same amount of energy, see section 4.1), and also address the land use per produced kWh_{el}. Based on this we can assess which of the policy settings is favourable if the land is to be used efficiently to reduce competition for land.

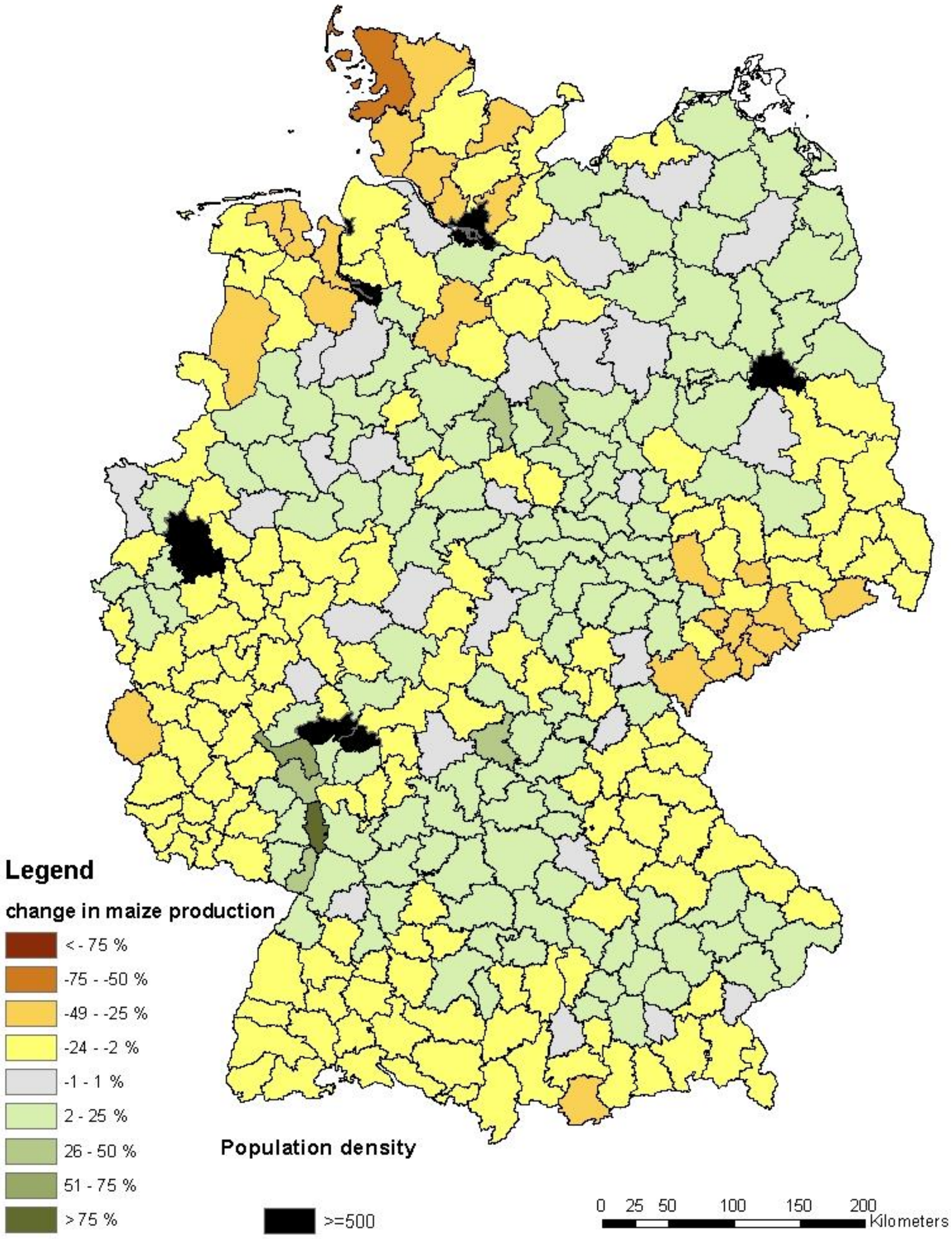
In the counterfactual scenario, maize production per kWh_{el} is lower in yellow shaded counties (see Figure 32), and increases in green shaded counties compared to the EEG 2004 scenario. The reason for these regional differences is the plant structure which results from these scenarios: in the counterfactual scenario mainly large-scale plants using only 1% of manure are constructed, complemented by medium-scale plants in some counties. In counties in eastern Germany or the Rhine-Main area, availability of manure is low in relation to maize availability, but given the 1% share of manure used in large-scale plants, the availability of manure does not cause restrictions for those plants. Figure 31 provides an example for a region with low availability of manure. We see that under the EEG 2004 scenario, at a maize price of 21€/tFW, less maize is demanded (red curve) compared to the counterfactual scenario (purple curve). This effect is even larger under the EEG 2008 where low manure availability causes the equilibrium price and quantity to drop considerably (green curve). Simulation results show that the available manure is consumed by small-scale plants, and even though larger plants using less manure would make profit, a lack of manure restricts the construction of further plants

Figure 31: Maize market in Mainz (MZQ) under the three scenarios



Besides availability of inputs, another factor for a high demand for maize is low transport costs. Transport costs are low in central and northeastern Germany and some districts in Bavaria (driving distances are also compared in Figure 25). As a result, compared to the EEG 2004 scenario, in these counties more maize is demanded under the counterfactual scenario (green shaded counties).

Figure 32: Change in maize production from EEG 2004 to counterfactual scenario



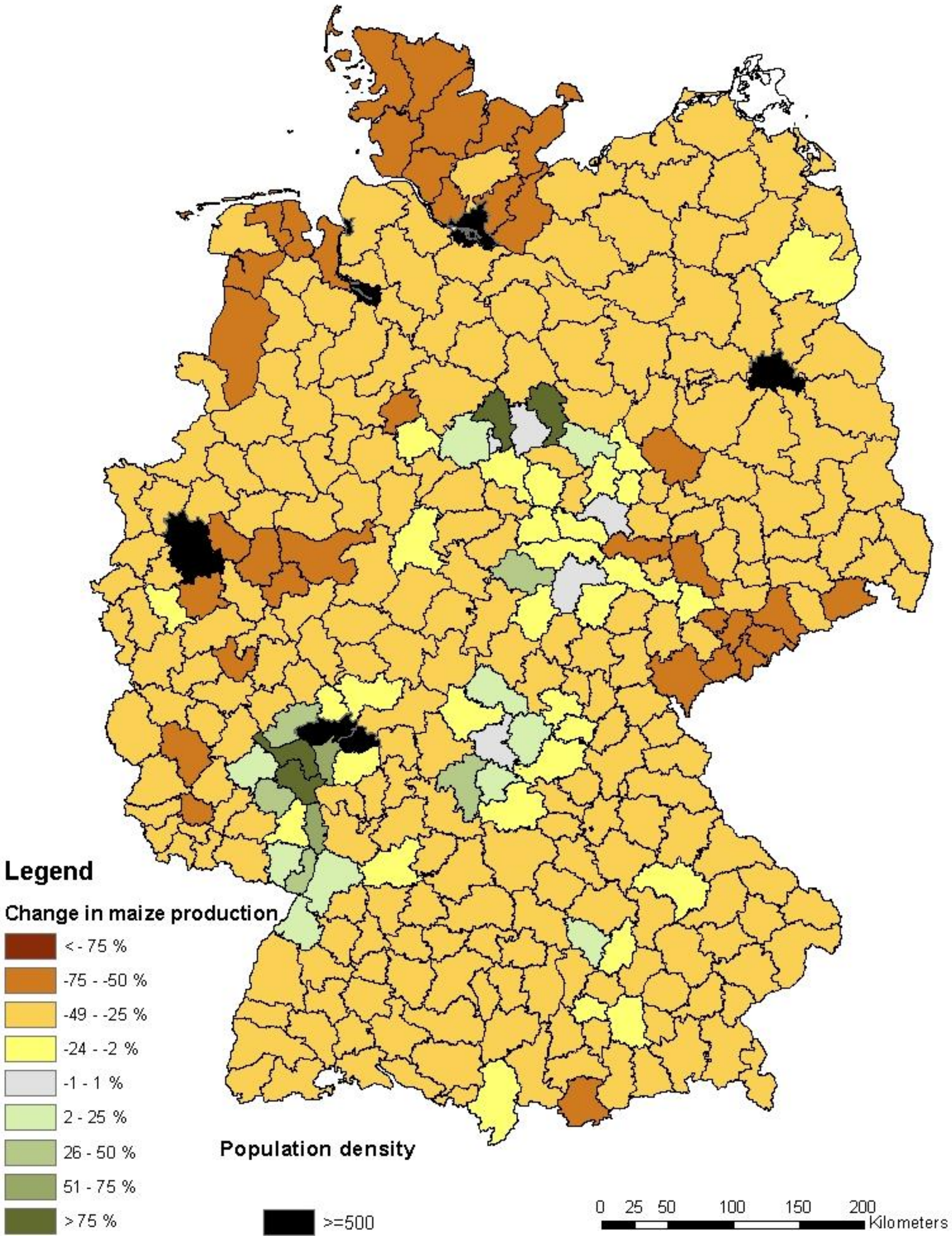
Data: RAUMIS and ReSI-M simulation, population density BBR and SOFL (2005)

To assess the efficiency of land use between the two scenarios, we compare the land use per produced kWh_{el}. In total, about 4% more land per kWh_{el} is used under the counterfactual scenario compared to the EEG 2004. With a majority of plants which use 10% maize, in the EEG 2004 more maize is substituted by manure due to the differing plant structure, as explained before. Hence, a uniform FIT leads to regional changes in maize production, and more land is consumed. An advantage of the counterfactual scenario with respect to CO_2 emissions is that it favours maize production in regions with short transport distances. This information is used in section 4.2.4 on CO_2 emissions of transports.

If we compare the counterfactual scenario with the EEG 2008 scenario (see Figure 33), less maize is produced in most counties (yellow to brown shaded regions), whereas in regions with a low availability of manure and low transport costs, maize production increases (green shared regions). Thus, the effects explained for the comparison of the EEG 2004 and the counterfactual scenario are stronger in the case of the EEG 2008, as here the availability of manure has an important influence on biogas production. We see that particularly in northwestern Germany and the Ore Mountains (Erzgebirge) in Saxony, where the share of maize on arable land under the EEG 2008 is high (see Figure 28), under the counterfactual scenario maize production decreases (brown shaded regions in Figure 33). As explained in section 1.1.3, maize production for feeding livestock is already high in regions in northwestern Germany with a high amount of manure production (see Figure 24), which causes a risk of nitrogen surpluses.

With respect to the efficiency of land use (ha per kWh_{el}), in contrast to the EEG 2004 scenario, about 4% less land is consumed for biogas production under the counterfactual scenario when comparing it to the EEG 2008 scenario. Although mainly plants using 99% maize are constructed in the counterfactual scenario, less land is needed compared to the plant structure in the EEG 2008 scenario, in which mainly plants using 70% maize are constructed. The reason for this, as explained in detail in 4.2.3.2 , is the low energy content of manure and the higher energy efficiency of large-scale plants.

Figure 33 Change in maize production from EEG 2008 to counterfactual scenario



Data: RAUMIS and ReSI-M simulation, population density BBR and SOFL (2005)

In summary, the model results for regional maize production show considerable differences throughout the applied scenarios. Most maize is produced under the EEG 2008 scenario, which is caused by higher FITs. They allow biogas plants to pay higher prices for maize and thereby crowd out other production activities in a region. Due to different plant structures which are simulated under the scenarios, results show differences in regional maize markets. In regions with already high maize production for animal feed, maize production for biogas further increases the share of maize on arable land under the EEG 2008 scenario. Land use per kWh_{el} is the lowest under the EEG 2004 scenario, followed by the counterfactual scenario. Hence, the same amount of energy production causes the least amount of land consumption under the EEG 2004 scenario.

The impacts of these differences in regional land use are used to assess the differences in transport distances and plant structures in the scenarios serve to address CO_2 emissions in transport in the next section.

4.2.4 CO_2 Emissions from Biogas Production

Another important issue when comparing different policy options for biogas promotion is the performance with respect to climate protection, as this is one of the targets of the EEG (see section 4.2.1). As stated in the literature review in section 4.2 there is currently no extensive information available of the impact of regionally divergent transport distances on total greenhouse gas emissions of biogas production. Based on modelling results, we therefore calculate region-specific CO_2 emissions from transports of maize and residues caused under each policy setting and relate them to studies of overall greenhouse gas emissions of biogas production. Moreover, the simulations allow us to assess the resulting plant structure caused by the policy settings with respect to transport emissions per produced kWh_{el}. We first address CO_2 emissions of transporting maize, followed by a look at transporting processed and unprocessed residues.

4.2.4.1 CO_2 Emissions from Maize Transport [7]

In our scenarios, biogas is produced by simulated plants and, in the case of the EEG 2004 and 2008 scenarios, existing plants are additionally taken into account. Thus, maize transports from existing and simulated plants need to be considered in the calculation of CO_2 emissions per kWh_{el}. For the simulated plants, the model results show transport distances for the number and sizes of plants built under the applied scenario. These transport distances differ depending on the plant size, yields and distribution of land. In addition, the amount of electricity in kWh_{el} produced annually is shown.

To determine electricity production of existing plants in the EEG 2004 and 2008, the number of plants per state and per capacity class is taken from SCHLOWIN ET AL. (2007b). However, sizes of existing plants can only be found as average values or shares in literature. Average values denote that the number of plants is known and that the average plant size of these plants and information on average shares contains information on the shares of plants

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[7] Parts of this section were utilised in the paper "Modelling regional maize market and transport distances for biogas production in Germany" by DELZEIT, R., W. BRITZ AND K. HOLM-MÜLLER, (forthcoming) in: Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaus e.V. "Agrar- und Ernährungsmärkte nach dem Boom".

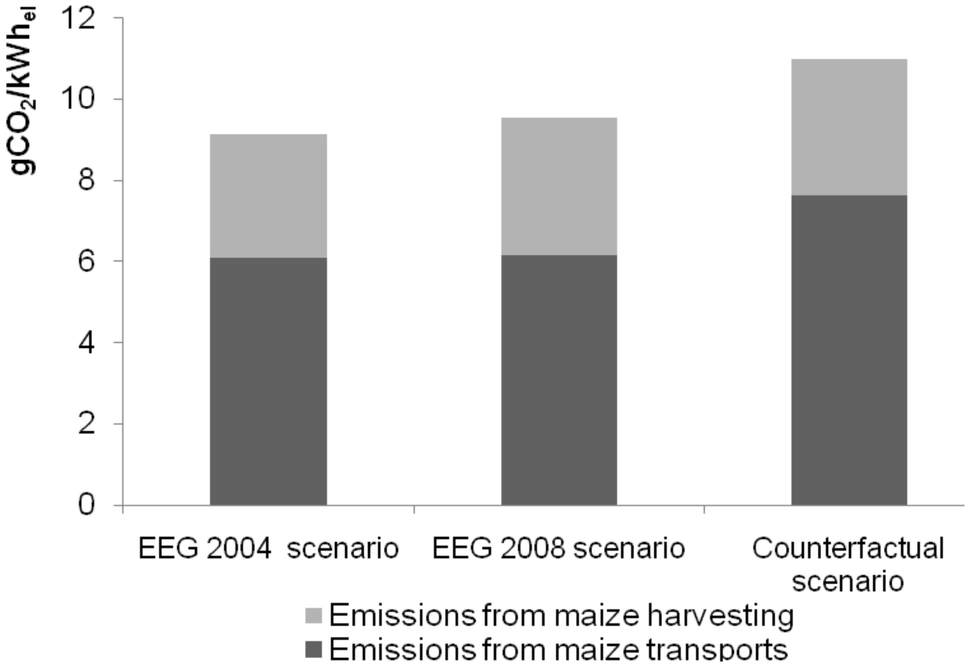
within a defined range of plant sizes. Since a distinct value for shares of plant sizes on a regional scale cannot be found in literature, the shares of plant sizes are taken from model results and the number of plants for each plant size is calculated. Multiplying the number of plants per plant size with regional transport distances (from ReSI-M) for the respective plant size determines transport distances for existing plants in every region. The electricity produced annually in kWh_{el} and transport distances caused by existing plants are added to respective values simulated by ReSI-M for newly constructed plants.

CO_2 emissions from transport are caused by diesel consumption of the chaff cutting machine during harvest and by transport units which move the chaff cut maize from the field to the plant. As for transport costs of maize used in the model, TOEWS AND KUHLMANN (2007) have calculated the fuel consumption per ha for defined driving distances. We use our respective regional transport distances and the harvesting areas to calculate CO_2 emissions from those transports. Furthermore, we add CO_2 emissions from the chaff cutting machine, adapting assumptions from TOEWS AND KUHLMANN (2007): 0.4 hour/ha for chaff cutting and a diesel use quantity of 32.6 litres/hour. To calculate fuel consumption, we multiply the harvesting area (ha) from the model results with the chaff cutting speed (h/ha) and the diesel consumption (litres/hour). The resulting diesel consumption of the chaff cutting machine and transport units (in litres) is then multiplied by CO_2 emissions caused by each litre of diesel (2.65 kg/litre) (BMU 2008).

Emissions from maize transports in g CO_2 per kWh_{el} are displayed in Figure 34. Given different amounts of energy production in the scenarios, they are compared based on the emissions per kWh_{el} produced. In the EEG 2004 scenario, emissions of 8.9 g CO_2 per kWh_{el} emerge. Emissions in the EEG 2008 scenario are slightly higher, whereas in the counterfactual scenario, emissions increase by 24% compared to the baseline scenario and 17% compared to the EEG 2008 scenario. Note that no transport of manure input is considered, as these transports would have occurred for manure application anyway and are accounted for in livestock production.

In the counterfactual scenario, longer distances can be driven to harvest maize with higher revenues and, as we see in section 4.2.3.3, plants are constructed in regions with low transport distances. However, compared to smaller plants, transports show diseconomies of scale and less manure is used in large-scale plants. With higher energy efficiencies of BHPPs and better possibilities to use the heat by-product resulting from processing biogas (see section 1.1.2) large-scale plants built under the counterfactual scenario might feature better CO_2-performance than small-scale plants. Nevertheless, these potential CO_2-balance gains in processing are at least partly offset by rising CO_2 emissions from transports.

Figure 34: CO_2 emissions per kWh_{el} from transports for the scenarios



Besides these average CO_2 emissions for scenarios displayed in Figure 34, model results also display regional differences in CO_2 emissions, which depend on transport distances.

Taking again the example of AHQ as a county with low transport distances and Olpe (OE) as one with very high transport costs, Table 7 illustrates the influence of driving distances on CO_2 emissions for different plant sizes. Transport emissions of maize consist of emissions from the chaff cutting machine and emissions from transport units, which deliver maize from the chaff cutting machine to the plant or storage location. The latter factor depends on driving distances. In OE, for the 500 kW_{el} (10% manure) plant type distances are seven times higher than in AHQ, which causes the CO_2 emissions from transport to almost triple and the impact of driving distances on total maize transport emissions increases as plant size grows.

Furthermore, we see different emission levels across the four plant types and the two regions in Table 7: in AHQ due to low transport distances, the difference in CO_2 emissions per kWh_{el} between the plant types varies between 8.9 and 8.2 g CO_2/kWh_{el} and is the smallest for a 2000 kW_{el} plant. On the contrary, in OE the variance between transport emissions is large and here large-scale plants have the worst performance with respect to CO_2- emissions per kWh_{el}.

Table 7: CO_2 emissions in AHQ and OE for different plant types

	AHQ	**OE**
Plant type	**Transport emissions in g CO_2/kWh_{el}**	**Transport emissions in g CO_2/kWh_{el}**
150 kW_{el} (30% manure)	8.9	19.2
500 kW_{el} (10% manure)	8.4	22.9
1000 kW_{el} (1% manure)	8.3	25.8
2000 kW_{el} (1% manure)	8.2	30.0

As a result, a policy on biogas production which aims to protect the climate should restrict biogas production from large-scale plants to regions with low transport distances, and at the same time should encourage small-scale plants using manure to be constructed in regions with high transport costs.

Residues from the fermentation process need to be transported back to arable land. We will now analyse emissions from transport of residues.

4.2.4.2 Calculation of CO_2 Emissions from Residues Transport

In studies on LCA of biogas production, transports of residues are neglected as manure from livestock and dairy production would have had to be transported regardless if it had not used for biogas production. However, the share of residues from maize is considerable and has grown for biogas production in particular. This share is especially high for large plants using a high share of maize from large harvesting areas, which is why residue transport becomes more important for overall greenhouse gas emissions. In recent years, techniques have been developed to process residues in order to make the application of residues more profitable and transport them over longer distances to substitute mineral fertilisers. Yet data and information on processing of residues, their transport and emissions is significantly lacking. Therefore, we conducted expert interviews with operators of biogas plants in order to gain information on driving distances for processed and unprocessed residue transport. The interviewed operators, which in some cases are farmers and produce the needed inputs for biogas production themselves, could not state average distances they drive for residual application directly, but provided some information on distances to the most distant fields. Further information includes the influence of regional factors such as yields, field size but also the amount of nutrients in residues and plant sizes on driving distances – and hence CO_2 emissions from residue transport. The different plants these operators gave information about are indicated in Table 8. We see that they cover a broad variety of inputs and plant types. Additionally, the plants are distributed across Germany with regionally differing location characteristics. We consider these factors to calculate CO_2 emissions for disposing processed and unprocessed residues.

Table 8: Overview on biogas plants

Biogas plant	**Capacity**	**Inputs**		
	kW$_{el}$	**Inputs in t**	**Type of inputs**	**Share**
Plant 1	225	8.900	Liquid manure (pig) Solid manure (cow/turkey) Maize Grass silage Entire-plant silage	35% 31.5% 23% 5% 5.5%
Plant 2	450	15.800	Liquid manure (pig) Liquid manure (cow) dry excrement (chicken) Salate waste Maize corn waste	16% 25% 3% 32% 19% 5%
Plant 3	500	13.000	Maize Liquid manure (pig) Solid manure (chicken)	60% 30% 10%

Plant 4	500	k. A.	Cooking fat Food remains Straw Solid manure (chicken)	k. A. - - -
Plant 5	1.000	15.000	Sugar beet CCM,GPS, sun flowers. Solid manure (chicken) Liquid manure (pig/cow)	40% 14% 20% 26%
Plant 6	1.050	18.250	Maize dry excrement (chicken) grain	70% 20% 10%
Plant 7	4.000	80.000	Maize Grass silage GPS Interim crops Liquid manure (cow)	50% 10% 20% 10% 10%
Plant 8	5.250	70.000	Maize Grass silage Grain flour Solid manure (chicken) t	66% 12% 12% 10%
Plant 9	20.000	450.000	Maize Liquid manure (pig) Grains	80% 15% 5%
Plant 10	22.000	380.000	Maize Grains GPS Grass silage	85% <1% 13% 2%

An important factor to determine driving distances for processed and unprocessed residues is the maximal amount of residue that can be disposed on the soil. Based on the German regulation on fertiliser (BGBL 2007) and its implications on residue (see section 1.1) we assume that a farmer can dispose the same amount of nitrogen (N) and phosphate (P) per ha annually, which is extracted by maize per ha over the course of a year, in order to determine the area needed for residual application. According to FRUHSTROFER ET AL. (2004, p. 110), a harvest of 50 tFW maize production per ha extracts 190 kg N and 80 kg P. Therefore, it is assumed that a maximum amount of 190 kg of nitrogen per ha and 80 kg per ha of phosphate is returned to the field. Depending on the ratio of nitrogen and phosphates (phosphorus-containing compounds) in residue, the amount of residue able to be used on arable land is restricted by either the nitrogen or phosphate content of residue.

In the next section we analyse and compare CO_2 emissions for processed and unprocessed residue and discuss how to include the results in total transport emissions.

Emissions from Unprocessed Residues

The amount of nutrients in residue varies with the inputs used for biogas production. Based on the assumption that farmers apply the same amount of nutrients as are extracted during a year, we determined average values of the eight investigated plants from values determined by expert interviews. They result in 6.32 kg N and 2.61 kg P_2O_5 per t of residue. These values are comparable with average values from the KTBL (see BECKER 2007, p. 128). In order to compensate for nutrition losses from harvesting, approximately 23 m^3/ha of residue is needed in the case of N and 30 m^3/ha in the case of P. Assuming there are 30 m^3 of residue per ha, we calculate the area needed for residue application by dividing the annual amount of residue by 30m^3/ha. We use this area to calculate radii around biogas plants, which reveal the average driving distance around a plant (column “radius application” in Table 9). Note that an average radius is applied given that transport units do not always drive to the outermost line of a circle surrounding the biogas plant (see section 3.2).

A drawback of this approach is that we implicitly assume that the total area around a plant is agricultural land, which is not true in reality.

Table 9: Arable land needed for residues' application

Biogas plant	**Capacity (kW_{el})**	**Residues (m^3/year)**	**Application area (ha)**	**Average radius application (km)**	**Average radius harvest (km)***
Plant 1	225	12,344	411.5	1.1	2.1
Plant 2	450	13,768	458.9	1.2	1.3
Plant 3	500	24,688	822.9	1.6	1.4
Plant 4	500	13,768	458.9	1.2	1.9
Plant 5	1,000	27,536	917.9	1.7	2.0
Plant 6	1,050	27,536	917.9	1.7	3.0
Plant 7	4,000	70,831	2,361.0	2.7	5.6
Plant 8	5,250	88,539	2,951.3	3.1	10. 7
Plant 9	20,000	389,573	12,985.8	6.4	10.9
Plant 10	22,000	389,573	12,985.9	6.4	8.3

* see section 3.2

Therefore, we utilise another approach to calculate driving distances for residual application in which we combine outcomes from ReSI-M with results from expert interviews with operators of biogas plants. ReSI-M shows the radii of harvesting areas (right row in Table 9, calculation see section 3.2) for the respective NUTS 3 region for each plant. The radii from ReSI-M include factors such as the distribution of arable land, which therefore takes into account that fields of arable land are disconnected by, for example, settlement areas and infrastructure. The resulting radii are then larger than radii from the first approach (application area). An exception is plant 3, where the average harvesting radius is smaller than the other average radii. This exemption is caused by a high share of arable land and its homogenous distribution in Unna county (information from ReSI-M), which leads to a low average harvesting radius. At the same time the plant generates a relatively high amount of residue, which results in a large application area. Compared to plant 4, which has an equal plant size, plant 3 produces almost 80% more residues, and consequently according to the second approach the resulting radius is larger.

Given the advantages of respecting regional factors, the second approach is applied to calculate transport emissions resulting from the application of unprocessed manure in the following analysis. Therefore, if we presume that residues are brought back to the fields where the used maize stems from, the same area as the harvesting area is needed for application.

Beside the average driving distances, another factor which influences CO_2 emissions for residue application is average field size. Even with the same driving distances, more fuel is consumed at small field sizes as transport units need to stop and change fields more often. Different field sizes are not included directly in ReSI-M (only explicitly by distribution of land). For the case studies of the ten biogas plants, field sizes are requested as part of the interviews. We tested its sensitivity by comparing diesel consumption in the case of different field sizes with results of diesel consumption when applying average field sizes of 10 ha. Results show that diesel consumption per ha differs by only 3-4%.

Field sizes gained from interviews, diesel consumption and resulting CO_2 emissions are illustrated in Table 10. Applying the "diesel consumption calculator" by KTBL for operation group "manuring" (for detailed assumptions on techniques, see WESTERSCHULTE 2010), diesel consumption per ha is calculated. As we know the harvesting area (ha), we can determine diesel consumption per year. Using CO_2 emissions caused by each litre of diesel (2.65 kg/litre) (BMU 2008), we obtain CO_2 emissions per year in g/kWh_{el}. The resulting amounts of CO_2 emissions and influencing factors are displayed in Table 10, where values range between 2.49 g CO_2/kWh_{el} at plant 7 and 6.1 g CO_2/kWh_{el} at plant 1. The main reason is the amount of manure input: a high amount of manure (60% in plant 1 see Table 8) results in a relatively high amount of residue (see section 3.8.4 on a conversion index). The amount of residue is also high at plant 3, but compared to plant 1, the average radius is smaller, which results in less CO_2 emissions per kWh_{el}. The other plants use lower shares of manure as inputs (see Table 8), but diesel consumption per ha differs tremendously, which is caused by average radii and field sizes (see Table 10). Plants using mainly maize, such as plant 5 and 6 (both about 20% manure) have a capacity of about 1000 kW_{el}, but CO_2 emissions per kWh_{el} are lower in plant 5 due to lower transport distances. Comparing biogas plants 7 and 8, both use about 10% manure input, CO_2 emissions per kWh_{el} are higher at plant 8 than at the plant 7 (see Table 10).

Another factor influencing CO_2 emissions per kWh_{el} is plant size: when determining CO_2 emissions per kWh_{el} from diesel consumption per ha, energy efficiency of plants has a substantial impact on the values of different plant sizes. As explained in section 4.2.3, energy efficiency increases with plant size, which lowers values of CO_2 emissions per kWh_{el} of larger plants compared to values for diesel consumption per ha.

Table 10: CO_2 emissions of unprocessed residue

Biogas plants	Capacity	Average radius	Field size	Diesel consumption	CO_2 emissions per year
	kW_{el}	km	ha	l/ha	g/kWh_{el}
Plant 1	225	1.6	4	9.6	6.1
Plant 2	450	0.9	6	8.6	2.9
Plant 3	500	1.0	10	8.3	4.6
Plant 4	500	1.4	7	9.1	2.8
Plant 5	1,000	1.5	12	9.1	2.6
Plant 6	1050	2.2	10	10.3	2.9
Plant 7	4,000	4.2	2	14.1	2.5
Plant 8	5,250	8.0	13	19.3	3.3
Plant 9	20,000	8.2	45	19.4	3.8
Plant 10	22,000	6.2	40	16.3	2.9

Biogas plants 9 and 10 are hardly comparable to the other plants, given their sizes of 22,000 and 20,000 kW_{el}, as well as difficulties of ReSi-M to calculate driving distances accurately (the distance seems to be low compared to distances driven in reality). However, biogas plant 9 has relatively high diesel consumption per ha and CO_2 emissions per kWh_{el} despite low shares of manure and large field sizes, but driving distances are comparatively high.

In the following section we analyse CO_2 emissions if residue is processed.

CO_2 Emissions from Transport of Processed Residue

Processed residue can be transported over longer distances as their water content is reduced, which allows for its transportation at lower costs and therefore makes it profitable to transport over longer distances. Therefore, we have surveyed operators of biogas plants on their driving distances for processed residue (see “max. driving distance” in Table 11). A comparison of model results of driving distances of unprocessed residue and interview results on processed residue shows that distances for all plants are higher for processed residue, as expected (cp. Table 10 and Table 11). The difference is especially high for plants 9 and 10 (large-scale plants). However, the transport medium is different for processed residue and therefore diesel consumption.

To determine CO_2 emissions from transports of residue, we need to consider a liquid and solid phase in which residue is separated during processing. Based on information on transport distances, field sizes and nutrients contained in residues, as for unprocessed residues, the “diesel consumption calculator” is applied, however with a different machine combination due to the two phases (for more detail, again see WESTERSCHULTE 2010). Resulting diesel consumption of the processed solid and fluid residue per ha is displayed in Table 11. The plants are aggregated into three groups according to the shaded fields in different grey scales.

Table 11: Diesel consumption per ha for processed solid and liquid residues

Biogas plant	**Max. driving distance Interviews**	**Field size**	**Diesel consumption solid phase**	**Diesel consumption liquid phase**
	km	**ha**	**l/ha**	**l/ha**
Plant 1	3	4	7.5	9.1
Plant 2	4	6	6.1	-
Plant 4	2	7	5.4	5.5
Plant 6	5	10	3.9	-
Plant 7	10	1,5	22	23.3
Plant 8	15	13	17.2	24.4
Plant 9	20	45	18.5	35.6
Plant 10	30	40	32.5	43.9

The calculator only displays diesel consumption per ha. In the case of the unprocessed residues we derived the application area in ha by assuming it to be equal to the harvesting area. Given the longer driving distances, as well as different nutrient contents in processed residues it would not be an adequate assumption for processed residues. Therefore, we have to use a different approach in which we first calculate CO_2 emissions per ha (*eh*) (l/ha times 2.65 kg CO_2/litre, BMU 2008). We use this values as well as t residue per ha (*res*) and g N/t residue (*nres*) (from interviews) to determine CO_2 emissions per g of N (*en*) according to the following formula:

$$(9) \qquad en = \frac{eh}{res * nres}$$

Interview results show that *nres* varies between the biogas plants, and accordingly different N and P values have been stated. To make them comparable, we assume that all plants process residues completely. The resulting value of *en* (in g CO_2/g N) is multiplied by the absolute amount of N in residue and divided by the annual production of energy in kWh_{el} for the respective plants.

Table 12 illustrates CO_2 emissions per kWh_{el} for the different plants. They are lowest in plants 4 and 8 due to good processing performance, which means that water content is low and less material needs to be transported. At plant 10 the driving distance for processed residue is 30 km, which causes CO_2 emissions to be the highest compared to the other biogas plants (cp. Table 12). As a result, CO_2 emissions for processed residue depend on processing performance on the one hand (the higher the nutrition content the lower CO_2 emissions for transports) and on driving distances on the other hand.

Table 12: CO_2 emissions for processed residue

Biogas plant	**capacity**	**CO_2 emissions in g/g N**		**CO_2 emissions in g/kWh$_{el}$**
		Solid	liquid	
Plant 1	225	5918.4	6293.5	7.1
Plant 2	450	11257.8	-	3.1
Plant 4	500	3131.9	290.3	0.9
Plant 6	1,050	49492.7	-	5.6
Plant 7	4,000	42159.2	96875.6	3.9
Plant 8	5,250	87651.1	24303.9	2.4
Plant 9	20,000	106340.9	489224.5	3.0
Plant 10	22,000	470507.2	848445.0	7.4

In order to determine how CO_2 emissions from transporting residue should be included in total transport emissions, we compare the results for CO_2 emissions for processed and unprocessed residue in the following section.

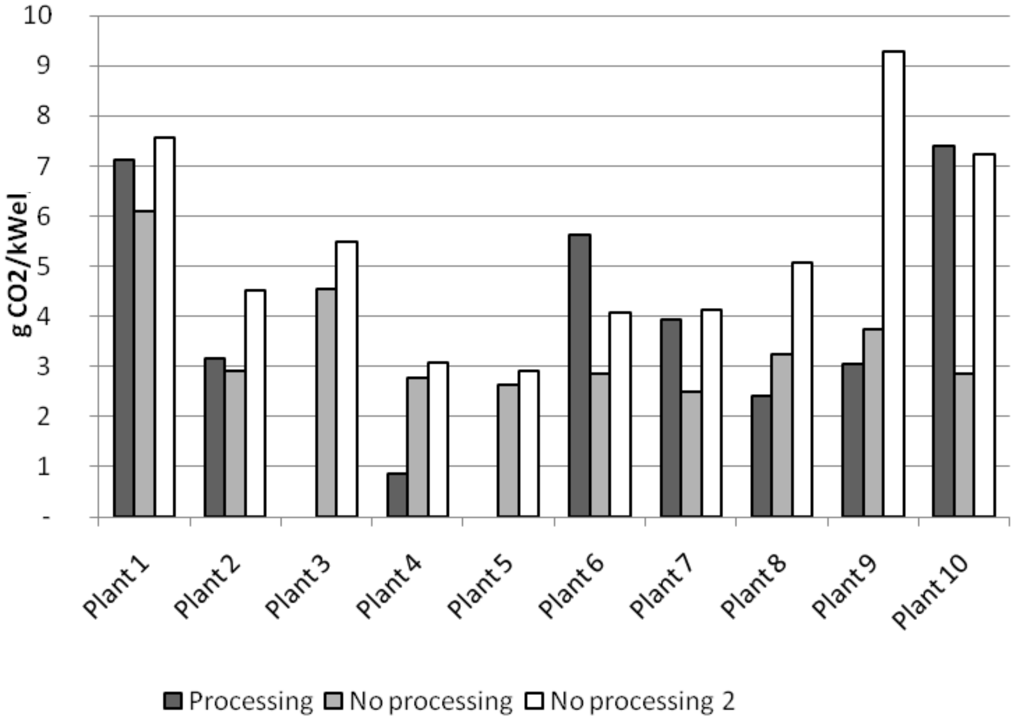
Comparison of CO_2 Emissions from Processed and Unprocessed Residues

Figure 35 illustrates CO_2 emissions per kWh$_{el}$ for the case of unprocessed and processed residue. In the previous sections we explained that driving distances for unprocessed residue are determined by simulation results of ReSI-M while driving distances for processed residue are obtained from interviews. In addition to the distribution of land in terms of distances from ReSI-M, in the interviews other factors might be included for the determination of driving distances. A farmer might not be the owner of all fields surrounding a farm, for example. In order to show the impact of these different driving distances, white columns (no processing 2) display CO_2 emissions per kWh$_{el}$ for unprocessed residue if the same driving distances as for processed residue (gained in interviews) are assumed. From left to right, plant capacities increase.

In the case of plants 4, 8 and 9, processing of residue reduces CO_2 emissions per kWh$_{el}$ of residue transport, whereas at the other plants not processing residue is more beneficial. This is mainly caused by greater driving distances applied in the calculations. In particular, processing residues at plant 10 causes high emissions per kWh_{el}, given that driving distances in interviews were stated to amount to 30 km. Note that at plants 2 and 6 no liquid residue remains from processing. However, there is a high difference in CO_2 emissions of processed residue, which is caused by a comparably low amount of residue in the case of plant 2.

On average for the eight biogas plants that process their residue, processing causes 4.2 g CO_2 per kWh_{el}, not processing 3.42 CO_2 per kWh_{el} and processing assuming driving distances from interviews generates 5.3 g CO_2 per kWh_{el}.

Figure 35: Comparison of CO_2 emissions for processed and unprocessed residues

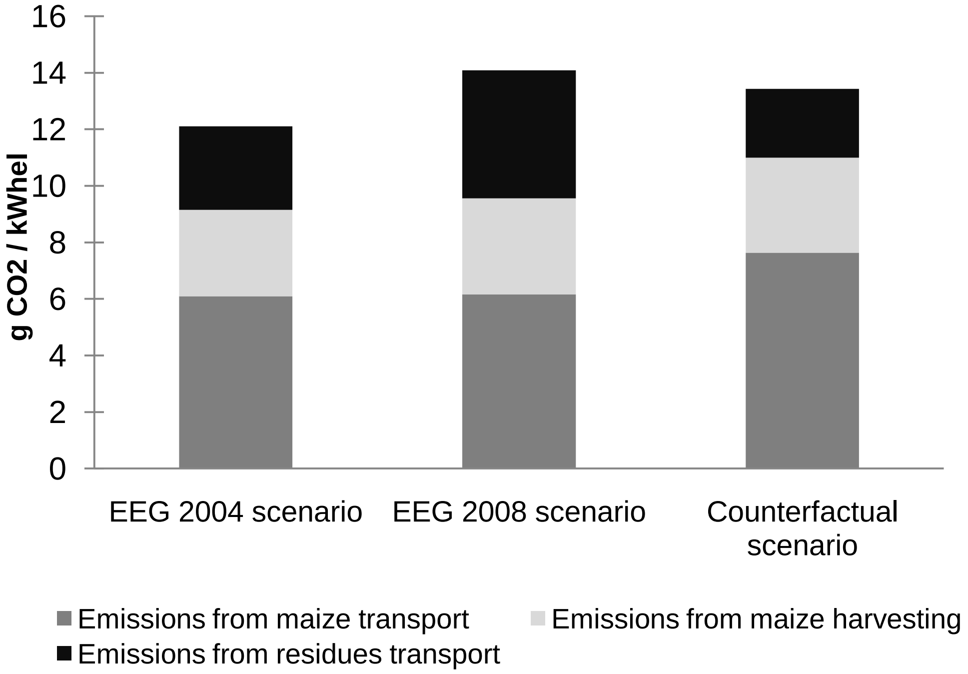


To conclude findings of the study on CO_2 emissions of residue, processing of residue creates different values which highly depend on driving distances, used input shares and processing technique. Given the poor data on processing residues, average values from the calculations (see Figure 35) are used for the four plant sizes used in ReSI-M. In the next section, CO_2 emissions from maize and residue transport are compiled and determined for the three policy scenarios.

4.2.4.3 Total Emissions of Transports

In each scenario, modelling performance provides us with data on location-specific driving distances, number and size of plants. Adding up resulting transport emissions from maize and residue, Figure 36 illustrates CO_2 emissions in g CO_2/kWh$_{el}$ for the three policy scenarios. Due to higher emissions for residue transport per kWh$_{el}$ in the EEG 2008 scenario, more emissions are generated overall compared to the other two scenarios. The lowest levels of emissions, again, are caused in the EEG 2004 scenario.

Figure 36: Total CO_2 emissions from transports



To validate these results we compare them to a study of ZIMMER ET AL (2008), which has been described in section 4.2.1.2. In this study, emissions of transports are displayed explicitly. They account for diesel emissions of 16 g CO_2 per kWh$_{el}$ for 500 kW$_{el}$ plants and 15 g CO_2 per kWh$_{el}$ for 1000 kW$_{el}$ plants (ZIMMER ET AL. 2008, p.42ff) and are therefore in line with our results.

Furthermore, our results show that transport emissions vary largely between regions. We saw in the analysis of land use change from maize production (section 4.2.3) that the three policy settings favour different regions for biogas production. Therefore, it is interesting to analyse which impacts the production of biogas in different regions due to the policy setting has on the overall climate balance of biogas. This is done in the following section.

4.2.5 Greenhouse Gas Emissions for the Entire Production Chain

Adapting values from the LCA of ZIMMER ET AL. (2008) and supplementing them with data of regionalised emissions from transports from ReSI-M, the sensitivity of greenhouse gas emissions with respect to transports is examined. Besides CO_2 emissions in this study, emissions of other climate relevant materials such as nitrous oxide (N_2O) and methane (NH_4) are considered and transformed into CO_2 equivalents (ZIMMER ET AL. 2008, p. 11ff.)

Data from ReSI-M includes four plant sizes, which could be compared in the following analysis. However, the analysis is restricted to the plant sizes of 500 and 1000 kW_{el} because ZIMMER ET AL. (2008) conducted the LCA for a 150 kW_{el} plant, which is 100% based on manure. This does not suite to our plant types and 2000 kW_{el} plants are not investigated. Table 13 shows changes in greenhouse gas emissions when a plant is constructed in a region with high (C) and low (B) transport emissions compared to average values (A) taken from ZIMMER ET AL. (2008). Based on higher CO_{2eq} emissions (A) of a 1000 kW_{el} plant, greenhouse gas emissions decrease by 3.8 % in regions with low transport distances and increase by 6.2% in regions with high transport distances.

Table 13: Total greenhouse gas emissions for biogas plants with high and low transport emissions

	500 kW$_{el}$ plant*	**1000 kW$_{el}$ plant****
	in g CO$_2$/kWh$_{el}$	
Transport emissions (low)	8.4	8.3
Transport emissions (high)	22.9	25.8
Transport emissions (ZIMMER ET AL. 2008)	15	15
Input emissions (without transport emissions)	128	125
Emissions from processing	109	276
Credits*	101	242
A) CO$_{2eq}$ emissions transports (ZIMMER ET AL. 2008)	**151**	**174**
B) CO$_{2eq}$ emissions transport low	**144.36**	**167.26**
C) CO$_{2eq}$ emissions transports high	**158.87**	**184.82**
% Change at low transport emissions	- 4.4 %	- 3.8 %
% Change at high transport emissions	5.2 %	6.2 %

*Credits are defined in section 4.2.1.2

The influence of high transport distances compared to the average ones is smaller in the case of a 500 kW$_{el}$ plant (5.2%), but the effect of low transport distances on decreasing total greenhouse gas emissions is larger. However, if we compare the sensitivity of transport distances with sensitivity of, for example, assumptions on using or not using the heat by-product (23 times higher emissions, cp. section 4.2.1), it appears that transports only have a minor influence on the overall greenhouse gas emissions. Nevertheless, the example shows that greenhouse gas emissions can differ by about 10% between regions, which implies that the choice of location has a considerable influence of the greenhouse gas emissions of biogas production.

What effects do these findings have on greenhouse gas emissions of the different plant structures caused by the three policy options? The figures displayed in Table 13 allows for the conclusion to be drawn that total CO_2 emissions of large-scale plants (1000 and 2000kW_{el}) are worse compared to medium-scale plants. Transport emissions are more than four times higher in regions with high transport distances compared to those with low transport distances (cp. also Table 7) in the case of large-scale plants. Therefore, if they are constructed in regions with high transport distances rather than in regions where transport distances are low, a policy supporting large-scale plants would be disadvantageous with respect to climate protection. Our modelling results on plant structures and regional maize production for the counterfactual scenario show that large-scale plants are predominantly constructed in regions with low transport distances (the share of maize production in those regions is higher compared to the EEG 2004 scenario (see section 4.2.3.3). However, this cannot compensate for diseconomies of scale in transport for large-scale plants, while emissions of large-scale plants (total emissions and transport emissions) are higher in the counterfactual scenario.

In the EEG 2008 scenario, where small-scale plants dominate the plant structure, transport emissions in regions with high transport distances are more than double compared to regions with low transport distances (cp also Table 7). As a result, the difference is smaller than in the case of large-scale plants, but our modelling results show that maize production and therewith number of plants, also increases compared to the EEG 2004 scenario (see Figure 28) in those regions with greater transport distances (and costs) (see Figure 25). This is caused by the high FITs under the EEG 2008 scenario, which makes biogas production depend on the amount of available manure rather than on cost-minimal biogas production with low transport distances. This provides a further explanation for the higher transport emissions under the EEG 2008 compared to the EEG 2004 (compare Figure 36).

The amount of FITs paid per kWh_{el} in the applied policy settings will be analysed in the following section.

4.3 Subsidies of Biogas Production

Apart from the environmental perspective, questions also arise with respect to the socio-economic aspects. With the applied method, it is not possible to conduct a macroeconomic assessment of biogas production, but the aspects of efficiency of subsidies for different scenarios can be analysed.

Following a literature review of studies in this field of research, the efficiencies of subsidies for biogas production in the applied scenarios are discussed.

4.3.1 Relevant Studies

Many countries aim to increase the share of renewable energies in their energy mix. In doing so, incentives are established to trigger investments in new capacities, but the maintenance, upgrading, and improvement of existing capacities also has to be considered (HAASA ET AL. 2003, p. 834).

However, renewable energies are challenged for causing high societal costs. The German Federal Ministry of Economics and Technology estimates the cost of an energy transition to renewable energies up to ten times higher than that of conventional energy, though most of these costs are seen to occur in the transportation sector (FISCHEDICK ET AL. 2002). KREWITT AND NITSCH (2003) estimate external costs avoided by the German energy system due to the use of renewable energies for electricity production, and compare them to compensation to be paid by grid operators for electricity from renewable energies according the EEG. They conclude that, besides uncertainties associated with the assessment of external costs, reduced environmental impacts and related economic benefits outweigh additional costs for the compensation of electricity from renewable energies (KREWITT AND NIETSCH 2003, p. 540ff.).

The numbers of FISCHEDICK ET AL. (2002) are also questioned by JACOBSSON AND LAUB (2006), who compare subsidies for renewable electricity production with subsidies for hard coal for electricity generation, external costs of hard coal and lignite, government-funded R&D for coal-based electricity generation, R&D for nuclear fission and participation in the international nuclear fusion programme (JACOBSSON AND LAUBER 2006, p. 270). They estimate that the difference between the compensation for renewable electricity in Germany (mainly caused by the EEG) to conventional power generation was about €1.45 billion in 2002. In order to consider the societal costs of power generation, they related the compensation under the EEG to the social costs of conventional power generation. They conclude that *"First, if social costs are taken seriously (...) most renewables sourced electricity (though not solar cells) would be in the competitive range right now. Second, the renumeration under this act roughly equals the avoided social costs of coal generated electricity, which means that in social terms, the extra cost to society appears to be negligible."* (JACOBSSON AND LAUBER 2006, p. 271).

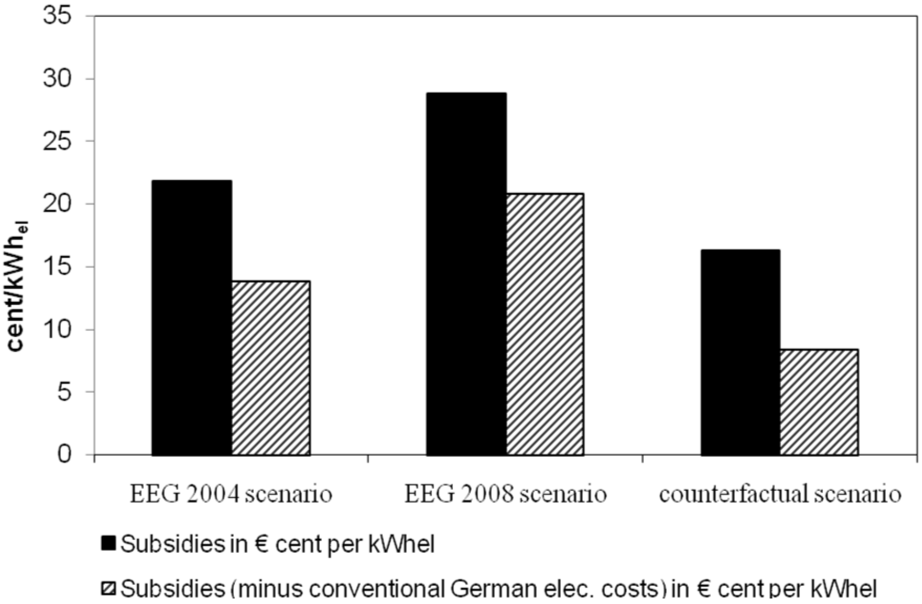
Besides challenging if renewable energies should be promoted, there are various studies on the question of how to promote renewable energies in a cost-effective way. These studies mainly compare price-driven strategies (e.g. FITs as in the case of the German EEG) and capacity-driven strategies (e.g. certificate-based quotas). Based on the same objective, these approaches begin with different starting points. Price-driven strategies have a given price and the quantity is decided by the market, whereas in the second approach, the quantity is set and the prices are determined on the market (HAASA ET AL. 2003, p. 834). In Europe, FITs are the predominant instruments. In case of wind energy, SIJIM (2002) concludes that they are *"an effective instrument to promote the generation of renewable electricity, notably to ensure a low-level market take-off of wind power at the national level. In the longer term, however, such a system may become hard to sustain as it may suffer from some major drawbacks, especially when the generation of green electricity accounts for a significant share in total power production." (*SIJIM 2002, p.16). He justifies these drawbacks with high costs for fixed premium prices and the fact that they become inefficient and distort competitive pricing. He thereby favours the creation of a liberalised European energy market (SIJIM 2002, p. 16).

We analyse the effectiveness of the German EEG by comparing subsidies paid per produced kWh_{el} in our policy scenarios. Therefore, the subsidies per kWh_{el} due to policy settings in our three scenarios are analysed in the following section.

4.3.2 Subsidies under the Different Policy Settings

Based on the total energy produced by scenario-specific numbers and sizes of biogas plants and FITs paid in the three scenarios, subsidies in €-cent per kWh_{el} are calculated. They are illustrated in Figure 37, which shows that the highest subsidies per kWh_{el} are paid under the EEG 2008 scenario, whereas the counterfactual scenario is the most cost-efficient scenario. To account for the electricity price consumers pay for conventional electricity, 8 cents/kWh$_{el}$ are subtracted from the subsidies paid for electricity from biogas. The striped columns display subsidies per kWh$_{el}$ when considering the 8 cents/kWh$_{el}$ paid for conventional electricity.

Figure 37: Subsidies per kWh$_{el}$ for scenarios



The difference in subsidies per kWh$_{el}$ produced under the EEG 2004 and counterfactual scenario depends on the plants' energy efficiency levels. In the counterfactual scenario, special FITs supporting certain shares of inputs or technologies are removed, which results in cost-effective production structures and technologies, while plants additionally have a good level of energy efficiency. However, being advantageous in an economic sense, there are bottlenecks with respect to environmental performance (see section 4.2).

Most energy is produced under the EEG 2008 scenario, which goes along with the political goals of increasing the share of renewable energies (see section 1.1.1). Nevertheless, subsidies are less cost-effective compared to the other two scenarios and the highest subsidies are spent on biogas production.

Results show that the applied policy options impact differently on analysed environmental and socio-economic indicators. In the following section the results are summed up, limitations are discussed and, conclusions as well as policy recommendations are made.

5 Conclusions

In order to analyse potential trade-offs between advantages and drawbacks of biogas production in Germany, the objective of this thesis is to simulate regional maize demand and transport costs for biogas production and to analyse environmental effects resulting from different policy options. Therefore, a modelling framework for the assessment of land use changes in Germany has been developed and applied to achieve the three research objectives, which have been introduced in section 1.1.3. In this last section, the main findings are summarised, limitations of this approach and future research needs are discussed, and finally policy recommendations for biomass production in Germany are made.

5.1 Summary of Results

In the course of the thesis a new method to determine locations and sizes for processing plants with a high number of possible type-location combinations is developed. Chapter 3 shows that compared to existing literature, the method allows for higher flexibility in decision rules to determine optimal type-location combinations as well as to treat both input and output quantities as endogenous variables. Furthermore, based on an iterative algorithm, parameter changes are possible based on results from previous iterations. In this application, the latter allowed for spatial heterogeneity to be taken into account, which lets unit transport costs increase depending on the number of already erected plants. Finally, the iterative algorithm allows for reduced solution times for large-scale applications, as the search volume decreases with iterations.

The method is successfully implemented into the ReSI-M framework, which simulates the number of biogas plants by size and sub-regional locations for all ~350 NUTS 3 regions of Germany at different maize prices and then derives resulting regional demand curves. Adding supply curves from a regionalised economic model of German agriculture enables the simulation of market clearing prices and quantities for maize. ReSI-M is sourced, among others, by a detailed GIS analysis which calculates per unit transportation costs for feedstock based on high resolution land use maps.

The framework and method are tested on simulations relating to German biogas and renewable energy legislation (EEG 2004) by paying guaranteed

FITs for electricity from biogas processing, adjusted by plant size and feedstock mix. The results under the EEG 2004 policy mainly suggest the establishment of medium-sized plants, which corresponds with what can be observed in reality; validation of this nature by means of the plant structure and regional share of produced electricity shows that ReSI-M displays the current observable plant structure well in simulations of the EEG 2004. Compared to existing literature, ReSI-M adds regionally differentiated market clearing prices. Our results indicate that previous studies might have overestimated the market potential in regions where feedstock availability is low. Later in the study, a sensitivity analysis shows the importance of energy efficiency for market clearing quantities and prices and, to a lesser extent, for most profitable plant sizes.

This modelling framework is applied in Chapter 4 to analyse the aforementioned research questions.

The first objective is to "*analyse regional land use changes caused by various policy settings*". To achieve this objective, the absolute area for maize production, as well as the land use per kWh_{el} is comprehensively assessed in simulations for four policy settings.

Land use in the reference scenario (applying RAUMIS without linking it to ReSI-M) shows higher maize production compared to the EEG 2004 scenario. Results from linking the models show that the integrated assessment allows for a consideration of regional characteristics of the demand side, such as crop yields, infrastructure and distribution of land, and therefore improves the representation of maize markets on the NUTS 3 level.

The largest absolute area for maize production is simulated under the EEG 2008 scenario, which is caused by the highest FITs. Breaking down the results on the NUTS 3 level, we see that maize production particularly increases in regions with a high livestock density under the EEG 2008. Since large amounts of maize are also cultivated for feedstuff in these regions, the expansion of maize usage for biogas plants further increases the total share of its production. Land use efficiency, however, is lower compared to the EEG 2004 and the counterfactual scenario. Consequently, despite of a higher share of waste material in the form of manure from livestock production, the intention of policy makers to reduce competition for agricultural land with the EEG amendment in 2008 has not been fulfilled. In contrast, the simulations show that the area used for maize cultivation will increase considerably by

2020 compared to the EEG 2004 scenario. Reasons include energy inefficiency of small-scale plants and the low energy content of manure.

Furthermore, the simulation results highlight that despite high energy efficiencies, large-scale plants, the profit maximising plant size under the counterfactual scenario, cannot compensate a higher share of maize as input compared to medium-sized plants mainly constructed under the EEG 2004 scenario. Large-scale plants simulated under the counterfactual scenario run with a manure share of only 1% due to lack of profitability of transporting manure and residues over long distances. Therefore, under the counterfactual scenario, regions with low transport costs (and distances) for maize are most profitable, while the share of maize on arable land increases compared to the EEG 2004 and 2008 scenarios. Large-scale plants feeding biogas into the natural gas pipelines are supported by the EEG 2004 and 2008, in order to reduce a dependence on natural gas imports. However, logistics for inputs as well as outputs are a challenging task and calls for a choice of location with minimal transport costs

The second objective of the thesis is to "*analyse transport emissions for biogas production caused by different policy settings*". Results show that the performance of the EEG 2004 is also the best scenario regarding CO_2 emissions of transports per kWh_{el}. Emissions from maize chaff cutting and harvesting are comparable to emissions under the EEG 2008 scenario, but due to higher amounts of manure inputs, more residues emerge and increase emissions from residue transport. One might argue that manure would have to be disposed regardless during livestock production and this share should therefore be allocated to emissions from livestock production rather than to emissions from residue. However, we did not assume that any transport of manure took place, which might compensate for not excluding the share of manure on residues. An additional factor for higher CO_2 emissions in transport is that plants are profitable at high maize prices, even in regions with high transport costs, due to higher FITs under the EEG 2008. As a result, it is profitable to drive longer distances compared to the EEG 2004. Again, it can be seen that the EEG 2008 has a less beneficial effect compared to the EEG 2004.

As expected, transport emissions per kWh_{el} of large-scale plants under the counterfactual scenario are the highest. Emissions from maize harvesting are especially increased, caused by the diseconomies of scale of transporting for large-scale plants. Emissions per kWh_{el} for residue transport is comparatively small, but could be further reduced if one assumed that advanced techniques for processing residues would be available in the future. Nevertheless, even without emissions from residues, harvesting and chaff cutting of maize results in higher emissions per kWh_{el} than the total transport emissions under the EEG 2004 and 2008 scenarios.

A limited analysis is performed with respect to the transport emissions share of total greenhouse gas emissions. Total greenhouse gas emissions along the life cycle of biogas production are smaller for 500 kW_{el} plants than for 1000 kW_{el} plants, while transport emissions have a share of about 4% to 6%.

Considering the contribution to the EEG goal of avoiding the use of fossil energy sources, the EEG 2008 scenario has the best performance. Here, the most energy compared to the EEG 2004 and the counterfactual scenario is produced. Production is, however, supported by subsidies paid per kWh_{el} introduced into the electricity grid and therefore covered by taxpayers. To assess the efficiency of subsidies paid under the applied policy option, FITs per kWh_{el} generated are compared. In total, they are the highest under the EEG 2008 scenario and the least costs emerge in the counterfactual scenario.

These findings are summarised in Table 14. The ranking shows that the EEG 2004 scenario has the best performance (indicated by **1**) with respect to land use efficiency and transport emissions. If all classes are weighted with an equal importance, the EEG 2004 would be the most beneficial policy option. If biogas were to be produced at the lowest cost, the counterfactual scenario would be chosen, although with environmental drawbacks. The current legislation, the EEG 2008, shows only average performance for land use efficiency and transport emissions, but the most renewable energy is produced with the highest amount of subsidies per kWh_{el}.

Table 14: Summary of results

	EEG 2004 Scenario	EEG 2008 Scenario	Counterfactual Scenario
Land efficiency	**1**	2	3
Transport emissions	**1**	2	3
Efficiency of subsidies	2	3	**1**
Energy security	2	**1**	2

Based on these finding we arrive at some policy recommendations, addressing the third objective as stated in section 1.1.3.

5.2 Policy Recommendations

A. The share of manure to receive additional subsidies for its use under the EEG 2008 accounts for 30% of total manure (mass content), but the share of energy content on the total energy production is only about 7%. In order to reduce land use competition under the EEG 2008, the share of manure necessary to receive these specific subsidies should be increased. This would then result in less maize used in biogas plants.

B. Alternatively, if additional subsidies for manure use (Güllebonus) were only applied to the share of manure employed in biogas plants, an incentive would be created to increase the share of manure and therewith the share of maize would be reduced.

C. Incentives should be established to improve energy efficiency of small-scale plants. Besides technological progress, there is room for improvement in terms of management, such as covering silage in storage. These management issues should be included in future legislation and be a precondition to receive subsidies.

D. Without major improvements in energy efficiency and logistics, the support of large-scale plants is not advantageous and their political promotion should be questioned.

5.3 Limitations and Suggestions for Further Research

In this modelling approach, as in many economic models, profit maximisation and rational behaviour is assumed, and decisions of single farmers or investors are aggregated in order to determine supply functions in the case of RAUMIS and demand functions in the case of ReSI-M. These assumptions can be criticised, as the behaviour of agents who invest in biogas plants in reality – mainly single farmers – often do not simply maximise profits, but take factors such as risk or sunk costs into account. Phenomena which cause individuals to deviate from rational behaviour (excluding strategic interaction) are discussed in BRANDES ET AL. (2001, p. 462ff). They call these phenomena “decision theoretical anomalies”, and specify, e.g. opportunity costs, sunk costs, the endowment effect and anchoring (BRANDES ET AL. 2001, p. 466-467).

For biogas production, sunk costs might be relevant, but given the long period for the guaranteed provision of feed-in tariffs, this effect can be neglected. Anchoring is the adherence to a judgment about a result or performance without considering or insufficiently considering new information. This has some influence on decisions in the agricultural sector. In the case of biogas production it can be observed in the regional distribution of plants. Farms which are dominated by cropping switch less easy to a production system in which the production process needs to be observed continuously, as is the case of livestock production or biogas plant operation. In ReSI-M, this is partly considered through the higher costs for developing manure.

Several further assumptions are necessary for this modelling exercise. A current limitation of the model is the exclusion of transports between NUTS 3 regions located within different NUTS 2 regions, since the model is run for NUTS 2 regions. This might influence results for NUTS 3 regions located on or near the border to a NUTS 2 region.

Data on existing biogas plants with respect to their location on the NUTS 3 level and information on their inputs and sizes are not available. As a result, assumptions for the share of maize and manure inputs and on the energy efficiency of existing plants had to be made during data processing. Other data for which information is lacking include the cost of residue processing. As biogas production is a relatively new technique, costs could not be determined during expert interviews, as these costs depend on a variety of plants and location-specific factors, which could not be captured by the model.

Although biogas is produced from a variety of inputs for biogas production, ReSI-M only includes the currently dominating inputs of maize and manure. But since maize alone makes up about 80% of total inputs, the inputs chosen are sufficient to model the choice of location of biogas plants. The representation of maize production for biogas can be improved by including other inputs such as grain, waste materials or grass – a task for future research.

Furthermore, the representation of costs for residue processing and application need to improved because there is a lack of data on the processing costs and applied technologies. Since the biogas sector is quickly growing in size but also in knowledge and technologies, more data should be available within the coming years.

Results might also be affected by the solving algorithm: with an iterative solving approach, no optimal solution can be determined by ReSI-M, rather a solution that is near the optimal result. Nevertheless, this disadvantage is compensated by the benefits the iterative solving approach provides for the problem at hand: it allows for a modification of transport costs depending on the amount of used feedstock and it considerably reduces the computation time compared to mixed-integer problems (see section 3.8 and 5.1).

In the 2004 and 2008 EEG, subsidies decrease over time (1% annually) in order to set an incentive for gradual energy efficiency and technology improvements. This is not taken into account in ReSI-M. However, this does not influence the comparison of the policy settings, since it is not considered in either of them. In future research, the time perspective of decreasing subsidies from the EEG should be included into the analysis and results with and without the decrease should be compared. Not only the declining FITs but also potentially increasing efficiencies of different plant types should be considered in future research.

Further assumptions are made for energy efficiencies of different plant types, which determine annual electricity and heat production. Consequently, they have a major impact on modelling results (see sensitivity analysis in section 3.6 and results on land use efficiency and CO_2 emissions per kWh_{el} in section 4).

Our results are driven by the policy settings applied in ReSI-M and RAUMIS and their model structures. Consequently, different plant structures, maize supplies and therefore maize markets will evolve under different frameworks. To identify the influence of the structure of RAUMIS on the results and to see the degree to which results are driven by the model type, demand curves from ReSI-M could be included in another agricultural sector model. Including maize demand into, for example, the Common Agricultural Policy Regional Impact Analysis (CAPRI)[8] model would additionally allow for the analysis of the effects of the German EEG on land use as well as environmental effects within Europe.

Some environmental indicators, such as nitrogen and phosphate balances, can be depicted by RAUMIS. RAUMIS includes the environmental indicators nitrogen balance, phosphate balance, NH_3 balance, pesticide risk-potential and soil erosion. Based on the structure of RAUMIS explained in section 1.2, it is possible to evaluate direct and indirect environmental impacts of agricultural production and changes of agricultural environmental policies on a regional level (cp. GÖMANN ET AL. 2002, KREINS ET AL. 2009). By determining regional input and output positions of the materials, activity-specific coefficients are multiplied by the level of each agricultural activity (GÖMANN ET AL. 2002, p.212). Therefore the area used for maize production, for instance, is multiplied by the coefficient for the nitrogen balance of maize production and links the coefficients to different agricultural activities. In previous studies, GÖMANN ET AL. 2002, GÖMANN ET AL. 2004, GÖMANN ET AL. 2005 AND JULIUS 2005 have analysed impacts of different policy settings on the environment, but the effects of the EEG has not been investigated yet. For "energy maize for biogas production" activities, the respective coefficients have not yet been included into the model. Once they are implemented into RAUMIS by coupling the partial supply model RAUMIS with ReSI-M, we are able to analyse nutrient balances for the applied scenarios.

The assessment of greenhouse gas emissions is restricted to biogas production in the scope of the thesis and does not consider competition with other products and agricultural activities. An inclusion of CO_2 emissions of different land use activities into RAUMIS or any other agricultural partial equilibrium model coupled with ReSI-M would allow for emissions indirectly caused by an increase in maize production to be displayed. However this analysis is currently not available in RAUMIS. CAPRI comprises an energy module, in which energy used for different agricultural activities is estimated based on a

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[8] CAPRI is a partial equilibrium model for the agricultural sector, and designed in the late 90s to analyse measures of the Common Agricultural Policy of the European Union and trade policies for agricultural products (see BRITZ 2008, BRITZ AND WITZKE 2008 or http://www.capri-model.org/)

life cycle analysis approach (see KRÄNZLEIN 2008). Supplementing this information with detailed transport emissions from ReSI-M would allow for greenhouse gas emissions for the whole biogas production process to be determined and would take into account emissions from indirect land use change. Developing some of these suggestions for future research to overcome the aforementioned limitations of the modelling approach would allow for further scenario calculations as well as a more comprehensive and reliable assessment of biogas production in Germany.

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