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David Balussou

AN ANALYSIS OF CURRENT AND FUTURE ELECTRICITY PRODUCTION FROM BIOGAS IN GERMANY

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Karlsruher Institut für Technologie (KIT)
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from biogas in Germany

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Abstract

With the development of renewable energy sources in Germany the use of biogas for electricity and heat production has rapidly expanded since the year 2000. This expansion has been encouraged by several Federal governmental incentives and in particular by the electricity Feed-In-Tariffs introduced in the Renewable Energy Sources Act (EEG). Agricultural plants valorizing energy crops now constitute almost 80% of total biogas installations. However volatile energy crops and electricity prices, combined with continuously evolving framework conditions, are a source of uncertainty for German plant operators. In this context, investment decision making for biogas plant projects is a difficult task that requires the development of decision support tools.

In order to provide an assistance to plant operators two models are developed in this work. The first one deals with the analysis of the current electricity production from biogas in Germany (simulation model) and the second one with mid-term developments up to the year 2030 (optimization model).

The simulation model is based on a process modelling approach which calibrates and simulates reference biogas plant types by considering a variable and differentiated biomass input. The analysis concerns the three major installation types in Germany valorizing energy crops, biowaste and manure. An integrated economic evaluation tool leads to the identification of the most profitable biogas plant sizes taking into account various subsidy schemes. Under EEG 2014 a paradigm shift is observed. Small-scale manure and large-scale biowaste plants appear as the most profitable installations whereas agricultural plants are no longer profitable mainly due to the cut in the subsidy for energy crops implemented in 2014.

The optimization model based on a plant operator perspective aims to determine the economically optimal capacity development for the three main installation types at the Federal State level and under various scenarios. The results highlight the influence of regional biomass potentials, revenues and electricity production costs as well as plant flexibilization and decommissioning. Future capacity expansion should mainly concern small-scale manure plants and biowaste installations rather than agricultural plants which, on the contrary, should undergo only modest development.

Based on the model results recommendations for plant operators and policy-makers are formulated. Maintaining current subsidy levels for biowaste and small-scale manure installations appears necessary in order to ensure the profitable and sustainable development of German biogas plants. Strategy planning and flexible plant operation as well as the increased valorization of residues in agricultural plants represent key challenges. An improved mobilization of biowaste potentials combined with better heat valorization would contribute to the creation of local and circular bio-economies in line with the planned national energy transition. The transferability of the methodological framework used in this work to other countries and bioenergy pathways is further analysed. A model implementation is possible especially in countries showing stable legal framework conditions for bioenergy (e.g., Feed-In-Tariffs) and benefiting from lessons learned and best practices from past projects.

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Abbreviations

ADEME:	French Environment and Energy Management Agency
BioSt-NachV:	Biomass Electricity Sustainability Regulation
CC:	capacity component
CDM:	Clean Development Mechanism
CHP:	Combined Heat and Power systems
CNG:	Compressed Natural Gas
DM:	Dry Matter
DVGW:	German Technical and Scientific Association for Gas and Water
$E_{Base\text{-}Load}$:	Energy amount in base-load operating mode
$E_{Full\text{-}Load}$:	Energy amount in full-load operating mode
$E_{Part\text{-}Load}$:	Energy amount in part-load operating mode
EEG:	Renewable Energy Sources Act
EEWärmeG:	Renewable Energy Heat Act
EEX:	European Energy Exchange
EIFER:	European Institute for Energy Research
EnWG:	Energy Economics Law

EPEX:	European Power Exchange
EWärmeG:	Renewable Heat Law
EWI:	Institute of Energy Economics
FAME:	Fatty acid methyl ester
Fcor:	correction factor
FIT:	Feed-In-Tariffs
FLH:	full-load hours
FM:	fresh mass
FNR:	Fachagentur Nachwachsende Rohstoffe e.V.
FP:	flexibility premium
FTE:	full-time equivalent
GAMS:	General Algebraic Modeling System
GHG:	greenhouse gas
ICT:	information and communication technologies
IRR:	Internal Rate of Return
IWES:	Institute for Wind Energy and Energy System Technology
KWKG:	Cogeneration Act
MA_{EPEX}:	Monthly average value of the hourly contracts passed on the EPEX Spot bourse
MATIF:	Marché à Terme International de France

MILP: Mixed-integer linear programming

MP: Market Premium

NPV: Net Present Value

oDM: organic Dry-Matter

OH: operating hours

OH_{Flex}: operating hours for flexible plants

ORC: Organic Rankine Cycle

$P_{El,Base\text{-}load}$: electric power in base-load operating mode

$P_{El,Flexible}$: flexible electric power in part-load operating mode

P_{inst}: installed power

P_{rat}: rated power

PLH: part-load hours for flexible capacity

RAL: German institute for Quality insurance and labelling

RPJMN: National Medium Term Development Plan

SNG: synthetic natural gas

TLL: Federal Office for Agriculture of Thuringia

TSO: Transmission System Operator

WACC: Weighted Average Cost of Capital

$\eta_{CHP,Base-Load}$: electric CHP efficiency in base-load operating mode

$\eta_{CHP,Flexible}$: electric efficiency for flexible CHP in part-load operating mode

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Blagnac, 23rd July 2018 David Balussou

1 Introduction

1.1 Motivation

Climate protection, sustainable energy supply, natural resource preservation as well as the satisfaction of a constantly increasing energy demand currently represent key challenges worldwide. The substitution of limited fossil resources combined with the improvement of energy efficiency and energy savings appear vital. In this context, Germany has embarked upon an energy transition (so called "Energiewende") which has been described as "the most important growth and modernization for the German society" [1]. Nature and environmental protection as well as global climate change, the finite character of fossil resources and the need for a secure and profitable energy supply are the main drivers of this transition. In this context renewable energies have an important role to play in the future energy system. Among all renewable energy carriers bioenergy is often defined as a "multi-talent" [2]. Bioenergy can deliver a significant share in the production of renewable electricity, heat, cold and liquid biofuels. It greatly contributes to security of supply, climate protection, and a demand-oriented electricity production. Bioenergy leads further to the establishment of circular and sustainable bio-economies with new job creation especially in remote areas [3].

Another advantage of bioenergy in comparison with other energy carriers lies in its local character. The German energy supply is strongly dependent on energy carriers mostly imported from countries where supply is unstable and characterized by high energy price volatility. According to the German Energy Balance Association (AGEB). Germany imports 100% of its uranium resources used for nuclear energy, 96% of its natural gas, and 78% of its hard coal [4]. Only lignite and renewable energy sources stem from national energy carriers. A possibility for Germany to increase its energy security is thus to use local and inland biomass potentials and to diversify its energy carrier mix. The rational use of biomass potentials and especially residues can thus ensure a long-term and sustainable security of supply. In the field of climate protection, bioenergy strongly contributes to greenhouse gas reduction when compared with fossil energy. In comparison to other renewable energies in the heat sector, bioenergy shows the highest mitigation contribution with about 31.2 million t of avoided greenhouse gases [5].

Among the portfolio of available bioenergy technologies in 2014, the electricity and heat production from biogas with Combined Heat and Power systems (CHPs) remains in a dominant position. It represents about 72.3% of the German electricity production from biomass, which was estimated at about 38.17 $\mathrm{TWh_{el}}$ in the framework of the Renewable Energy Sources Act [6]. A supplementary amount of 14.12 $\mathrm{TWh_{el}}$ has to be added and corresponds to the total electricity production from biogas by other technologies than CHP (e.g., gas turbines or Stirling engines) [6]. The total electricity production from biomass in Germany can thus be estimated at about 52 $\mathrm{TWh_{el}}$ at the end of 2014. In the electricity sector, biogas flexibility of use and storability makes it a suitable complement to fluctuating energy sources like wind or sun in the electricity sector. This is the case especially in biogas plants using Otto or Diesel gas engines. In these plants the employed gas engines can be easily started or shutdown in short time intervals in order to control the power [7]. Flexibility can also be obtained by expanding the gas engines capacity and the gas storage volume [8].

Since the year 2000, the German biogas sector expanded rapidly so that the current installed capacity in this country accounts for around half of the European total [9], [10]. This capacity development has been supported by several Federal governmental incentives and in particular by the Renewable Energy Sources Act (EEG) with the help of electricity Feed-In-Tariffs (FIT). However, the German biogas sector had to cope with major structural changes in 2014. The Renewable Energy Sources Act 2014, proposed by the Federal Government and starting on the 1st of August 2014, represents a paradigm shift for German biogas plants. Indeed, a major cut in subsidies attributed to biogas plants was proposed by the legislator in particular for agricultural plants valorizing energy crops. For this plant type the specific subsidies dedicated to energy crops valorization have been removed [11]. This subsidies cut has been carried out for two main reasons. The first one is linked to high end-user electricity prices, especially for residential customers. In the residential sector the electricity price including taxes increased from 14 $\mathrm{ct/kWh_{el}}$ in year 2000 up to 29 $\mathrm{ct/kWh_{el}}$ in 2014 [12]. By giving priority to the development of more economical renewable energy conversion technologies, like wind energy or photovoltaic, the Federal Government intends to lower electricity bills for end customers. With average electricity production costs at about 18 $\mathrm{ct/kWh_{el}}$ for agricultural plants, biogas belongs to the most expansive renewable energy conversion technologies [13], [14].

Another reason for this cut concerns the competition in the past between the energy and food value chains regarding biomass resources and surface area. In the past fifteen years priority was given to the valorization of energy crops due to their high energy content and their high hectare yields in comparison with other feedstocks. This led to the exclusive cultivation of certain agricultural plants, so called monocultures, like maize silage or rape. In addition, fertilizers and pesticides were intensively used for yield improvements. These aspects negatively impacted the agricultural sector and generated ecological risks (degradation of humus balance and biodiversity, risks of soil erosion, reduction of the ground-water formation, landscape modifications, loss of ecologically valuable surface areas). The subsidies for biogas plants valorizing energy crops created tensions on maize and wheat markets and have led to a “food versus fuel” debate. A consequence of this induced competition was a generally poor public acceptance of biogas in Germany [15].

In addition to frequently evolving subsidy mechanisms, plant operators have to cope with major uncertainties concerning mid-term electricity prices, energy crop costs development and biowaste valorization revenues. Decision support tools based on modelling approaches represent a valuable assistance in order to minimize these uncertainties and to maximize profitability. A first issue for plant operators concerns the identification of the most profitable installation sizes and types under current framework conditions. Another problem is related to the forecast of future plant capacity development and electricity production from biogas. The objective of German biogas plant operators is to run and maintain reliable and profitable installations over their whole lifetime, which generally corresponds to 20 years (EEG subsidy time period). For this a model-based forecast of future costs and revenue development is required so that the operators can minimize the risks in particular linked to the previously mentioned uncertainties. On this basis an economically optimal development plan of future biogas plant capacity could be foreseen on a mid-term horizon (up to 2030). The model-based assessment of current and future electricity production from biogas would then provide an economic foresight to German plant operators and contribute to substantial profitability improvements.

1.2 Objectives and overview

This work has the objective to provide an economic analysis of the current and future electricity production from biogas in Germany. It focuses on the analysis of onsite electricity and heat production with Combined Heat and Power systems (CHPs). It was realized between the years 2010 and 2016 and takes into account the legal frameworks of the 2012 and 2014 versions of the Renewable Energy Sources Act (EEG 2012 and EEG 2014). The recent EEG 2017 framework enacted in January 2017 is therefore only marginally considered. The outcomes of the economic analysis should provide insights for German plant operators into economically optimal electricity production from biogas both on short-term and mid-term horizons. For this purpose, two main research questions have to be answered. The first one concerns the identification of the most profitable biogas plant sizes[1] and types[2] under the economic frameworks of EEG 2012 and EEG 2014. Which installation types and sizes should be built under these framework conditions in order to lead to the highest profitability for German biogas plant operators?

The second research question concerns future developments regarding new built biogas plant capacity on a mid-term time horizon, i.e. up to the year 2030. Which future capacity developments can be foreseen up to the year 2030 at the Federal State level in order to ensure maximal operating profits for German biogas plant operators? In order to provide answers to these two fundamental research questions the present thesis is structured as follows.

Chapter 2 aims to provide background aspects regarding the main bioenergy and biogas conversion pathways. In particular a complete biogas supply chain is assessed, from the biomass feedstock management up to biogas valorization.

Chapter 3 has the objective to analyse the current situation of biogas in Europe and in Germany regarding the valorized biomass feedstocks and potentials, the installed capacity, the legal framework conditions and subsidy schemes. A literature review aims to provide an overview of existing studies related to the economic analysis of current and future electricity production from biogas in Germany. Based on this assessment, the scientific contribution of the present work is further highlighted.

Chapter 4 deals with the elaboration of a simulation model which aims to calibrate and simulate reference biogas plant types by considering a variable and differentiated biomass input. The results of the simulation enable an

[1] The biogas plant size is defined by the installed electric power of the Combined Heat and Power engines (CHP engines) transforming the biogas produced into heat and electricity.
[2] The biogas plant type is linked to the feedstock valorized, e.g., energy and/or manure employed in mono- or co-digestion plants or communal and/or household biowaste used in biowaste plants.

economic analysis of current electricity production from biogas which is further described in chapter 7.

In chapter 5 a regional linear optimization model is developed. It aims to forecast the optimal economic development of future installed biogas plant capacities by considering various scenarios and frameworks at the level of each German Federal State and up to the year 2030.

Chapter 6 has for objective to define the system boundaries related to both of the simulation and optimization models and to describe the methodology for determining all required model input data. Three biogas plant types are considered and valorize energy crops with manure (EM plant[3]), as well as energy crops (E plant) and biowaste (B plant). For each plant type the main model input data refers to the existing capacity, to current and future available biomass potentials as well as to current and future costs and revenues. Chapter 6 ends with an analysis of the main input data uncertainties that impact the model results.

Chapter 7 presents and analyses the results of the simulation model. The model outcomes provide an answer to the first research question dealing with the identification of the most economically attractive plant types and sizes under current legal framework conditions. The profitability criterion refers to the determined specific operating profits[4]. The most profitable plant sizes can be identified for each plant type and the corresponding costs and revenue structures are then analysed. In a further step sensitivity analyses of the specific operating profits are performed for each of the most profitable plant sizes. These analyses aim to identify and quantify the main profitability drivers in each case. In addition to the economic analysis, a technical assessment of the most profitable plant sizes is carried out by determining

[3] This plant type is divided into two sub-categories: plant sizes from 0 to 75 kW_{el} using mono-digestion of manure and larger plant sizes employing co-digestion of energy crops with manure.
[4] For a given plant the specific operating profit (in ct/kWh_{el}) is defined as the difference between specific revenues and specific electricity production costs. Taxes (e.g., value added, property, income, corporate and trade taxes) and levies are not considered in the present work.

biological and global energetic efficiencies. The methodology employed is further discussed, the results are validated and a comparison with the EEG 2017 framework for plants smaller than 150 $\mathrm{kW_{el}}$ is carried out. The model outcomes lead further to the formulation of strategy and policy recommendations concerning current electricity production from biogas in Germany.

In chapter 8 the results of the optimization model are presented and analysed in the framework of a base scenario. The model outcomes provide an answer to the second research question dealing with the forecast of future capacity for electricity production from biogas up to 2030, at the Federal States level and under various legal frameworks. A further scenario aims to quantify the impact of fundamental drivers on future capacity development. A comparison with a capacity development forecast done under the new EEG 2017 framework is further carried out. The model results analysis enables the formulation of strategy and policy recommendations concerning future electricity production from biogas in Germany.

The main interactions between the model input data, the simulation and the optimization models are represented in Figure 1-1. Three main plant types are defined corresponding to the valorization of energy crops in mono-digestion plants, to the co-digestion of energy crops and manure as well as to biowaste fermentation. In a given plant type, the simulation model aims to determine the most profitable plant sizes showing the highest specific operating profit. For this a variable biomass input mass flow mi (in t/a) is considered and leads in each simulation step to the determination of the installed electric power pi (in $\mathrm{kW_{el}}$). In section 4.3.3 a technical correlation involving 49 biomass input mass flow steps and 49 electric power outputs is obtained over the whole electric capacity bandwidth [0:20,000 $\mathrm{kW_{el}}$].

Based on these correlations an economic evaluation follows involving specific costs and revenue data from plant operators, from the literature and from EEG 2012 and EEG 2014 subsidy schemes (chapter 7). The combination of these costs and revenue data (in $\mathrm{ct/kWh_{el}}$ or in €/t) with the previous technical correlations leads to the determination of economic correlations (section 7.1). These correlations represent the evolution of specific costs and revenues (in ct/kWh_{el}) as a function of the electric power. Based on these results the evolution of specific operating profit as a function of the electric power can be determined and the most profitable plant sizes can then be identified in each installation type (section 7.2). For these most profitable plant sizes, sensitivity analyses and technical assessments are further carried out (sections 7.4 and 7.5).

In the framework of the optimization model, the previous costs and revenues correlations are firstly regionalized with the help of energy crop costs determined in each Federal State for the base years 2013 and 2015 (section 6.6.1). These regional costs as well as other costs and revenues positions are then forecasted up to the year 2030 (section 6.7). In addition, biomass potentials for electricity production are annually calculated and forecasted up to the year 2030 in each Federal State (section 6.4). Existing capacity for the base years 2012 and 2014 is then determined with the help of a dedicated biogas plant database (section 6.3).

With the help of these input data the optimization model aims to maximize the total operating profit year on year up to 2030, over the 49 plant sizes p_{i} and in all Federal States r_i (section 5.3). Two main constraints apply and correspond to capacity development limitations by regional biomass potentials as well as to annual capacity expansion caps set in the framework of EEG 2012 and EEG 2014. In each Federal State and year on year a development plan for plant capacity and electricity production from biogas is obtained up to 2030 (section 8.1). Further scenarios quantify then the impact of shocks related to energy crop costs, EPEX electricity price and biowaste fee revenues on future developments (section 8.2).

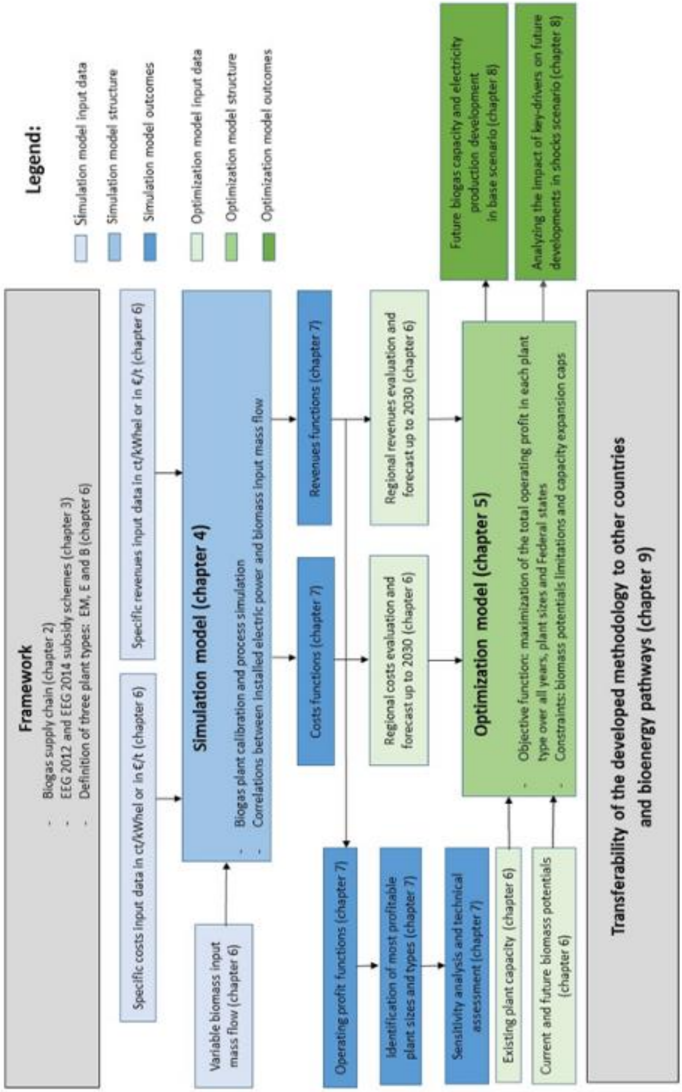

Figure 1.1: Interactions between input data and the simulation and optimization models (author's own representation)

Chapter 9 evaluates the transferability of the developed modelling approaches in Germany to other countries and other bioenergy pathways. Biomethane injection in France, biomass district heating in Finland as well as bioethanol production for transport in Brazil and the valorization of jatropha into biodiesel in Indonesia are analysed. For each conversion route and in each country the current situation and lessons learned are described. In a further step the main barriers and challenges for a future model implementation are identified.

The thesis ends with summary, conclusions and outlook in chapter 10. Recommendations and further challenges concerning current and future German electricity production from biogas are outlined.

2 Background aspects regarding bioenergy and biogas

In this chapter the main bioenergy conversion pathways valorizing biomass for energetic purpose are firstly described based on literature data in section 2.1. A focus is then set in section 2.2 on the biochemical conversion of biomass feedstock into biogas. A complete biogas supply chain is described starting from the biomass feedstock management up to the biogas production process and further valorization into electricity, heat or gaseous biofuels (sections 2.2.1, 2.2.2 and 2.2.4). The technological options available for the digestate treatment and valorization as fertilizer are also described in section 2.2.3.

2.1 An overview of bioenergy conversion pathways

The term “biomass” refers to energy crops (e.g., miscanthus or maize silage), residues (e.g., straw or agricultural residues), by-products (e.g., manure or industry residual wood) and waste (e.g., sewage sludge or household biowaste). Bioenergy is defined as the conversion of these resources into renewable electricity, heat or fuel [16].

The conversion of biomass into solid, gaseous and liquid fuels and into heat and/or electricity can be realized through various processes (see Figure 2-1). Basically, one should distinguish between the thermochemical, physical-chemical and biochemical conversion processes which will be further described in detail.

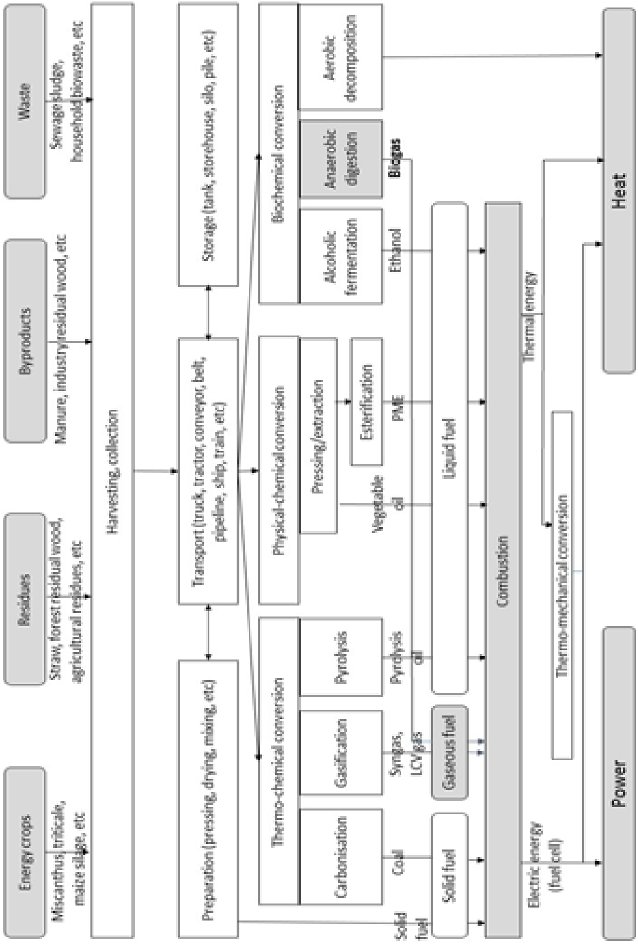

Figure 2.1: Main bioenergy conversion pathways (author's own representation according to [16])

2.1.1 Thermochemical conversion

2.1.1.1 Biomass combustion

The direct valorization of biomass feedstock in combustion plants represents the major technological pathway for bioenergy worldwide. This valorization can be realized in domestic small plants (e.g., wood stoves, tiled stoves, wood pellets and wood chips plants) but also in cogeneration plants. A quasi-complete oxidation of the solid biofuels occurs during the combustion process. Biomass is converted into thermal energy as well as into ash contained in combustion by-products. The main solid biomasses employed correspond to woody biomass, e.g., residual forest wood, straw or to energy crops. The heat generated by the combustion reaction can be used for water heating in local or district heat networks or in ORC-plants (Organic Rankine Cycle plants) for electricity production [17]. It can also be valorized in steam production processes, e.g., in steam boilers for the supply of an industrial area. A last possibility consists in producing electricity with the help of steam turbines. The hot exhaust gas issued from the combustion can be further used by gas turbines or Stirling processes. The main existing combustion technologies can be classified according to the type of contact between the solid fuel and the combustion air. One should distinguish between fixed beds, fluidized and dust combustion processes.

In the fixed bed combustion process the solid biofuel slowly moves following combustion air and without leaving the fixed bed. Fixed beds are used in underfeed or in grate combustion processes. Solid biomasses characterized by fine-grains and low-ash-content are employed in the case of an underfeed combustion. Possible fuels are pellets, cereal grains, barks or wood chips. Usually, this combustion process concerns a rated thermal input lower than 6 $\mathrm{MW_{th}}$. Grate combustion processes are more suited to woody combustion plants with larger rated thermal input. Grate combustion plants can be divided according to their forms into push, reciprocating, travelling, vibration and roller grates. All these grate types use fuels with different particle sizes, water contents and mixtures and can easily resist to slaggings. The flue gases produced are characterized by a low dust content.

In fluidized bed combustion processes the inflow velocity and the flow force impacting the fuel particles increase strongly. During this combustion process the fuel particles are suspended in a bed of ash, sand or limestone. Jets of air provide the necessary oxygen for the combustion process. One should distinguish between stationary and circulating fluidized bed combustion processes. The relatively low combustion temperatures (800 to 900 °C) avoid the presence of slaggings and of nitrogen oxides. Stationary bed combustion processes are mainly characterized by a rated thermal input between 10 and 20 $\mathrm{MW_{th}}$. Circulating bed combustion processes are operated starting from 30 $\mathrm{MW_{th}}$ and are subjected to a higher flow velocity than in the case of stationary processes. This leads to a better control of the solid fuel combustion process with high ash-content. A large range of biomasses including finely chipped wood or barks can be employed in fluidized bed combustion processes.

A dust combustion occurs if all fuel particles are conveyed together with the gas flow. These combustion systems are suited for the valorization of very fine and dry fuels with 15 to 20% water content (e.g., chips, sawdust and other fine-grained wood residues). Dust combustion processes are employed starting from a rated thermal input of 200 $\mathrm{kW_{th}}$. However, they appear to be unprofitable in most cases due to a high level of specific investment-related and operating costs [18].

2.1.1.2 Biomass gasification

Similarly, to combustion, gasification belongs to thermochemical conversion processes and leads to the production of a synthetic gas (so called "syngas"), ashes and tar. Syngas mainly contains hydrogen, carbon monoxide and carbon dioxide. Gasification processes can be autothermal or allothermal according to the heat production process. In an autothermal process the required thermal energy is produced by a partial oxidation of the employed biofuel. In an allothermal process an external heat source is employed e.g., from heat carrier materials such as water vapor or heat exchangers. The syngas issued from autothermal gasification processes shows a gross calorific value between 3 and 6 $\mathrm{MJ/Nm^3}$ whereas syngas from allothermal processes are characterized by higher gross calorific values between 10 and 15 $\mathrm{MJ/Nm^3}$[19]. The produced syngas can be further transformed into heat and/or electricity e.g., in cogeneration processes. It can also lead to the production of liquid or gaseous biofuels (e.g., Synthetic Natural Gas bio-SNG, methanol or Fischer-Tropsch-Diesel). The syngas quality depends on the gas composition, on the share of organic components and on the particle content. In the case of bio-SNG production a gas cleaning process is necessary in order to meet the required technical specifications for an injection into the grid. Gasification processes display some advantages in comparison to combustion technologies. Firstly, higher electric efficiencies can be reached especially in the case of small to mid-scale installations. Secondly the possible storage and transport of bio-SNG issued from syngas cleaning processes offers more valorization pathways than with a direct combustion [20]. However, the production and use of bio-SNG currently remains at the research and development stages and the industrial scale is not yet reached.

Gasification processes concern fixed bed, fluidized and entrained flow gasifiers. The gasifier types are defined according to the type of contact occurring between the gasification medium and the valorized biomass. Other criteria relate to the heat supply type (autothermal or allothermal), the employed gasification medium (air, oxygen, water vapor) and the pressure ratio in the gasification reactor [21].

Fixed bed gasifiers can be divided into co-current and counter-current gasifiers. The first one is the most frequently used technology due to the fact that tars can be easily cleft by the hot gases. Co-current gasifiers refer to plants with about 2 $\mathrm{MW_{th}}$ rated thermal input whereas counter-current gasifiers are used in larger plants (about 10 $\mathrm{MW_{th}}$). Both of these gasifier types can be further combined e.g., in a double combustion gasifier.

Fluidized gasifiers can be split into circulating and stationary gasifiers, depending on the gas velocity. The fuel particles move at high velocity flow rates under high temperatures between 700 and 900 °C, which leads to a low tar-content in the gasifier. Fluidized gasifiers are mainly employed for rated power thermal input between 10 and 100 MW_{th}. The combination of several fluidized gasifiers is also possible, e.g., in two-bed circulating technologies, and increases the syngas quality.

Finally, entrained-flow gasifiers valorize solid biomasses in the form of dry pulverized solids, atomized liquid fuel or fuel slurry in the presence of oxygen (much less frequent: air) mostly in co-current flow. The gasification reactions take place in a dense cloud of very fine particles under temperatures between 1,200 and 2,000 °C. This type of gasifier is used for high rated thermal output, superior to 100 MW_{th}, mainly for coal gasification and more rarely for biomass [22].

2.1.1.3 Biomass pyrolysis

The pyrolysis of biomass feedstock consists of the thermal deconstruction of chemical components under an absence of oxygen. This process is defined as allothermal as the required thermal energy for the components deconstruction is exogenous to the system. An overview of all available pyrolysis processes is given by [23]. The products of the pyrolysis process consist of a solid char, liquids like bio-oils, tar or pyroligneous liquors and a biogenic gas (syngas). Table 2-1 provides the products composition according to different pyrolysis processes.

Table 2.1: Process conditions and products composition according to various pyrolysis processes [23]

Pyrolysis mode	Process Conditions	Mass share of liquid (%)	Mass share of char (%)	Mass share of gas (%)
Fast	Temperature at about 500 °C Very short hot vapour residence time at about 1 s Short solids retention time	75	12	13
Intermediate	Temperature at about 500 °C Short hot vapour residence time between 10 and 30 s Moderate solids residence time	50 in two phases	25	25
Slow	Temperature at about 400 °C Long hydraulic residence time Very long solids residence time	35	35	30

The objective of a fast pyrolysis is to maximize the share of liquids in the reaction products. For this, very high heating rates are employed. The highest yields are provided by clean wood which delivers about 75% of the dry biomass mass input. Charcoal represents about 10 to 15% of the mass products and retains in particular all the alkali metals. The main commercially employed reactors for the fast pyrolysis process are linked to fluid beds, spouted fluid beds, transported beds, rotating cones and ablative reactors. Fast pyrolysis processes are mainly used for materials pre-treatment and densification and as a source of biofuels or chemicals. They are also used in the processing of by-products or residues in lignocellulosic bio-refineries. The use of fast pyrolysis for biomass pre-treatment aims to substantially increase biomass density through the production of bio-oils (density at about 1,200 kg/m^3). Bio-oils produced by fast pyrolysis processes can be valorized into heat and/or electricity with the help of boilers, engines or turbines. Another possibility consists of substituting phenolics in wood resin with bio-oils. The use of bio-oils as liquid biofuels represents a sustainable alternative to fossil liquid fuels. Biofuels can be directly produced from bio-oils with the help of catalytic upgrading of liquid or vapour. An indirect pathway consists of gasifying bio-oils and processing them using a hydrocarbon or an alcohol synthesis [23]. The intermediate pyrolysis can process more difficult biomass feedstock than the fast one. This especially concerns materials subject to handling, feeding and/or transport problems. Charcoal represents in this case about 25% of the mass products and is made of small size particles. The liquid products can be divided into the organic phase which can be used in engines and the aqueous phase. The gas products can for their part be valorized in engines.

Slow pyrolysis can occur under indirect or direct heating with air addition. It mainly applies to pre-sorted and processed organic waste with an optimal particle size of 1 to 2 mm and having a moisture content lower than 10%[5]. Slow pyrolysis processes are traditionally used in order to obtain solid fuels for cooking and also for the metallurgy and silicon industries in Brazil and Australia [23]. A recent application concerns the production of biochar as a fertilizer in order to increase soil fertility and agricultural productivity. A

[5] A low feedstock moisture content ensures a high heat transfer rate.

further advantage of biochar is that it contributes to climate change mitigation through carbon sequestration [24].

2.1.2 Physical-chemical conversion

2.1.2.1 Pressing / Extraction

Pressing and extraction process is used to produce fuel oils from biomass. The biomasses employed are rape and sunflower seeds, peanuts and corn which contain fatty or oily components. These crops are only cultivated in certain regions and are difficult to grow so that their potentials are very limited. The production of vegetable oils from biomass can be realized by pressing, simple extraction or a combination of both processes. A one- or two-stage pressing operation aims at separating the oil from the oil seeds. An oil cake containing 4 to 10% oil is produced and can be used e.g., as a cattle feed material [25]. The extraction process is realized by using a solvent applied to large-scale units. The extraction products correspond to a saturated solvent containing oil and an oil-free extraction residue also saturated with the solvent. In a further step the solvent is removed from the two product streams by heating and then reused in a recycling loop. The use of a solvent enables the extraction of a much higher share of oil than in the case of the simple pressing process.

The combination of pressing with extraction leads to a maximization of vegetable oil production and profitability. The oils produced generally contain between 0.5 and 6% of oil-free solid residues which have to be removed. For this, filtration and sedimentation processes are used and are followed by a refining step. This refining step is performed through de-acidification, de-colouring and steaming. It aims to remove unwanted substances like fatty acids, wax, heavy metals or pesticides. The vegetable oil produced can be directly used as a liquid biofuel especially in rural areas for decentralized electrification [25]. However, the combustion of vegetable oils lowers engine lifetime and generates supplementary maintenance requirements and costs.

2.1.2.2 Esterification

Another valorization possibility consists of converting the vegetable oils into a fatty acid methyl ester (FAME) which can be used in conventional diesel engines as an environmentally-friendly substitute for diesel. For this purpose, an esterification process is required. The vegetable oil reacts with methanol under the presence of a catalyst, generally NaOH. This mixture is pumped through a vertical pipe at a low velocity which removes the glycerine. After the removal of the remaining methanol, the liquid is cleaned by a multi-stage washing process [25]. The FAME produced can be also used as a liquid biofuel (biodiesel).

2.1.3 Biochemical conversion

2.1.3.1 Alcoholic fermentation

Alcoholic fermentation is defined as the conversion of sugar $\mathrm{C_6H_{12}O_6}$ by yeast into ethanol $\mathrm{C_2H_5OH}$, carbon dioxide $\mathrm{CO_2}$ and low temperature heat used for micro-organism growth. The fermentation reaction occurs under anaerobic conditions. After the fermentation the yeast is removed from the slurry and then recycled. The main sources of sugar are starch, celluloses as well as sugar cane and sugar beet. The ethanol produced has to be further refined in order to obtain a pure liquid biofuel [25]. The slurry issued from the fermentation process contains between 8 and 10% alcohol, water and residues derived from the sugar-containing or starch material. In order to purify the slurry a crude alcohol column is used for distillation or rectification. The products obtained are an alcohol-water-mixture containing more than 80% alcohol and a secondary slurry with no alcohol content.

This slurry can be further used as a feedstock for biogas production or as a fertilizer. Several distillation and rectification steps are necessary in order to reach an alcohol-water-mixture with a maximal ethanol content of 96%. For a use in an engine an ethanol content of 99.9% has to be achieved. For this an absolution step is necessary. An expedient is added to the alcohol-water mixture in order to produce an alcohol-chemical mixture as well as a water-chemical. The chemical is then removed and can be further reused. The final product has an ethanol content satisfying the specifications for use as fuel in a combustion engine. The engines employed must be adapted to ethanol as its combustion behaviour is different from gasoline. Ethanol is generally mixed with compressed natural gas (CNG) to a maximum rate of 10% in order to meet engine and distribution net-works specifications [25].

2.1.3.2 Aerobic decomposition

The aerobic biomass decomposition process corresponds to the transformation of organic waste into compost in the presence of oxygen. More precisely compost represents a humus-like product obtained under controlled conditions. Composting operators firstly break down large waste particles e.g., through grinding or chopping. After this physical pre-treatment a colonization phase of the organic material by microbes occurs in the presence of oxygen. The composting process then starts and is initiated by mesophilic microorganisms at temperatures between 30°C and 40 °C [26]. In a further step and for higher temperatures thermophilic microorganisms are active. Most of the microbes involved in the composting process are already located in the organic waste. Additional soil microbes such as bacteria, fungi or protozoa are introduced when the waste is mixed. Carbon compounds are used by the bacteria then transformed into CO_2 and released.

The reaming oxygen in the compost is continuously consumed by microorganisms. A strong temperature increase takes place in the compost material from 55 °C to 65 °C within 24 to 72 hours [26]. The compost temperature then remains constant at 65 °C for several weeks which characterizes the active phase. The active phase represents the most intensive decomposition phase and continues up to full transformation of the nutrient- and energy-containing materials. Then during the curing phase, the microbial activity decreases and the temperature falls. The length of this phase[6] can increase if the compost remains in an unfinished state. This can happen e.g., if the compost contains too little oxygen, an inadequate moisture content, a high level of organic acids or has extreme pH values. Ideal conditions for an optimal composting process correspond to temperatures in the range of 55°C to 65°C, pH values going from 6.5 to 8 and moisture mass contents of 50 to 60% [26]. The optimal C:N ratio[7] should vary between 25:1 and 35:1 and the available O_2 concentration remains higher than 10% [26]. Finally, feedstock particle sizes smaller than 25 mm also contribute to an optimal composting process [26].

2.1.3.3 Anaerobic digestion

The anaerobic digestion process can be defined as the microbial degradation of organic substances in an oxygen-free environment (anaerobic). It occurs naturally e.g., in moors or in the bellies of ruminants and also in controlled reactors (fermenters). The products of the anaerobic digestion process are a methane-rich gas and a digestate further valorizable as a fertilizer. A detailed process overview is given in section 2.2 which deals with the complete description of a biogas supply chain.

2.2 Description of a complete biogas supply chain

The biological production and conversion of biogas into electric and thermal energy can be divided into four main steps as described in Figure 2-2: biomass feedstock management (biomass harvesting, transport, delivery and storage, biomass pre-treatment, on-site conveying and loading), biogas and digestate production, biogas management (storage, treatment and valorization) and finally digestate management (storage, treatment and valorization).

[6] The curing phase length can vary widely between one to four months in most of the commercial processes [26].
[7] Among the many elements required for microbial decomposition, C and N appear as the most critical [26].

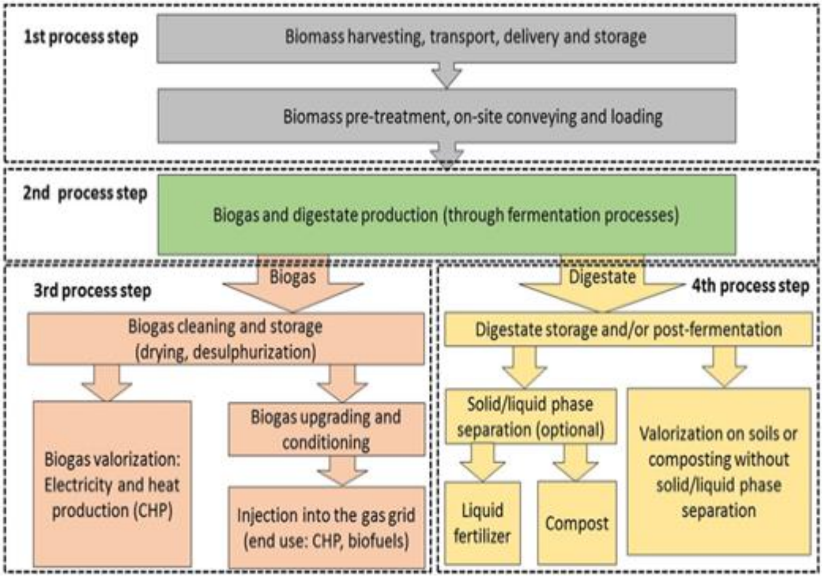

Figure 2.2: Main process steps involved in the operation of a biogas plant (author's own representation according to [27])

2.2.1 Biomass feedstock management

2.2.1.1 Biomass harvesting, transport, delivery and storage

Logistic aspects can considerably impact the profitability of a biogas plant especially in the case of the valorization of large biomass feedstock amounts. The logistic chain of a biogas plant can be basically divided into four sequential steps.

The harvesting of energy crops or the collection of biowaste represents the starting point of a biomass logistic chain for biogas applications. The energy crops mainly harvested are maize silage, grass silage, cereal silage and cereal grains. The harvesting yields for maize silage are strongly dependent on the cultivation location and the environmental conditions and can vary in Germany between 35 $t_{Dry-Matter}/ha$ up to 65 $t_{Dry-Matter}/ha$ [28].

The entire maize plant is chopped during the harvesting step and loaded in bunker silos. The Dry-Matter content (DM-content) must remain between 28% and 36% in order to avoid leachates and energy losses and to limit the lignin share in the feedstock [28]. After the storage in bunker silos the reduced maize plant components are compressed with the help of wheel loaders and covered with a hermetic film for approximately 12 weeks (ensilage phase). They are then transported to the biogas plant. Chaff is the most widespread harvesting technique for grass silage. The DM-content of grass silage can theoretically vary between 25 and 50%. In the case of further valorization in biogas plants the value of 35% should not be overrun [29]. For higher DM-contents the high lignin- and fibre-contents can affect the feedstock degradability and thereby lower the methane yield. Most of the cereal categories are suited for the production of cereal silage but rye and triticale are generally used. The harvesting process is similar to that for maize silage with a chopping and ensilage step. The harvesting phase should ideally take place at the beginning of the dough stage. At this time point the harvesting yields reach their highest values. The harvesting yields of cereal silage can vary between 7.5 and 15 t_{DM}/ha and the DM-content remains between 30 and 35% [29]. Cereal grains display high methane yields due to their high level of degradability. The methane yields can be further maximized by a preliminary shredding step. Cereal grains can be also used in the food industry, as livestock feed or for alcohol production. Seven classes of cereal grains exist: wheat, barley, rye, oat, corn, sorghum and rice.

Household biowaste is collected by citizens in household bins separately from green waste. Important optimization potentials remain in the separate sorting of biowaste and green waste in spite of a good level of interest and acceptability by the German population. According to [30] about 44 million of citizens in Germany were not using bins for biowaste sorting at the end of the year 2012, which represents about 65% of the population. The European Union’s waste framework directive and the §11 of the Waste Management Act 2012 defined an obligation for all waste producers and for waste management authorities in Germany to collect biowaste separately starting from the 1st of January 2015 [31], [32]. This measure aims to enable a more sustainable biowaste valorization especially in biogas plants. At the end of the year 2012 a global potential of about 4.2 million t kitchen biowaste and 4.7 million t green waste in households was estimated [33]. In [33] it is further assumed that 60% of kitchen biowaste and 25% of green waste potentials could be valorized into biogas. Thereby a total potential of 3.7 million t for biowaste plus green waste feedstock was estimated to be available for biogas applications.

Beside the improvement of biowaste and green waste collection, the substrate composition also plays an important role for the optimization of the feedstock logistic chain. The biowaste composition fluctuates during the year and depends on the consumption habits of each citizen. An information and sensitization campaign to encourage sorting of the waste produced is extremely important. Another key-aspect concerns the detection of impurities in the collected biowaste. These impurities if not adequately removed could inhibit biogas production e.g., by generating over-acidification or scum build-up in the fermenters.

The harvested energy crops and manure are transported to the biogas plant location by using agricultural vehicles. Agricultural vehicles are generally tractors with two tipping trailers or with a tank trailer. In the case of biowaste transport closed collection trucks are mainly employed. The transport distance and the amount of transported biomass feedstock logically increase with the plant size. After the transport step the feedstock mass is quantified during the feedstock delivery process which takes on the site location of the biogas plant. This step also applies to co-substrates that do not belong to the agricultural farm and whose quality and quantity should be drastically controlled. After the biomass feedstock delivery, the storage step follows. The biomass feedstocks should be stored in a closed building equipped with an exhaust air purification system. Finally, some legal requirements apply to the storage of feedstocks that are submitted to hygienisation criteria like biowaste. For example, critical feedstocks must be stored separately from the harmless ones and legal immission control requirements must be respected [34].

2.2.1.2 Biomass pre-treatment, on-site conveying and loading

The biomass feedstock pre-treatment step aims to reduce process perturbations and to improve the fermentability so as to meet feedstock hygienisation criteria. The pre-treatment of liquid substrates is limited to a solid phase separation where the non-degradable solid materials like sand or solid biomass are removed. Liquid substrates containing fine or dissolved components can be directly valorized in the fermenter without any supplementary pre-treatment.

The pre-treatment of solid substrates can be very complex depending on the feedstock type and on the biogas production process employed. The steps involved can be sorting, impurities removal, shredding, mashing or hygienisation. Sorting and impurities removal processes are mainly used for heterogenic materials like biowaste. The separation of non-organic materials such as stones, glass or eggshells improves the quality of solid substrates and protects plant equipment from premature deterioration. Impurities removal consists of several sequential steps. First rough impurities are removed using visual controls. Automated devices like metal separators and star-screens are then employed and remove ferrous particles as well as other impurities. Sorting and impurities removal phases improve the digestate quality and lead to humus-rich fertilizers and composts[8]. The shredding step increases the feedstock surface and improves feedstock degradability and methane production. Shredders, mills or screws with cutting systems can be to this end employed. During the mashing step, solid substrates are transformed into a pumpable feedstock due to a water-content increase. The mashing process generally takes place in a preliminary tank directly located before the

[8] Since EEG 2012 a post-composting unit for the raw digestate combined with a valorization as compost is compulsory in the case of biowaste plants [35].

fermenter loading unit. In this process, manure, pressed liquid digestate or even fresh water can be employed as possible liquids.

A feedstock hygienization step is only legally required for certain epidemic or phytologic critical substrates like biowaste. Hygienisation can be carried out before or after the fermentation process. Plant operators must fulfil several legal requirements regarding the valorized feedstock and the digestate. Firstly, the requirements of the EU-Hygiene Ordinance (Nr. 1774) or the Biowaste Ordinance must be respected [36], [37]. The EU-Hygiene Ordinance mainly concerns the valorization of animal effluents (e.g., manure) whereas the Biowaste Ordinance applies to kitchen and household biowaste and to organic waste [38]. The EU-Hygiene Ordinance classifies the feedstock into three classes of risks and simultaneously defines the conditions for their valorization into biogas. Several conditions are defined and concern hygienization, installation security and control as well as cleaning and disinfection processes. The valorization of feedstocks belonging to the risk class I (highest risk class) is not allowed as these feedstocks can contain BSE[9]-suspicious materials [39], [40]. Biogas plants valorizing biowaste should meet the requirements of the Biowaste Ordinance. In principle, all listed biowaste plants in Appendix 1 of the Biowaste Ordinance can be transformed into biogas if epidemiologic and phytohygienic treatment conditions are respected [41]. These conditions are limited to the feedstock pre-treatment phase and to the digestate treatment. They are set up according to Nr. 2.1 of Annex 2 of the Biowaste Ordinance and concern both mesophilic and thermophilic anaerobic digestion processes (see Table 2-2) [42].

[9] Bovine Spongiform Encephalopathy is commonly referred to as “mad cow disease”.

Table 2.2: Process conditions according to epidemiologic and phytohygienic criteria for biowaste plants [42]

Process type	Mass flow category	Treatment Process	Treatment process temperature	Treatment period
Mesophilic fermentation	Raw input feedstock	Pasteurization plant	At least 70°C	At least 1 hour
	Digestate			
Thermophilic fermentation (with 20 days minimal residence time)	Raw input feedstock	Heating plant	At least 50°C	At least 24 hours

The onsite supply of biomass to fermenters consists of the conveying and the loading steps. Several conveying and loading technologies can be used according to biomass feedstock quality (pumpable or stackable). Electric pumps are used to transport pumpable feedstock like manure to the fermenters. Various technologies are available, e.g., centrifugal pumps or positive displacement pumps depending on the valorized feedstock type [43]. The pumpable feedstock conveyed is stored and homogenized in a closed dump. The dump can be further used to mix, shred and liquefy stackable co-substrates that cannot be directly loaded into the fermenter [40]. The conveying step for stackable feedstock is carried out automatically. For this, scrapers, pusher plates, connecting rods and screw conveyors are mainly used and can horizontally convey most of the stackable feedstock. These devices are however not suited to loading processes. Screw conveyors can transport stackable, cleaned and shredded feedstock in all directions [43]. The loading processes can be divided into direct and indirect loading. In the case of an indirect loading the stackable feedstocks are firstly brought to the dump and mixed with pumpable substrates. Direct loading offers the possibility to treat the stackable feedstock independently from pumpable substrates. The DM-content and consequently the biogas productivity are generally increased if stackable and pumpable feedstocks are loaded separately.

2.2.2 Biogas production process

2.2.2.1 Biogas formation

In biogas plants the anaerobic digestion process occurs in fermenters under controlled biological, thermal and physicochemical conditions. The gas mixture released (biogas) consists of methane, carbon dioxide and a variety of trace gases. Gas composition is variable and depends on the valorized feedstock as well as on the fermentation processes employed. Table 2-3 shows an average composition of biogas.

Table 2.3: Average biogas composition (author's own representation according to [44])

Component	Percentage concentration
Methane (CH_4)	45 to 75 Vol.-%
Carbon dioxide (CO_2)	25 to 55 Vol.-%
Water (H_2O)	2 to 7 Vol.-% (20-40 °C)
Hydrogen sulphide (H_2S)	20 to 20,000 ppm (2 Vol.-%)
Nitrogen (N_2)	< 5 Vol.-%
Oxygen (O_2)	< 3 Vol.-%
Hydrogen (H_2)	< 1 Vol.-%

The biogas formation step can be divided into four phases, as described below. The organic matter is degraded by various interdependent groups of bacteria. The organic raw material has a complex structure of proteins, carbohydrates and fats. This structure is decomposed during the first phase of the degradation process, i.e., the hydrolysis phase, into simple organic components like amino acids, fatty acids and sugars. The hydrolytic bacteria involved in this process use a variety of enzymes, e.g., cellulases, amylases and proteases, in order to build monomers. These intermediary products are then transformed into short-chain organic acids like propionic and butyric acids and into carbon dioxide, alcohols, and hydrogen. For this, acid-forming bacteria are employed during the acidogenesis phase. The anaerobic bacteria require oxygen and are the basis for further anaerobic methane formation.

The acetic acid formation, i.e., acetogenesis phase, represents the third phase of the biogas formation process. The organic acids and alcohols built are further transformed into acetic acids and hydrogen under the action of bacteria. Another possible reaction corresponds to the conversion of hydrogen and carbon dioxide into acetic acid [45]. The methane formation, i.e., methanogenesis phase, can be carried out following two pathways. Methane can be built through the separation of acetic acid according to following equation (Eq. 2.1).

$$CH_3COO + H^+ \rightarrow CH_4 + CO_2 \qquad (2.1)$$

The second possibility is the transformation of hydrogen and carbon dioxide into methane and water (Eq. 2.2).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (2.2)$$

Kaltschmitt identified that about 70% of the biogas production is derived from the separation of acetic acid (Eq. 2.1) and only about 30% from the reaction between carbon dioxide and hydrogen (Eq. 2.2) [43]. On the other hand, in [40] and [46] biogas produced by agricultural plants mostly results from the oxidation of carbon through the reaction between carbon dioxide and hydrogen. The four phases of the biogas formation process take place simultaneously and without physical separation. The term “single-phase process” is employed e.g., for agricultural plants. The term “two-phase processes” characterizes a separation of the hydrolysis and the acidogenesis from the acidogenesis and methane formation. This last process is never employed in practice mainly due to its unprofitability. The living conditions of methane bacteria[10] are clearly improved by the phase separation into two reactors. This increases the biogas yields but generates higher costs due to

[10] The microorganisms involved have different and specific requirements regarding their living environment (e.g., pH-values, temperature, nutrient supply).

the construction, operation and maintenance of a supplementary reactor dedicated to acidogenesis and methane formation [40].

2.2.2.2 Characterization of biogas fermentation process

In Table 2-4 the main criteria used to characterize biogas formation processes are detailed. They concern the feedstock DM-content, the loading method and the process temperature and enable a differentiation of all available fermentation processes [47].

Table 2.4: Employed criteria for the characterization of different biogas processes (author's own representation according to [47])

Criteria	**Differentiation factors**
Feedstock DM-content	- Wet fermentation - Dry fermentation
Feedstock loading method	- Discontinuous (batch process) - Quasi-continuous - Continuous
Process temperature	- Psychrophilic - Mesophilic - Thermophilic

The feedstock DM-content has a decisive influence on the choice of wet or dry fermentation processes. A wet fermentation process is generally characterized by an organic pumpable material and by a DM-content lower than 12%. A dry fermentation concerns feedstock with a DM-content generally higher than 20% and containing a watertight and stackable organic matter. Nevertheless, an exact delimitation between the two above mentioned processes does not exist in practice [48], [49]. The loading step corresponds to the fermenter supply with the microorganisms contained in the raw biomass feedstock. In principle one can distinguish between continuous, quasi-continuous and discontinuous loading concepts.

Continuous and quasi-continuous loadings characterize a fermenter supply with at least one charge of raw feedstock. In practice the repeated loading of the fermenter with small charges is the best concept. A permanent fermentation process takes place and leads to relatively homogenous biogas production. Most of the biogas plants are operated according to this principle which is continuous flow process. The term “continuous flow” refers to a loading situation where the same feedstock amount is present in the fermenter input as in the fermenter output [40]. The discontinuous process, also named as batch process, relates to a single feedstock loading during which the fermenter is entirely filled. The anaerobic digestion process takes then place during a determined residence time. The digester is subsequently emptied and filled again with new raw material feedstock.

A further criterion concerns the fermenter temperature which remains in psychrophilic, mesophilic or thermophilic domains. The psychrophilic domain is defined by a fermentation temperature lower than 30°C and is characterized by very slow organic substance degradation and by low biogas production. Currently no practical applications exist in this temperature domain for biogas plants. Most of the existing biogas plants are operated in the mesophilic temperature domain between 37°C and 42°C which represents a suitable temperature bandwidth for a stable process and an optimal biogas production. A thermophilic process temperature mainly concerns biomass feedstock hygienization processes that remain between 50 and 60 °C. If the temperature level is maintained during more than 24 hours, then the epidemic and phytosanitary requirements for biowaste are fulfilled [50]. A high degradation rate and a low viscosity are reached at this temperature level which favours biogas production. However, the requirements in terms of process control are higher [50]. Figure 2-3 describes the currently existing fermentation processes classified according to the loading method and feedstock consistency (dry or wet). The dry fermenter technologies most employed, i.e., the horizontal plug-flow fermenters, are operated under a continuous dry fermentation process (grey-marked in Figure 2-3). Most of the wet fermenter technologies are also operated under quasi-continuous processes and generally employ single-phase continuous flow fermenters (grey-marked in Figure 2-3).

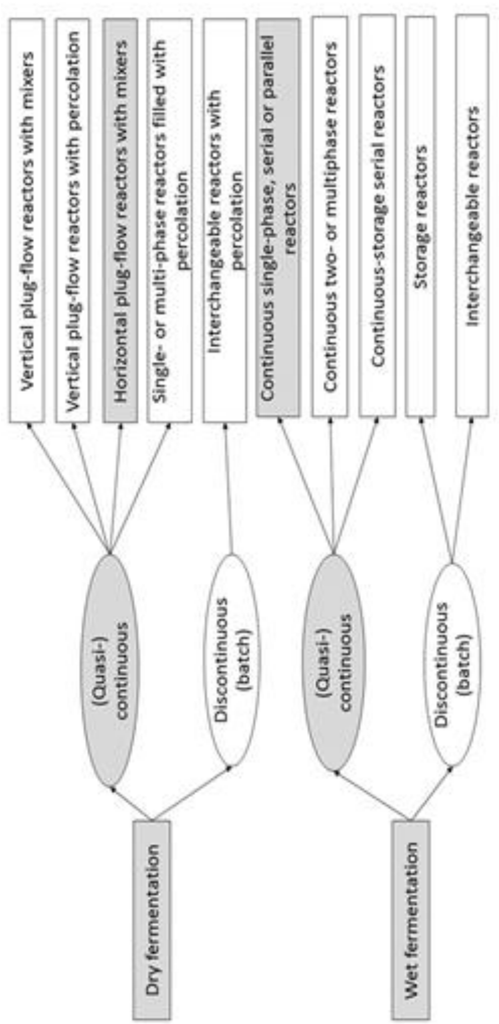

Figure 2.3: Classification of available fermentation processes (author's own representation according to [47])

Wet fermentation is the most widespread process worldwide. In Germany, about 89% of existing biogas plants are operated according to this principle [51]. In practice wet fermentation generally uses single-phase continuous flow processes. These processes are mainly characterized by a continuous fermenter loading. More precisely the fermenter is supplied daily with raw biomass feedstock in small charges. Simultaneously, the same feedstock amount is drained from the fermenter into the digestate container. During the design phase of a continuous single phase and fully mixed fermenter it is however not possible to estimate an exact residence time as a part of the raw feedstock can immediately leave the reactor [40]. Horizontal plug-flow fermentation technologies are used for dry fermentation processes and initially come from communal biowaste treatment. Nowadays they can also be applied to the valorization of energy crops. This technology uses horizontal fermenters which can contain several cross-mixers equipped with paddles or slowly moving axial agitators. The biomass substrates circulate along the length of the quasi-continuous plug-flow fermenters. A part of the digestate can be recycled into the fermenter in order to be used as inoculating material for the raw biomass feedstock input. A plug-flow fermenter is generally characterized by a thermophilic fermentation temperature at about 55 °C and a residence time of 20 to 28 days [52], [53].

2.2.3 Digestate treatment

During the fermentation process a digestate of biologically degraded material is formed. The digestate properties can be estimated by biomass input feedstock analysis and by the fermentation process. The digestate issued from the fermentation process is then conveyed to a storage tank. Since the year 2012 this storage tank, defined as a post-fermenter, has to be covered in order to avoid gas releases. The tank volume must be calculated in order to enable a minimal storage period of 180 days. The digestate displays a high fertilizing value due to high nitrogen, phosphorus and potassium contents. It can be valorized directly on soils or further treated e.g., through a solid-liquid phase separation. Digestate storage tanks are mostly designed for the storage of fermented manure. The digestate treatment consists in solid/liquid phase separation which offers the best valorization possibilities. The separated liquids can be reused in mashing processes applied to the raw biomass feedstock or valorized as liquid fertilizer. The solid digestate can be further treated using composting units in order to obtain a valuable compost. Screw separators are the main technology employed and apply to feedstock with a DM-content between 10 and 30%. Screening belts and centrifuges can also be employed [54]. The composting process involves the biological treatment of light valorizable organic materials which can be degraded by bacteria and fungi. Fertilizers and humus are then produced in the presence of air (aerobic treatment). This process is generally employed as a down-stream step following the biowaste fermentation. Several composting processes exist in Germany and can be divided into windrow composting, box composting, line composting or “brikollare composting”. These various composting processes are characterized by different designs, ventilation systems and by different intensive decomposition periods. Digestate mass flows greater than 10,000 t/a must only be exclusively treated by encapsulated composting processes in order to respect legal immissions control requirements applied to biowaste installations. In this case box composting and windrow composting processes appear to be the most suited technologies for the digestate treatment. Both of these processes minimize odours and are equipped with a closed intensive decomposition unit and a full exhaust and forced-ventilation system. Box composting processes produce a fresh compost[11] with a rotting degree of II to III and can be further treated into a finished compost by a post-rotting process [56]. Windrow composting systems are fully encapsulated with principal and post-rotting processes and directly produce a finished compost with a rotting degree of IV to V.

[11] Fresh and finished composts are defined according to the RAL quality insurance (German institute for quality insurance and labelling). A fresh compost is hygienized and has a rotting degree of II or III. This corresponds to an intensive decomposition process. A finished compost refers to a hygienized and biologically stabilized compost with a rotting degree of IV or V [55].

2.2.4 Biogas valorization

Biogas can be transformed into power and heat through a combustion process in Combined Heat and Power systems (CHPs). Another possibility is to upgrade biogas to biomethane which can then be fed into the natural gas grid. Independently of these two valorization routes, biogas must be first cleaned and buffered.

2.2.4.1 Biogas buffering and cleaning

A buffer storage corresponding to at least 25% of the daily biogas production must be installed in order to avoid strong variations in the production levels. These gas storage units can be divided into low-, medium- or high-pressure storage units. In practice low pressure storage unit is the most common technology used. A gas storage unit is made of foils and can be directly installed at the gas hood on the fermenter (integrated storage), as a foil cushion in buildings or stored in the open air (external storage). The buffered biogas must be cleaned using desulphurization processes. Biogas drying is realized by a cooling process and the desulphurization is carried out e.g., with the help of active coal filters containing potassium carbonate. The combination of these two processes aims at protecting for instance CHP gas engines, from a high wear rate as well as from corrosion [57].

2.2.4.2 Biogas valorization in Combined Heat and Power Systems

The cleaned biogas can be further valorized (e.g., in CHP gas engines) for simultaneous electricity and heat production. According to [58] about 77% of the engines employed for biogas combustion are gas-Otto-engines. The electricity produced is then fed into the grid and directly sold on the electricity market and/or subsided in the framework of Feed-In-Tariffs (FITs) defined by the Renewable Energy Sources Act (EEG). The heat produced can be recycled to the biogas plant for fermenter heating among other uses. Supplementary external heat sinks have to be found in order to improve plant efficiency and its profitability. External heat sinks are generally social buildings, stalls, drying processes or district heating networks [59].

2.2.4.3 Biogas valorization through biomethane injection

Biogas upgrading processes represent a suitable alternative to onsite electricity production especially if not enough heat sinks are located near the plant. The upgraded biogas, biomethane, can be fed into the natural gas grid and decentrally valorized in cogeneration plants or used as a gaseous biofuel. The biogas upgrading process must be carried out according to DVGW worksheets G260 and G262 [60], [61]. The first step of the biogas upgrading process is water removal. The biogas output volume flow contains saturated water vapour which can potentially generate condensation in the gas pipelines and lead to corrosion. Water removal can be carried out by compression, cooling or absorption using glycol solutions. Adsorption processes employing SiO_2 or activated carbons represent another possibility. Hydrogen sulphide (H_2S) is formed during the microbiological reduction of sulphur and must also be removed. The objective is to decrease H_2S concentration in the biogas produced. For this purpose, a precipitation reaction can be directly created in the digester by adding Fe^{2+}or Fe^{3+}. This eliminates the iron sulphide from the produced biogas. Another possibility is adsorbing H_2S using activated carbon in the presence of oxygen and water which leads to sulphur production. The H_2S removal process can also be achieved by a chemical absorption employing sodium hydroxide (NaOH), by washing or by treating biogas by an iron oxide-coated support material. H_2S can be removed from biogas by employing biological treatments involving microorganisms such as Thiobacillus and Sulfolobus. These treatments are carried out in the presence of oxygen and inside the digester [62].

In the second step of biogas upgrading oxygen and nitrogen must be separated from the biogas stream. This removal is carried out by adsorption processes involving activated carbons, molecular sieves or membranes. In a subsequent step ammonia, siloxanes and particulates are removed. Ammonia is eliminated by using drying processes. In the case of siloxanes cooling, absorption, adsorption or activated carbon processes are used. Finally, particulates, which can cause mechanical wear in gas engines, are removed using mechanical filters [63]. The central step of biogas upgrading processes is the removal of CO_2 from the crude biogas. This can be carried out by means of various technologies (e.g., Pressure Swing Adsorption, water scrubbing, organic physical or chemical scrubbing, membranes, cryogenic upgrading). A detailed description and comparison of all CO_2-removal processes employed can be found in [64]. Before injection into the grid the cleaned biogas has to be conditioned in order to meet the combustion characteristics of natural gas (e.g., gross calorific value and Wobbe index). This conditioning step is generally realized using liquid gases and potentially by adding air (in L-gas grid areas). Odorization according to the DVGW G280-1 worksheet and a pressure in-crease up to 16 bar[12] are then carried out before the final injection. Biomethane injection stations are equipped with measurement technologies in order to monitor limit values for different parameters according to DVGW worksheets G260 and G262. For example, biomethane volume, composition and gross calorific values must be estimated using process gas chromatographs and combustion calorimeters [65].

2.3 Summary

In this chapter an overview of all available bioenergy conversion pathways has been given with a focus on the biochemical conversion of biomass into biogas. Due to the variety of resources and valorization pathways bioenergy can be considered as the most versatile energy conversion technology. The anaerobic digestion of biomass feedstock can further lead to a flexible and demand-oriented electricity from biogas. It enables the production of renewable heat and digestate which can be further valorized as a fertilizer. These two products generate local markets and facilitate the implementation of circular economy with sustainable job creation. This added value contributes to a decentralization of the German electricity system in line with the objective of the German energy transition. In the next chapter the past and current situation of biogas in Europe and more particularly in Germany is

[12] Corresponds to the natural gas grid pressure level.

analysed with a focus on legal aspects. A literature review provides then an assessment of studies dealing with current and future electricity production from biogas in Germany.

3 Situation of biogas in Europe and in Germany

In this chapter the situation of biogas in Europe and Germany is described regarding past developments and current situation (sections 3.1 and 3.2). In section 3.3 the legal framework for bioenergy and biogas in Germany is assessed. In particular the Renewable Energy Sources Act is presented as an important subsidy scheme for the electricity production from biogas. A literature review follows in section 3.4. Its objective is to describe all main existing studies related to the analysis of current and future electricity production from biogas in Germany. In addition, a review of existing biomass potentials studies for biogas applications is realized. Based on these assessments the scientific contribution and added value of this thesis is emphasized by pointing out the knowledge gap filled by the present work. This chapter ends with a summary in section 3.5.

3.1 Biogas situation in Europe

By the end of 2015 about 15,391 biogas plants were installed in Europe and represented a total installed capacity of about 8.73 GW_{el} [10], [66], [67]. Germany is the undisputed leader of the European biogas market with about 8,861 existing plants for a total installed electric capacity of approximatively 4 GW_{el} [10], [66] (Figure 3-1).

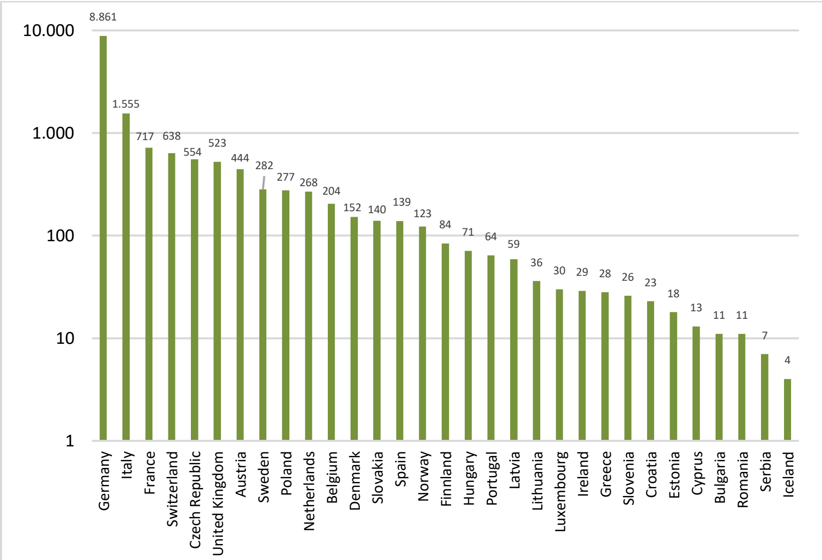

Figure 3.1: Biogas plants number repartition in Europe at the end of the year 2015 [10], [66]

There are strong discrepancies in biomass feedstock use between countries [68] (Figure 3-2). For example, in Germany and in Italy energy crops and agricultural residues represent the majority of the valorized biomass types, whereas in the United Kingdom (UK) and in Sweden mostly sewage sludge and industrial waste are employed. In France biomass feedstocks are equally divided between agricultural residues, industrial waste, waste from agro-food industry and households (category “other”). These substrates together represent more than 90% of the total mix. With less than 3% mass share, energy crops (catch crops) play only a minor role in the French biogas industry.

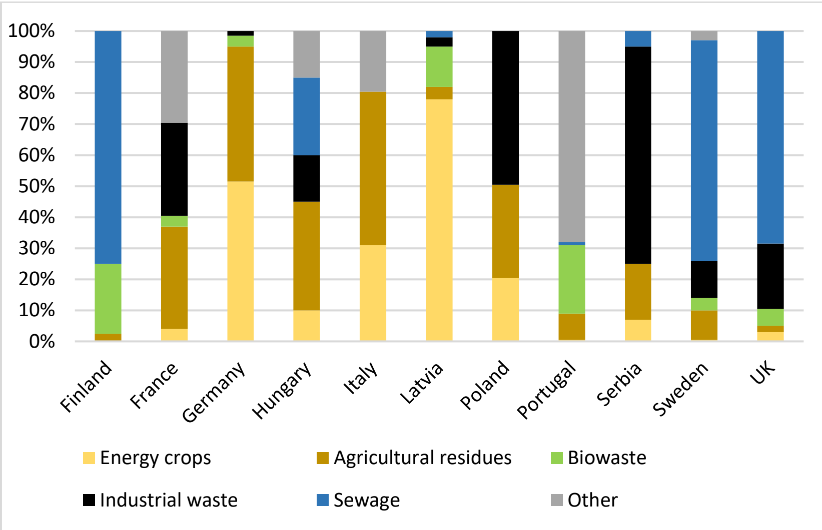

Figure 3.2: Biomass feedstock mix used in 2015 for biogas production in various European countries (in % mass) [68]

An assessment of future biomass feedstock potentials is carried out with the help of the Biomass Policies toolkit [69]. The total European biomass potential dedicated to biogas production is estimated at more than 400 million t by 2020. The main potentials would still be in Germany, France, Italy, Spain and UK amounting to more than 265 million t. Future potentials would be mainly dominated by manure (about 279 million t) and by organic waste (about 100 million t). Potentials for energy crops and agricultural residues would appear to be limited at only 21.75 million t (Figure 3-3).

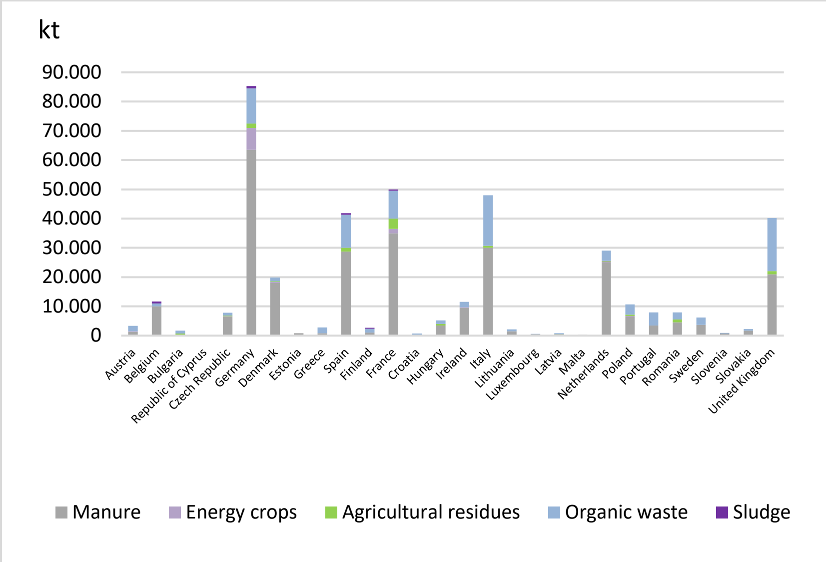

Figure 3.3: Biomass feedstock potentials in all European countries by 2020 [69]

The support schemes currently involved in each European country are shown in Table A-1 of the Appendix [70]. The most common support schemes are Feed-In-Tariffs and national subsidies (existing in 14 countries). Premium mechanisms like the market premium model in Germany have been developing strongly in the past five years and are currently employed in 9 European countries. Incentives for research and development programs are only existing in 3 countries.

The environmental benefits of biogas in Europe are further pointed out. According to the European Biogas Association, biogas plants achieved in 2015 about 33.5 million t of greenhouse gas (GHG) savings in Europe. These savings relate to the heat, power and transport sectors (12.5 million t), to the avoided emissions from manure digestion in the case of agricultural plants (10.5

million t) and to carbon sequestration[13] (10.5 million t) [71]. The total European GHG savings should increase to 230 million t GHG by 2030, which shows the mid-term environmental benefits potentially generated by the European biogas sector [71]. The European Commission (DG of Energy) mentioned that biogas production in Europe could be doubled by 2020 and highlighted in particular the relevance of biogas in circular economies and sustainable farming systems [72]. The necessary development of “the best regulation” frameworks was pointed out by Mr. Katainen, Vice-President of the European Commission. This would thereby “enable the creation of better business models and business opportunities” [72].

3.2 Past developments and current situation for biogas in Germany

Since the year 2000 the Renewable Energy Sources Act (EEG) has encouraged the development of German biogas plants. The corresponding subsidy schemes based on FIT have given a major impetus to the biogas plants expansion. As shown in Figure 3-4 the different versions of the EEG for the years 2000, 2004, 2009, 2012 and 2014 have led to a continuous development of the biogas sector over the past fifteen years [10]. The first version of the EEG in 2000 was characterized by the introduction of plant type and capacity dependent Feed-In-Tariffs. In the 2004 version of the EEG a specific bonus dedicated to the valorization of energy crops into biogas was introduced in order to enable the development of agricultural biogas plants. In 2009 a supplementary bonus linked to manure valorization was set which has accelerated the expansion of agricultural co-digestion plants. The EEG 2012 introduced the possibility for plant operators to directly market the electricity produced according to demand and price. For this a market and a flexibility premium were defined [73]. The following version of the EEG, which came into force in August 2014, reinforced the market integration objective for

[13] Carbon sequestration occurs in soils through organic carbon building-up.

biogas. The main objective of the EEG 2014 is to continuously and cost-efficiently increase the share of renewable energy sources in the gross electricity demand [74]. The target to be reached is for about 40% of German gross electricity demand to be met for renewable energy sources by 2025 and about 55% by 2035 [74]. As mentioned in the EEG 2014 the support schemes for German renewable electricity should focus on the least cost intensive technologies [74]. With an electricity production cost of about 18 ct/kWh_{el}, biogas belongs to the most expensive renewable electricity sources [13], [14]. This is mainly due to high energy crop costs, which represent more than half of total electricity production costs [75]. By removing the subsidies for energy crops valorization, the EEG 2014 clearly intends to slow down the development of agricultural plants. This also aims to avoid competition with the food value chain in terms of surface area and resources.

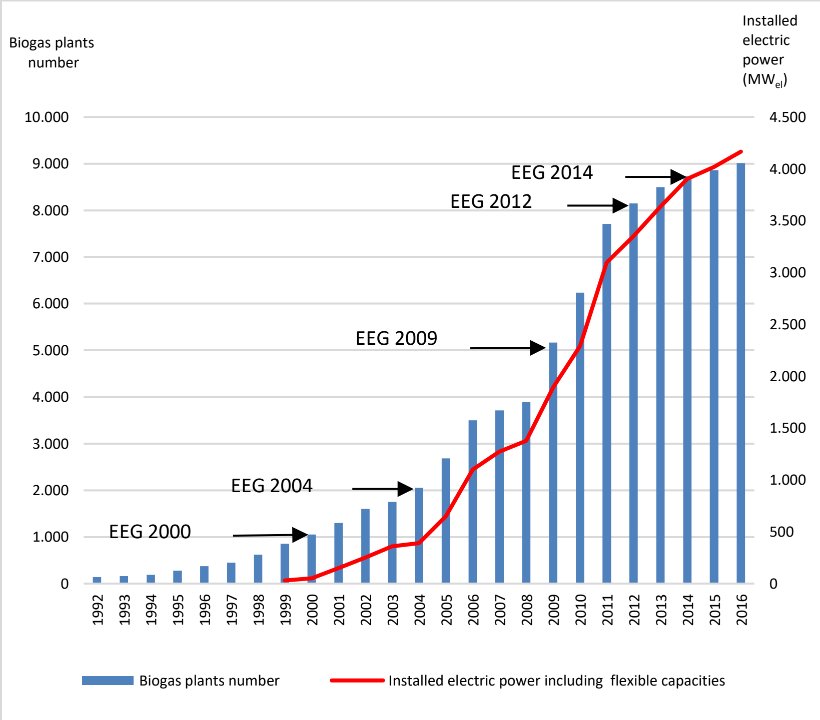

Figure 3.4: Historical development for German biogas plants [10]

About 614 TWh_{el} electricity have been produced annually in Germany by the end of 2014 [76]. Renewable energy sources have, with 26.2%, the main share in the total German electricity generation before brown coal and hard coal. Nuclear energy has a share of about 15.8%. This share will continue to decrease following the decommissioning plan for nuclear reactors which was decided in Germany after the Fukushima disaster in 2011. Natural gas and fuel oil currently play a secondary role in the electricity mix with production shares lower than 10% [76]. German renewable electricity production - about 160.9 TWh_{el} by 2014 - is mainly driven by wind energy and bioenergy with respective shares at about 34.8% and 30.6%. Photovoltaics follows with a share of approximatively 21.7% whereas hydropower supplies 12.8% of the total renewable electricity production. With a share of 0.1% geothermal energy plays only a marginal role [76].

Electricity generation from biomass, considered under the EEG legal framework, can be estimated at about 38.16 TWh_{el} [14] (Figure 3-5). It is mainly driven by biogas with about 72.3% of the total production mix [77].

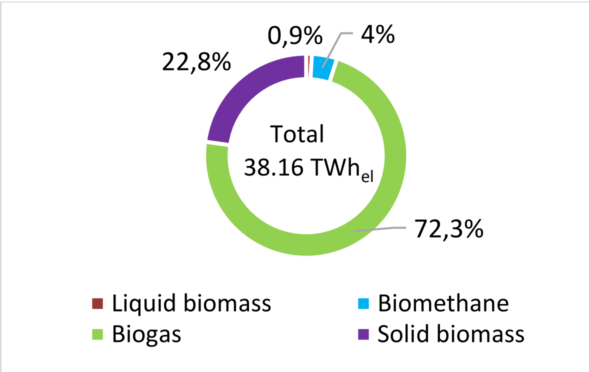

Figure 3.5: German electricity production from biomass in 2014 under the EEG framework [77]

Finally Figures 3-6 and 3-7 provide information regarding the main feedstocks employed in German biogas plants. With about 52% and 43% respectively energy crops and manure represent the main biomass types used in Germany for biogas production. Biowaste and agro-industrial residues play a minor role with shares lower than 4% [78]. The valorization of energy crops into biogas is principally driven by maize silage with a share of 73% in the total energy crops feedstock mix. The remaining 27% are made up of grass silage (12%), cereal silage (7%) and miscellaneous energy crops (cereal grains, sugar beet, catch crop, miscellaneous crops) [79].

[14] A supplementary amount of 14.12 TWh_{el} has to be added and corresponds to the total electricity production from biogas by other technologies than CHP (e.g., gas turbines or Stirling engines) [6].

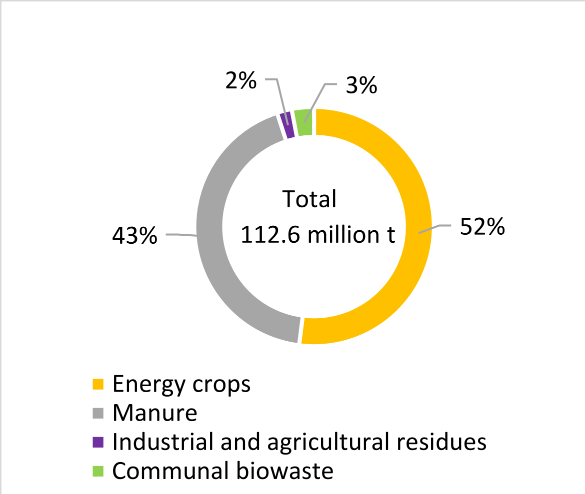

Figure 3.6: Main feedstocks employed in German biogas plants at the end of 2014 [78]

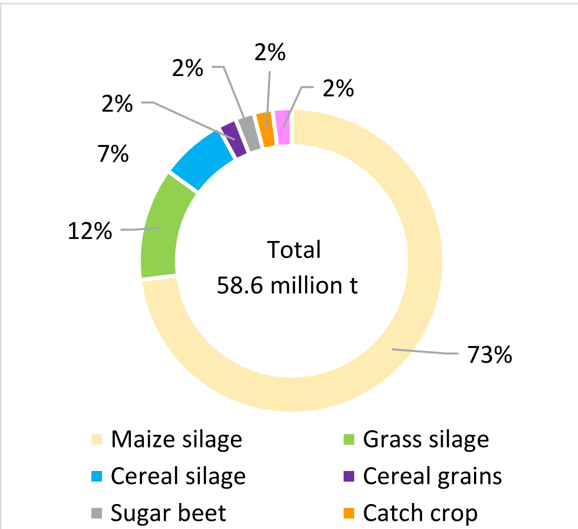

Figure 3.7: Main energy crops employed in German biogas plants at the end of 2014 [79]

3.3 Legal framework for renewable energies and biogas in Germany

Continuous investments in renewable technologies and infrastructure are necessary in order to achieve a more sustainable energy supply. This requires a stable political and legal framework in order to facilitate the development of new markets from the local up to the national levels. Up to now the financial support schemes for renewable energies have successfully contributed to the emergence of new technologies and new markets in the past fifteen years. A further integration of renewable energies in national and international energy markets remains however necessary in order to simultaneously reach the environmental objectives set for Germany and slow down the energy price increases for end-customers. In the following, the main laws and regulations concerning renewable energies and biogas in Germany are described.

3.3.1 Energy Economics Law (EnWG)

The Energy Economics Law concerns the heat, electricity and gas supply in Germany. It came into force on July 13^{th} 2005 and was updated on August 29^{th} 2016. The objective of the EnWG is based on the so called “target triangle”. The EnWG defines targets for economic efficiency, security of supply and environmental compatibility regarding the supply of heat, electricity and gas in Germany [80], [81].

The Energy Economics Law defines in particular the rights and duties between energy suppliers and consumers and encourages the liberalization of the German electricity market. One of the key tasks of this law is the unbundling of discrimination, cross-subsidization and other distortions of competition in the field of network operation. To achieve this, the energy economic functions like production, sale and storage should be separated from network operation, i.e. transmission and distribution. Another important task of the

EnWG is to regulate network operation. This is done by defining network operator missions and the conditions for network connection and access. Under this framework, all gas and electricity consumers can benefit from standardized access to energy supply networks and the collected network charges must be approved by the regulatory authority [82].

3.3.2 Renewable Energy Heat Act (EEWärmeG)

The Renewable Energies Heat Act (EEWärmeG) came into force on January 1st 2009 and deals with the use of renewable energies in new residential and non-residential buildings. According to the EEWärmeG, a certain share of the end energy heat consumption has to be covered by renewable energies. A share of 14% by 2020 is set as an objective [83]. The heat energy consumption relates to heating, hot water production and cooling. Further objectives concern the limited use of fossil resources, an independence from energy imports as well as the continuous development of innovative heating technologies. The share of energy consumption that should be covered by the building owners is specifically defined for different technologies. For example, solar collectors must cover at least 15% of the heat/cold energy consumption. If solid biofuels, geothermal or environmental heat are used then 50% of the demand must be satisfied. Finally, if biomethane is used for heating then it must represent at least 30% of heat energy consumption [84].

Numerous renewable energy technologies can be used in order to meet these objectives: solar energy, solid biomass combustion (e.g., wood pellets, wood chips, biogas in micro-CHPs, biogenic oils in boilers), geothermal energy or environmental heat combined with efficient heat pumps [85]. No obligations linked to the EEWärmeG are foreseen for existing buildings. Nevertheless, alternative measures can be applied but are not compulsory. For example, the use of cogeneration, insulation measures or heat from local heating network can be considered as substitution measures or combined with the above-mentioned technologies [86].

3.3.3 Renewable Heat Law (EWärmeG)

The Renewable Heat Law is a Federal law applied in the state of Baden-Württemberg. It came into force in 2008 and was updated in July 2015 [87]. In the framework of the EWärmeG the owners of existing buildings[15] are obliged to use renewable energies if they modify their heating systems [88]. A difference is further made between residential and non-residential buildings. According to the EWärmeG, 15% of the heating energy demand has to be covered by renewable energies. Possible renewable heating technologies are solar thermal energy, wood based central heating, heat pumps, biogenic oils and biogas. Similarly, to the EEWärmeG alternative measures, such as thermal insulation, cogeneration, connection to heating networks or photovoltaic plants can be applied.

3.3.4 Cogeneration Act (KWKG)

The new version of the Cogeneration Act came into force by the end of 2015 and aims to increase the net electricity production of cogeneration plants (CHP-plants) up to 110 TWh_{el} by 2020 and 120 TWh_{el} by 2025 [89]. By the end of the year 2014, CHP-plants have produced electricity at a level of 97.6 TWh_{el} which is already close to the objective set for the year 2020 [90]. The new version of the Cogeneration Act is then characterized by a very moderate expansion strategy. The new Cogeneration Act regulates the use and subsidies linked to the electricity produced by existing, new modernised and repowered cogeneration plants employing lignite, hard coal, solid waste, waste heat, biomass, gaseous or liquid fuels. It further defines the modalities of the supplements payments by the Transmission System Operators (TSO) for the expansion of heat and cold networks and storage. The level of these supplements as well as the associated modalities are further described in [91]. Bioenergy conversion plants including biogas installations can be financially supported under the Renewable Energy Sources Act (EEG) or the

[15] Buildings constructed before the 1st of January 2009.

KWKG subsidy scheme. A double subsidy combining both of these incentives is therefore not allowed.

3.3.5 Biomass Electricity Sustainability Regulation (BioSt-NachV)

The biomass electricity sustainability regulation (BioSt-NachV) was enacted on July 23^{rd} 2009 and applies to liquid biofuels used to produce electricity according to the Renew-able Energy Sources Act [92]. The BioSt-NachV defines sustainability criteria linked to biomass cultivation and treatment mainly for rapeseed oil, soya oil and palm oil. The main criteria concern the protection of natural living spaces, sustainable cultivation of agricultural surface areas and the protection of surface areas of high natural value (e.g., forests, nature reserve or surface areas with high biological diversity). The liquid biofuels valorized should show a GHG-mitigation potential superior to 35% (60% by 2018). These sustainability criteria are a prerequisite that must be displayed by plant operators before they can obtain the EEG subsidies and the sustainability certificates for the used biofuels [92].

3.3.6 Renewable Energy Sources Act (EEG)

3.3.6.1 Past developments and time schedule

In the last fifteen years the Renewable Energy Sources Act (EEG) has mainly contributed to the expansion of renewable energies in Germany in the electricity sector. Targets of at least 35% renewable energies in the German gross electricity demand up to the years 2020 and at least 50% up to the year 2030 are defined by the German Federal Government [93]. These objectives should contribute to reach the renewable energies share set by the European Union for the year 2020 in the national end-energy demand[16]. In 1991 and

[16] In [94] a 18% share of national end-energy demand must be met by renewable energies in Germany by the year 2020.

under the “Electricity Feed-In Law”, which was the precursor of the EEG, the share of renewable energies in German gross electricity demand was only 3.1% [95]. On April 1st 2000, the first version of EEG came into effect. Since this date, the share of wind and solar energy, hydropower, biomass and geothermal energy has increased from 6.2% to about 31.6% in year 2015 [95]. The EEG contains some basic principles, which were defined in the first version of the year 2000 and which ensure a certain investment security for investors and plants operators. The grid operators must connect new plants to their electricity transport network. Simultaneously to the grid connection, the plants receive a feed-in priority as well as fixed Feed-In-Tariffs (FIT) for the electricity produced with a horizon of the next twenty years from the year of commissioning. In addition to these basic principles the EEG is regularly amended in order to follow current market conditions. Since the year 2009, numerous evolutions have been proposed by the German Federal Government in order to financially support the development of biogas. Figure 3-8 shows the time schedule used for the setting up of the different subsidy mechanisms. These mechanisms are further analysed from sections 3.3.6.4 to 3.3.6.7.

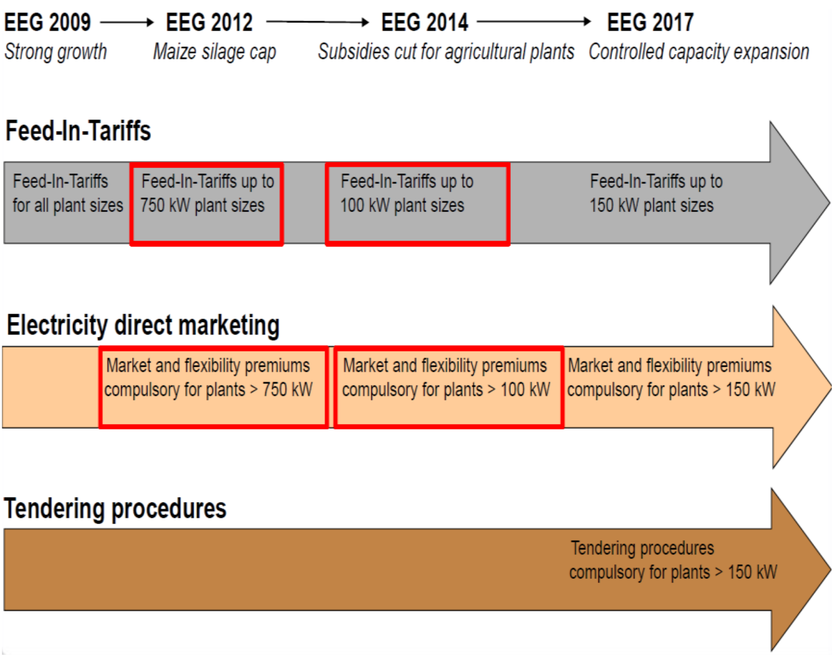

Figure 3.8: Time schedule for the setting up of the different subsidy mechanisms supporting biogas in Germany (author's own representation according to [96], [11], [35])

3.3.6.2 Main objective of the Renewable Energy Sources Act

The main objective of the EEG is to continuously and cost-efficiently increase the share of renewable energy sources in the gross electricity demand [74]. This development should focus on the support of the most cost-efficient technologies, in order to cope with the problem of renewable energy levy. The renewable energy levy corresponds to the difference between the costs generated by the subsidy support for renewable electricity production and the revenues generated by the electricity produced [97]. The level of this levy is set by the four main German power transmission network operators, which have a mission to administer and manage the account in which the subsidies are registered. The transmission network operators must publish each year on the 15th of October the amount of the renewable energy levy. This levy is paid by the industrial and private final consumers and appears on their electricity bill. For the year 2017 the highest historical value was reached at about 6.88 $\mathrm{ct/kWh_{el}}$ for household consumers [98]. The EEG aims to inhibit the strong cost progression of the renewable energy levy by limiting the development of the most expensive renewable energy conversion technologies. In particular in the field of electricity production from biomass a maximal increase of installed capacity of about 100 $\mathrm{MW_{el}}$ per year is defined in the framework of the EEG 2014 [99].

3.3.6.3 Definitions related to biogas plants under the EEG framework

3.3.6.3.1 Technical requirements

Existing biogas plants which were built before the 1^{st} of August 2014 must respect following technical measures. The plant operators are obliged to install a supplementary gas valorization infrastructure (e.g., gas flare) in order to avoid free emissions due to biogas production. In the case of biogas upgrading to natural gas quality, the plant operators must respect a maximal threshold value of 0.2% methane emissions in the atmosphere.

According to the EEG 2014 framework biogas plants with an installed electric power greater than 100 $\mathrm{kW_{el}}$ must be equipped with technical remote-control devices that enable plants operators to reduce the electrical output and avoid network overloads. At least one of the post-digesters has to be gas-proofed and must show a minimal hydraulic residence time of 150 days. A supplementary gas valorization infrastructure also has to be installed in order to prevent a high release of biogas into the atmosphere [100]. Biogas plants valorizing exclusively manure are free from the obligation of covering the post-digester and of respecting the minimal residence time [100].

3.3.6.3.2 Installation terminology

In § 3 Nr. 1 of the EEG 2009 the definition of a biogas plant is given and refers to the totality of all functional and technical components dedicated to electricity production from biogas (e.g., CHP, fermenter, gas storage, digestate storage tank, biomass feedstock pre-treatment unit) [101]. This broad definition is further considered in this work and it is also assumed that several CHP units connected to the same biogas production plant (anaerobic digester) are seen as a single plant.

3.3.6.4 Feed-In-Tariffs for biogas plants

3.3.6.4.1 Example of a remuneration system according to EEG 2014

The main changes regarding subsidy levels in the framework of EEG 2014 concern agricultural plants. For these plants the subsidies related to the valorization of energy crops have been suppressed and only the electric power dependent base subsidies have been kept, which leads to major simplifications. The subsidies for biowaste plants and small-scale manure plants remain approximatively at the same level as for EEG 2012.

The subsidy structure represented in Table 3-1 is applicable to plants which were commissioned before the 31^{st} of July 2015. Starting from the 1^{st} of August 2015 EEG-subsidies are decreasing by 0.5% per quarter of each year [102].

Table 3.1: Remuneration system for electricity generation from biogas following EEG 2014 [102]

Average annual capacity (kW_{el})	Remuneration for plants valorizing energy crops according to the definition of the Biomass Ordinance (ct/kWh_{el})	Remuneration for biowaste plants[17] (ct/kWh_{el})
≤ 75: with only use of manure	23.73[18]	
≤ 150	13.66	15.26
≤ 500	11.78	
≤ 5,000	10.55	
≤ 20,000	5.85	13.38

3.3.6.4.2 Miscellaneous categories for small-scale manure and biowaste plants

In the new subsidies structure manure plants up to 75 $\mathrm{kW_{el}}$ installed electric power fall into a miscellaneous category. In this category a subsidy of 23.73 $\mathrm{ct/kWh_{el}}$ is attributed (see Table 3-1). This subsidy cannot be combined with other revenues and is only attributed if at least 80% of manure per year is valorized in the biogas plants. According to the Annex 3 Nr.9, 11-15 of the Biomass Act manure consists of the following feedstock: horse, cow, sheep, pig and goat manure [105].

In order to receive subsidies biowaste plants should use at least 90% of the following three biowaste types coming from [105]:

- Biologic degradable biowaste like garden or landscape conservation waste

[17] With at least 90% biowaste mass amount according to the Annex 1 of the Biowaste Ordinance [103]

[18] For small manure plants: at least 80% of the manure must be valorized in the digester [104].

- Mixed municipal solid waste like separated biowaste from private households (in particular biowaste container)
- Vegetal market biowaste

In the case of biowaste plants rotting process equipment must be installed after the fermenters in order to treat the solid digestate [102]. Finally, the technical requirements for post-digesters described in section 3.3.6.3.1 must be satisfied.

3.3.6.5 Electricity direct marketing

Since EEG 2012 every biogas plant operator in Germany has the possibility to directly self-market the electricity produced in the framework of the so called "market premium" [73]. In addition to the revenues from the sale of the electricity German biogas plant operators receive a supplement i.e., the "market premium". The market premium corresponds to the difference between the plant specific EEG-subsidies and the revenues from electricity sales on the Exchange market (average EPEX values of the hourly contracts passed on the EPEX Spot EEX bourse). The market premium is determined for each past calendar-month as follows [106] (Eq. 3.1):

$$MP = FIT - MA_{EPEX} \tag{3.1}$$

With:

MP: Market premium; FIT: plant specific EEG-subsidies; MA_{EPEX}: monthly average values of the hourly contracts passed on the EPEX Spot EX bourse

In the middle of the year 2015, the direct electricity marketing model concerned a total biogas plant capacity of about 2,650 MW_{el} which corresponds to about 66% of the total installed capacity at this time point (4,018 MW_{el}) [107].

In addition to the market premium and in the context of EEG 2012 a "premium for the delivery of supplementary installed capacity for a demand-oriented electricity production”, the so called “flexibility premium”, has been defined [108]. This premium was intended to facilitate investments in larger gas storage units and supplementary CHP capacity. The objective is to reach a more demand-oriented and flexible electricity production from biogas. Contrary to the classical period of 20 years, under which EEG-subsidies are guaranteed, the flexibility premium is valid for a period of 10 years. In order to benefit from this premium, the biogas plant operators must firstly directly market the electricity produced in the context of the market premium model and secondly prove that a supplementary and permanently available biogas reserve is installed.

The supplementary CHP capacity can be defined as the difference between the installed power $\mathrm{P_{inst}}$ and the rated power $\mathrm{P_{Rat}}$ for the corresponding year. The value of the flexibility premium (FP) is defined according to Eq. 3.2 and expressed in $\mathrm{ct/kWh_{el}}$ for the electricity fed into the grid [109].

$$FP = \frac{(P_{inst} - (f_{Cor} \times P_{Rat})) \times CC \times 100}{P_{Rat} \times 8{,}760} \qquad (3.2)$$

The rated power $\mathrm{P_{Rat}}$ is multiplied by a correction factor $\mathrm{f_{Cor}}$ of 1.1 for biogas and 1.6 for biomethane representing the real load. The Capacity Component CC is set at 130 $€/\mathrm{kW_{el}}$of supplementary electric power, according to [110]. In the new framework of EEG 2014 the flexibility premium has been replaced by a flexibility supplement of 40 $€/\mathrm{kW_{el}}$ for new built plants larger than 100 $\mathrm{kW_{el}}$ and commissioned after the 1st of August 2014 [111]. In July 2015 the flexibility regime concerned about 2,692 plants with a total cumulated capacity of 1,519 $\mathrm{MW_{el}}$ [107].

3.3.6.6 Tendering procedure

In the context of the Renewable Energy Sources Act 2017, which came into force on January 1st 2017, tendering procedure mechanisms include an auction system[19] [112]. This mechanism aims to provide an impetus for the future development of bioenergy plants in Germany especially in line with the grid expansion. Another objective is to improve the economic competitiveness of bioenergy in order to facilitate in particular its integration into the German electricity system. In the planned auction process the best placed bioenergy plants thus receive a payment linked to the power that they can deliver. New built bioenergy installations smaller than 150 kW_{el} are excluded from the tendering procedure and will thus receive the Feed-In-Tariffs [112]. All existing plants including plants smaller than 150 kW_{el} can take part in the tendering procedure and be financially supported for 10 years if the electricity is produced under a flexibility regime [112]. The German Federal Ministry aims to support the most cost-efficient bioenergy technologies and the auction mechanism is consequently designed to support plants showing the lowest annual electricity bid price. New plants offering electricity bid prices higher than a value of 14.88 ct/kWh_{el} are automatically excluded from the auction system [112]. In this new mechanism installations showing the lowest electricity bid price receive an EEG subsidies level relative to their plant size. From 2017 to 2019, a total installed capacity of 150 MW_{el} per year is thus involved in this tendering procedure. This maximal allocable capacity will further increase to 200 MW_{el} per year from 2020 to 2022 [112].

3.3.6.7 Critical analysis of the past and current subsidy mechanisms for biogas in Germany

Since the year 2000 the Feed-In-Tariffs defined in the framework of the Renewable Energy Sources Act have provided a major impetus for the development of biogas plants in Germany. In particular the energy crops and manure bonuses, defined in EEG 2004 and EEG 2009, have contributed to a strong development of agricultural biogas installations and especially co-digestion plants. In the context of EEG 2014 the Federal Government has

[19] This price amounts to 16.9 ct/kWh_{el} for existing plants which can also participate in the tendering procedure.

enacted a cut for the subsidies related to an energy crops valorization into biogas. This has for effect to threaten the profitability of agricultural installations and to limit future developments to biowaste and small-scale manure plants. Pros and cons concerning this decision are pointed out in Figure 3-9. The shift towards a subsidy support scheme mainly dedicated to plants based on waste and residues will lead to a more ecological electricity production from biogas in the forthcoming years. Manure and biowaste installations generally show a lower green-house gas potential than the agricultural plants as well as lower GHG-mitigation costs [113]. The energetic use of biowaste and manure does not impact the food value chain and thus contributes to a better acceptance for biogas in Germany. On the contrary the past valorization of energy crops in order to produce biogas has led to a “food versus fuel” debate and to public criticisms [114]. Small-scale manure and biowaste plants often show higher specific investments and higher electricity production costs than energy crops installations [115], [116]. Consequently, trade-offs had to be found between the environmental benefits induced by biowaste and small-scale manure plants and the economic performance related to energy crops-based installations. By operating a cut on the energy crops subsidies, the Federal Government clearly intends to slow-down future capacity development and to move towards a more environmentally friendly electricity production from biogas.

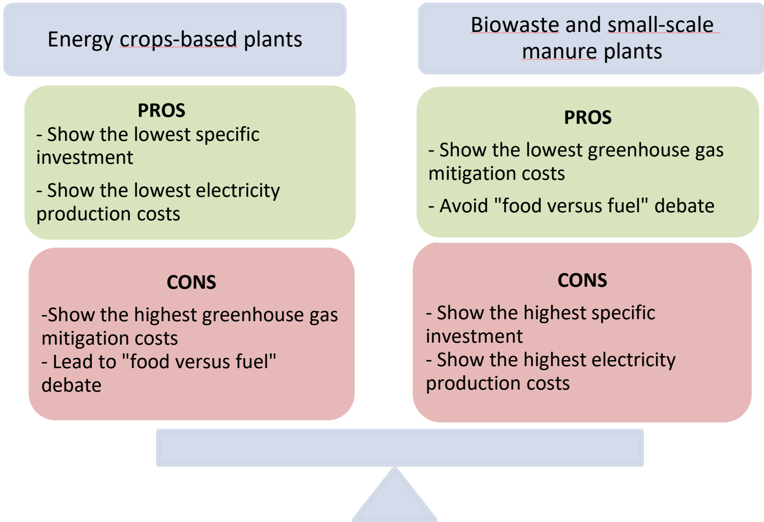

Figure 3.9: Pros and cons characterizing energy crops-based versus biowaste and small-scale manure plants (author's own representation)

Economic optimization possibilities remain however for biogas plant operators and represent new challenges. By enabling the electricity direct marketing, the EEG 2012 generates financial uncertainties for plant operators regarding the EPEX price level reached for the sold electricity. The new auction mechanism enacted by the EEG 2017 encourages plant operators to improve the techno-economic efficiency of their installation and strengthens the relevance of plant flexibility. However, the selection process defined in the tendering procedure could tends to favour systematically the same bioenergy conversion pathway, i.e., the one offering the lowest electricity bid price. Biogas plants have then to be competitive enough in comparison to other bioenergy technologies in order to continue to benefit from the EEG subsidy framework. Therefore, the new EEG 2017 mechanism is a source of opportunities but also of risks for the future German biogas market.

3.4 Literature review on techno-economic aspects

In this section a review of existing studies dealing with the economic analysis of current and future electricity production from biogas in Germany is carried out. Three main assessment categories can be distinguished. The first one concerns the economic evaluation of existing biogas plants. The evaluation is often carried out by comparing specific electricity production costs (in $\mathrm{ct/kWh_{el}}$) from various biogas supply chains. The second category deals with the estimation and forecast of technical biomass potentials for biogas applications. A last assessment category refers to the economic analysis of future mid-term developments for biogas plants up to the year 2030. Based on this review the added value of the present thesis is emphasized from a methodological point of view as well as regarding the scientific content.

3.4.1 Economic assessment of existing biogas plants

The economic assessment of existing biogas plants in Germany has been pursued in many recent studies. Most of these studies lead to the estimation of specific electricity production costs from biogas in $\mathrm{ct/kWh_{el}}$. The specific electricity production costs correspond to the total annual costs divided by the electricity amount annually fed into the power grid. Total annual costs can be split into annual operating costs and investment-related costs. Annual operating costs correspond to expenses related to the operation of a business, a device, a component, a piece of equipment or a facility. They include personnel costs, biomass feedstock, process utilities, maintenance, biomass transport, electricity consumption and digestate treatment costs. Investment-related costs consist of depreciation, interests and insurance costs. Numerous evaluations of specific electricity productions costs for both biowaste and agricultural biogas supply chains have been carried out in the past ten years. In [117] the case of a mesophilic wet fermentation plant valorizing 7,500 t/a biowaste with an installed power of about 312 $\mathrm{kW_{el}}$ is analysed. Total capital investment and specific electricity production costs are estimated at about 5.84 € million and 48 $\mathrm{ct/kWh_{el}}$ respectively. In [118] a systematic analysis of a 500 $\mathrm{kW_{el}}$ biowaste plant employing 15,000 t/a biowaste is carried out. Total capital investment amounts there 6.34 € million and specific electricity production costs are estimated at about 47.24 $\mathrm{ct/kWh_{el}}$. The economic situation of a 1 $\mathrm{MW_{el}}$ biowaste plant is also assessed and leads to total capital investment of about 12.28 € million and to specific electricity production costs of 42.71 $\mathrm{ct/kWh_{el}}$ [118].

In [119] the economic assessment focuses on co-digestion plants employing biowaste with manure. The co-digestion of 11,000 t/a biowaste with 11,000 t/a manure is thus characterized by an installed electric power of 600 $\mathrm{kW_{el}}$. Total capital investment is determined to be about 5.7 € million and specific electricity production costs about 39 $\mathrm{ct/kWh_{el}}$. In [120] continuous and discontinuous dry fermentation processes are economically assessed for the valorization of 18,000 of t/a biowaste. In the case of a continuous process total specific annual costs including digestate composting amount to 82 €/t, which corresponds to specific electricity production costs of about 32.8 $\mathrm{ct/kWh_{el}}$[20] [120]. In the case of discontinuous dry fermentation processes and for the same amount of valorized biowaste, total specific annual costs including digestate composting amount to 71 €/t, which leads to specific electricity production costs of about 31.6 $\mathrm{ct/kWh_{el}}$[21]. In [75] a 760 $\mathrm{kW_{el}}$ biogas plant is considered which employs 15,000 t/a biowaste in co-digestion with 41,000 t/a sewage sludge to produce heat and electricity in two CHP gas engines of 380 $\mathrm{kW_{el}}$. For this plant, specific electricity production costs have been determined to be about 34.6 $\mathrm{ct/kWh_{el}}$. Finally, the u.e.c Berlin carried out an economic evaluation of three biogas plants located in the Federal State of Schleswig-Holstein [121]. The results of this last economic assessment are set out in Table 3-2.

[20] It is further assumed that one t of biowaste corresponds here to 250 $\mathrm{kWh_{el}}$ in the case of continuous dry fermentation processes [120].
[21] Under the assumption that 1 ton of biowaste corresponds to 225 $\mathrm{kWh_{el}}$ for discontinuous dry fermentation processes according to [120].

Table 3.2: Results of an economic evaluation for three biowaste plants located in the Federal State of Schleswig-Holstein [121]

	Valorized biowaste amount (t/a)	Process	Installed electric power (kW_{el})	Specific operating costs including digestate composting (€/t)	Specific investment related costs (€/t)	Electricity production costs (ct/kWh_{el})
Biogas plant 1	20,000	Dry continuous fermentation	625	63	32	38
Biogas plant 2	30,000		1000	61.6	30	34.4
Biogas plant 3	50,000		1800	61	29	31.25

An evaluation of specific electricity production costs for biogas from agricultural plants is also realized. In [75] the profitability of a 500 kW_{el} agricultural plant employing 9,160 t/a energy crops is assessed and provides specific electricity production costs of about 18.8 ct/kWh_{el}. In [119] a first agricultural co-digestion plant with an installed electric power of 150 kW_{el} and valorizing 2,000 t/a maize silage and 8,000 t/a manure had specific electricity production costs of about 22 ct/kWh_{el}. A second agricultural installation with an installed electric power of 300 kW_{el} transforming 8,000 t/a maize silage and 2,000 t/a manure into biogas has specific electricity production costs of about 20 ct/kWh_{el}. In [122] a 250 kW_{el} agricultural biogas plant mainly based on maize silage shows specific electricity production costs of about 18.5 ct/kWh_{el}.

In [123] two biogas plants respectively with 500 kW_{el} and 1,000 kW_{el} installed power are economically assessed. Both of the two plants valorize 60% maize silage, 30% silage grains and 10% manure in co-digestion processes. The 500 kW_{el} plant size has specific electricity production costs at about 18.7

ct/kWh_{el} compared with 16.5 ct/kWh_{el} for the 1,000 kW_{el} plant size. In [124] the profitability of five agricultural biogas installations is assessed. A small-scale manure plant with 75 kW_{el} valorizing about 11,100 t/a manure shows specific electricity production costs of about 21.4 ct/kWh_{el}. The profitability analysis of a 150 kW_{el} plant valorizing exclusively maize silage gives specific electricity production costs of about 26.23 ct/kWh_{el}. A third plant with the same installed capacity employing 70% maize silage and 30% manure in co-digestion has specific electricity production costs of about 24.98 ct/kWh_{el}. Finally, the two last plants have an electric capacity of 500 kW_{el} and valorize maize silage in mono- and in co-digestion with manure. In this case specific electricity production costs amount to about 20.6 ct/kWh_{el} and 23.3 ct/kWh_{el}. Figure 3-10 sums up and compares all the previously mentioned electricity production costs both for biowaste and agricultural plants.

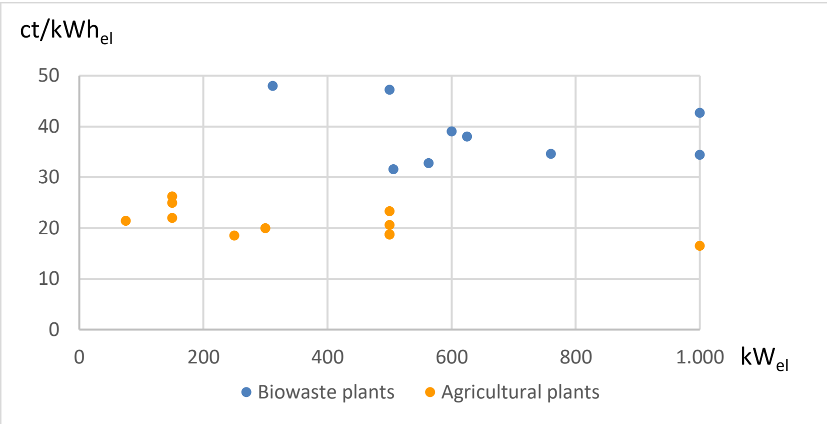

Figure 3.10: Literature values for specific electricity production costs relative to biowaste and agricultural biogas plants in Germany (own representation according to [75], [117], [118], [119], [120], [121], [122], [123], [124])

The results in Figure 3-10 show that the specific electricity production costs for agricultural plants are systematically lower than those for biowaste plants. Table 3-3 shows the positions involved in the electricity production costs of a biowaste and an agricultural plant of comparable size [75]. It appears that the investment-related costs are higher in the case of biowaste plants than for agricultural installations. This is mainly due to cost-intensive biowaste pre-treatments like hydrolysis, pasteurization or hygienization. These process steps are not required for agricultural plants where the substrates can be directly fed into the digesters. The biowaste pre-treatment operations also require supplementary manpower which impacts the personnel costs level. The digestate issued from the biowaste valorization has to be treated whereas no treatment is necessary for agricultural plants (direct valorization on the soils of the farmer's exploitation). All these factors explain then the visible gap in Figure 3-10 concerning the specific electricity production cost levels for these two plant types.

Table 3.3: Decomposition of the specific electricity production costs (in ct/kWh_{el}) for a biowaste and an agricultural biogas plants [75]

	760 kW_{el} biowaste plant	500 kW_{el} agricultural plant
Investment-related costs	14.3	6.1
Electricity consumption costs	0.7	0.7
Maintenance costs	2.8	0.2
Personnel costs	5	0.5
Biomass transport costs	2.8	3.2
Biomass feedstock costs	0	7.8
Digestate treatment costs	5.5	0
Process utilities costs	3.5	0.3

A further assessment concerns the economic analysis of real biogas plants based on data provided by plant operators. In the framework of its biogas measurement program II in 2010 the FNR (Fachagentur Nachwachsende Rohstoffe e.V.) compared 55 existing biogas plants [125]. The economic analysis has been made using the electricity production costs as the main evaluation criterion. The results show that about 90% of the installations show electricity production costs located between 10 and 20 $\mathrm{ct/kWh_{el}}$ (Figure 3-11). These values are in line with the results of the previous economic evaluation realized for agricultural plants in Figure 3-10.

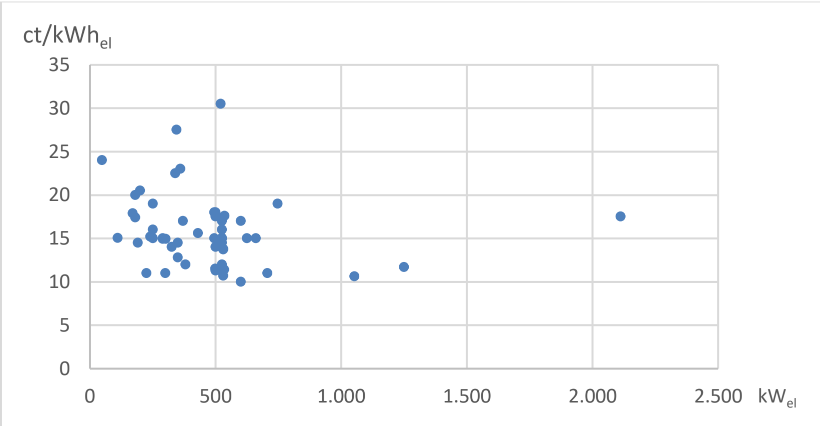

Figure 3.11: Electricity production costs from the biogas measurement program II [125]

In [126] an investment decision tool for agricultural biogas plants in Greece is described and employs other economic evaluation criteria than the specific electricity production costs. Based on mass and energy balances the electric and thermal outputs are determined for a fixed biomass input mix corresponding to 20,000 t/a manure, 10,000 t/a wheat straw and 20,000 t/a glycerol. The corresponding installed electric power amounts 5,324 $\mathrm{kW_{el}}$. Plant operator data and author's own assumptions lead to the estimation of the total capital investment and the total operating costs. Revenues are derived from the electricity, heat and compost sales as well as from the waste valorization fees. An annuity method leads to key economic indicators regarding the economic performance of the plant. An Internal Rate of Return of about 13.4%, a Net Present Value of about 2.3 € million and a Pay-Back Period of 8.76 years are determined.

Regarding methodological aspects one should distinguish between discrete and continuous economic assessments. Discrete assessments refer to single economic evaluations of given plant sizes whereas continuous assessments deal with an economic analysis over the whole plant capacity bandwidth e.g. [0:10,000 kW_{el}]. In [75], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126] a business full-cost accounting method is employed for assessing the profitability of single biogas plants. All operating and investment-related cost positions involved are determined individually and their sum gives an estimation of specific electricity productions costs (in ct/kWh_{el}) or leads to the calculation of Internal Rate of Return and Net Present Value in [126]. In each case a single plant type with a given installed electric power is economically analysed so that only discrete assessments are carried out. Currently no continuous profitability assessments of German biogas plants exist.

Three research works deal with the determination of most profitable biogas plant sizes in other European countries under a continuous assessment. In [127] the most cost-effective size of agricultural biogas plants in Austria is identified. The term “cost-effective” relates to the plant sizes showing the lowest costs of electricity production from biogas in ct/kWh_{el}. The plant type assessed valorizes maize silage in a mono-digestion process. The electricity production costs are determined based on the annual costs and on the amount of electricity produced annually. Annual costs are divided into investment-related, maize silage, personnel, maintenance, transport and insurance costs. Electricity production costs are continuously calculated for plant sizes varying from 25 to 2,000 kW_{el} in increments of 25 kW_{el}. For this, specific correlations linking each cost position to the installed power are obtained from surveys and literature data. The most cost-effective plant size is estimated at about 875 kW_{el} assuming a maize silage availability rate of 10%. For an availability rate of 20% the most cost-effective size would remain at about 1,150 kW_{el}. The effect of several key-parameters like maize silage costs and availability, investment-related costs and feedstock transport costs is quantified with the help of a sensitivity analysis. The calculations also demonstrate the influence of political regulations and subsidy schemes on the plant profitability. For this purpose, revenues from the sales of electricity are integrated into the calculations and remain between 10.3 ct/kWh_{el} for large-scale plants[22] and 16.5 ct/kWh_{el} for small-scale plants[23]. According to the author only small plants with a size of 100 kW_{el} or 250 kW_{el} can cover their electricity production costs through the sales of electricity.

In [128] an analysis of the most profitable size for manure co-digestion plants in the South of Italy is performed with the help of an investment decision tool. Based on mass and energy balances the plant electric power is expressed as a function of the biomass input mass flow. In a second step electricity production costs and revenues[24] as well as the projects Net Present Value and Internal Rate of Return are determined for five plant sizes all along the capacity bandwidth [50:1,000 kW_{el}]. Sensitivity analysis on the electricity production costs and on the Internal Rate of Return are also realized. The main profitability drivers are the plant location, the manure transport costs, the operating costs and finally the effect of co-digestion with other feedstock (energy crops, biowaste). The highest Internal Rate of Return is reached at about 22.9% for a 250 kW_{el} plant size.

The analysis carried out in [127] focuses exclusively on agricultural installations and does not cover the whole Austrian biogas plant park. It also considers electricity sale as the unique source of revenues and therefore does not take into account the heat and digestate sale. The work mentioned in [128] focuses only on the economic analysis of small-scale manure plants in the Italian province of Bari and does not integrate other plant types such as biowaste plants or plants valorizing agricultural residues. The present thesis aims to estimate the most profitable plant sizes with the help of a simulation model. Similarly, to [128] the mass and energy balances realized in the

[22] In the case of biogas plant sizes greater than 1,000 kW_{el}.
[23] In the case of biogas plant sizes up to 100 kW_{el}.
[24] Revenues from the electricity sale are notably derived from the Italian Feed-In-Tariffs for biogas plants.

process simulation lead to the determination of correlations between electric power and the biomass input mass flow. The combination of these correlations with economic input data enables the identification of the most profitable plant sizes. In comparison to other existing studies in Europe, the simulation model developed represents the most exhaustive analysis leading to the identification of the most profitable biogas plant sizes under various subsidy schemes. It not only focuses on a single plant type but also considers the whole biogas plant park portfolio. It further integrates all potential revenue sources and is not limited to revenues from electricity sale. At the scale of Germany this model delivers a unique contribution in comparison to other existing discrete economic evaluations. It provides a continuous economic assessment of the main existing plant types over the whole capacity bandwidth [0:10,000 $\mathrm{kW_{el}}$]. The simulation model developed in this thesis thus gives valuable assistance to biogas plant operators especially during the feasibility analysis of a new project. It helps them to identify which plant sizes and types appear as the most economically attractive under various legal frameworks.

The added value of the developed simulation model, further described in section 4, is to provide a systematized and continuous economic assessment of German biogas plants. The profitability of different biogas type plants is assessed by considering a variable and differentiated biomass input. This leads, for a given plant type, to the identification of the most profitable plant sizes over the full capacity bandwidth [0:10,000 $\mathrm{kW_{el}}$]. The specific operating profit is selected as the profitability criterion. Table 3-4 classifies the previous economic analyses according to their discrete or continuous character.

Table 3.4: Discrete versus continuous economic analysis of biogas plants

	Discrete economic evaluation			**Continuous evaluation**	
	Electricity production costs Calculations	Specific operating profit calculations	NPV, IRR calculations	Electricity production costs calculations	Specific operating profit, NPV or IRR calculations
[75], [117], [118], [120], [121], [122], [123], [124], [125]: German plants					
[119]: German plants					
[126]: Greek plants					
[127]: Austrian plants					
[128]: Italian plants					
This work: German plants					

3.4.2 Biomass potentials assessment

The estimation of biomass potentials for the future valorizable surface areas into electricity from biogas appears as a key-issue. It represents the basis for an estimation of future biogas plant capacity developments. This section aims to describe reference studies assessing current and future biomass potentials for biogas production in Germany. The study “Global analysis and estimation of the biomass area utilization potential” from the university of Hohenheim [129] is first analysed. This publication delivers a systematic analysis of surface area use, agricultural production, population and food demand. The objective is to estimate current and future potentials for bioenergy and food under different sustainability scenarios. A competition in surface use for food, animal feed, nature protection, settlement area and transport is taken into account. The methodology for the potential estimation concerning “non-food applications" is based on the simulation model GAPP ("Global Agrar Production-Potential"), which is applied to 148 countries. In order to estimate further developments, time series for the 20 last years are created and used for regression calculations.

In a further step the study estimates the surface area which is not dedicated to energetic applications. Technical potentials can thereby be determined. The global potential for Germany is calculated under the assumptions that the country first meets its food self-sufficiency rate and that supplementary potentials can be used for bioenergy applications. The global potential is corrected for agricultural export quantities in order to take into account the contribution to worldwide food security. Additional potentials come from agricultural over-production and from potentials for fallow land. In addition to the reference scenario, three scenarios consider alimentary behavior, productivity, expansion of bioenergy surface areas and the degree of surface utilization. In the reference scenario Germany shows a supplementary national area potential of about 2.26 million ha dedicated to "Non-Food-Production". This supplementary potential can be divided into fallow land (0.5 million ha) and about 1.8 million ha of arable land. The potential for energy crops is estimated at about 1.97 million ha which leads to a total potential area of about 4.23 million ha by 2012. For the year 2020 a global potential area of 6.15 million ha is calculated. By 2030 and by 2050, 7.46 million ha and 9.87 million ha are estimated.

The German biomass research center carried out a potential analysis relative to energy crops, forestry and organic waste residue at the Federal State level for the years 2008 and 2020 [130]. In this study technical potentials for several organic biomass fractions dedicated to energetic utilization are calculated. The potentials for energy crops are determined based on statistical data relative to cultivable areas, field crops, hectare yields and nature protection areas. The potentials are allocated according to the different utilization pathways for energy crops. Assumptions are made concerning the individual share of field crops involved in an energetic utilization. The technical biomass potential for energy crops in Germany amounts thus to 169 PJ for the year 2008. The calculations for the year 2020 are based on assumptions from [129]. The energetic potentials for animal effluents are determined for pigs, cattle and poultry. The input data is relative to the specific energy amount per animal category given several assumptions concerning livestock breeding. A technical potential of about 69.3 PJ is estimated for animal effluents by the year 2020. The quantification of the biowaste potentials is realized according to [131]. An average annual biowaste amount of about 100 kg per habitant is first taken into account. It is further assumed that the biowaste amounts are fully valorized into anaerobic digesters. A global potential for biowaste of about 24.1 PJ is calculated for the year 2020. A regional analysis shows that the potentials are mainly located in the Federal States of Bayern, Baden-Württemberg and Lower-Saxony.

In [132] an assessment of technical potentials for biogas is carried out for the year 2013. The biomass feedstocks are divided into four categories: energy crops (e.g., maize silage and wheat), animal effluents (e.g., pig and cattle manure), industrial and agricultural residues (e.g., material for landscape conservation, marsh) and finally municipal residues (e.g., biowaste). The potential calculations were realized at the level of each Federal State and the results are shown in Figure 3-12.

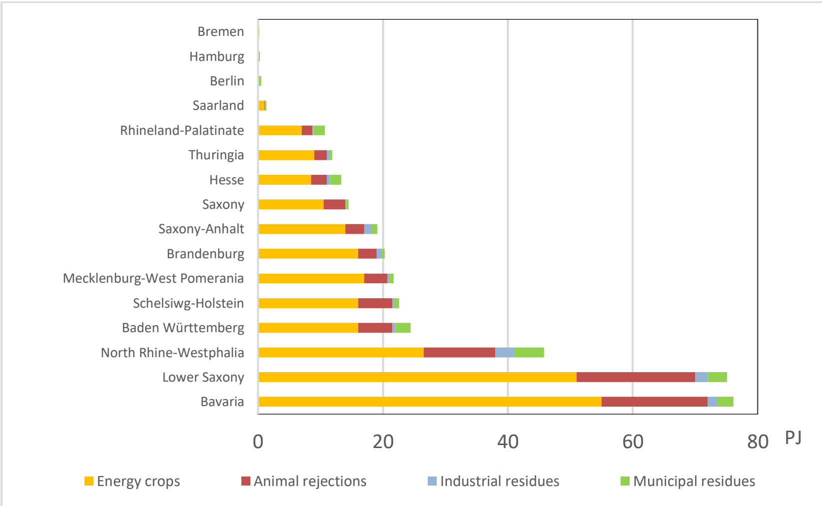

Figure 3.12: Technical biogas potentials for the main biomass feedstock types valorized in German biogas plants at the Federal State level [132]

In light of the results in Figure 3-12, it can be mentioned that the biogas potentials are dominated by energy crops which represent 70% of the total. The 30% remaining are mainly made of animal effluents. Three Federal States, Bavaria, Lower Saxony and North Rhine-Westphalia, represent more than 50% of the technical total biogas potentials. The study mentioned in [132] represents the only existing analysis dedicated to regional potentials for biogas substrates. It has been further used for the determination of biomass potentials input data for the optimization model (section 6.4.1).

3.4.3 Model-based analysis of future electricity production from biogas in Germany

The economic analysis of future electricity production from biogas in Germany can be carried out following different technology aggregation levels (Figure 3-13).

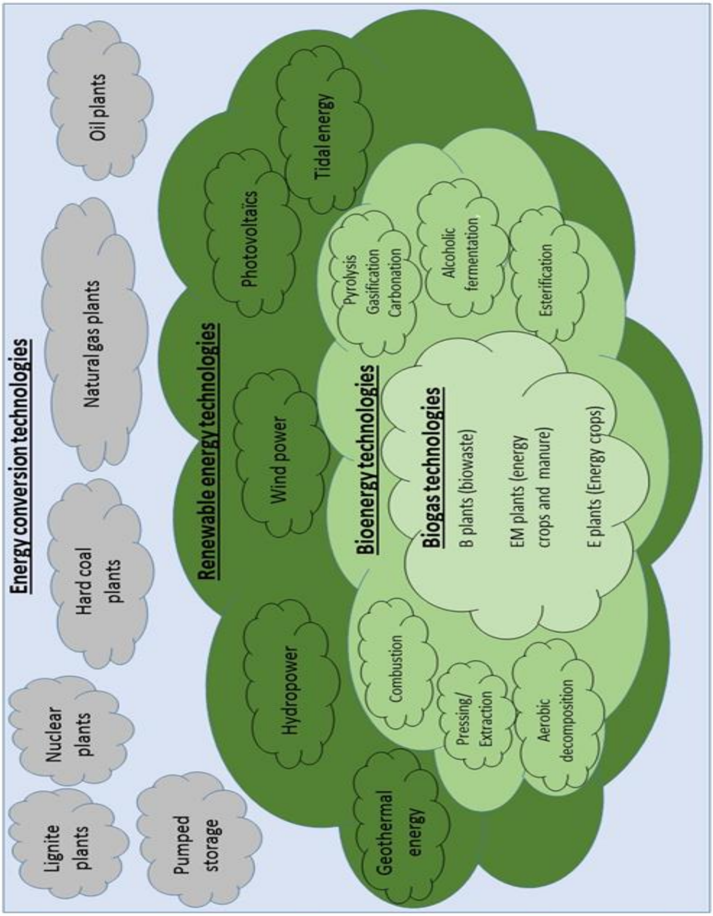

Figure 3.13: Aggregation levels of main available energy conversion technologies (author's own representation)

Future developments for biogas plants can be assessed by considering interactions with all available technologies of the German electricity system including conventional and renewable energy conversion plants. In [133] a model-based analysis of the future role of renewable energy sources in European electricity supply is realized. The development of both renewable and conventional electricity production technologies is analysed up to the year 2030. The assessment is realized under several scenarios and is based on a linear regional optimization model. The model objective function minimizes all system expenditures necessary to fulfil exogenously given electricity demand profiles. The approach considered is then systemic and involves the whole European electricity system. Technical, economic and environmental constraints are also taken into account and refers e.g., to capacity restrictions, plant availability limitations, load variation and CO_2 trading equations. The model results deliver insights regarding future renewable electricity production and installed capacity in each European country and for each energy carrier. In the case of biogas in Germany the results are aggregated so that no distinction is made between plants valorizing energy crops, biowaste and/or manure. The results are moreover not visible at the level of the German Federal States.

The research work in [134] aims to determine how a flexible biogas plants park should behave from the perspective of the whole German electricity system in 2030. This work provides answers regarding the potential changes to be operated in the baseload electricity production in order to lower the overall system costs. Interactions with conventional energy sources are considered and a flexible biogas plants park leads by 2030 to a reduction of the electric power from fossil plants dedicated to residual load coverage. This model focuses on the interactions of the future electricity production from biogas with other renewable and conventional electricity sources by considering a demand-oriented and systemic approach. It does not however highlight regional developments for differentiated biogas plant types, technologies and sizes. It considers further the flexibilization option more from a system perspective than from the plant operator point of view.

Another aggregation level concerns analysis carried out within the bioenergy system. In the framework of this assessment future developments for biogas plants are impacted by interactions with other bioenergy technologies.

In [122] a systemic analysis of all available bioenergy conversion routes is carried out. All bioenergy conversion options are put into competition under the perspective of an energy supply cost minimization. The linear optimization model TIMES (The Integrated Markal-Efom System) is employed. The model analysis aims to determine technology options leading to a sustainable development of bioenergy up to the year 2030 under economic, technical and environmental criteria.

In its “Milestone 2030” report, the German biomass research center delivers a comprehensive model-based analysis of the future bioenergy mix up to the year 2030 [135]. The employed Bioenergy Simulation Model (BENSIM) aims to model future competition between the main available bioenergy technologies. The assessment takes into account in particular the satisfaction of a certain demand level in the heat, electricity and transport sectors [135]. The model input data refers to investment-related and operating costs, to revenues for heat, electricity and to co-products including GHG-emissions and digestate. The starting point of the BENSIM model is the determination of existing bioenergy plant capacity. In a second step current and future available biomass potentials are estimated. The costs of production for the end products - heat, electricity and biofuels - are then determined. In the case of biogas, the production costs are linked to the bioelectricity produced through Combined Heat and Power systems (CHPs). The potentially new built biogas plants are then sorted by the solver according to their electricity costs of production level. Plants showing the lowest electricity production costs are built until enough biomass potentials remain. The BENSIM model offers then the possibility to carry out a complete simulation of the future German bioenergy system by considering interactions between the different available technologies. However, in the case of the BENSIM model, the evolution of the German biogas plant capacity is currently not regionalized and no differentiation between agricultural, biowaste and manure-based installations is done. The model results related to biogas show that an electricity production of about 11.8 TWh_{el} would be reached by 2030[25]. In particular the legal restrictions of the Renewable Energy Sources Act and a decommissioning plan starting from 2020 for plants older than 20 years strongly impact future developments [135].

A last possible aggregation level relates to assessments done within the biogas system. In this case future developments are analysed by considering interactions between several biogas plant types and sizes but without integrating other energy conversion technologies. The perspective is the one of a biogas plant operator having the objective of maximizing installations profit over their whole life time. The model approach is resource oriented and driven by the development of future biomass potentials as well as by the evolution of future costs and revenues for biogas plant operators. Currently no models related to the analysis of future electricity production from biogas based on this approach exist.

The German biomass research center published in 2016 a background paper dealing with the evolution of biogas plants up to the year 2030 in each German Federal State [136]. The capacity forecasts have been carried out by solely considering the effects on a plant decommissioning phase starting from 2020. From this time point biogas plants older than 20 years will not receive subsidies from the Renewable Energy Sources Act anymore which leads to massive unprofitability and then to capacity decommissioning. Thereby about 1.8 GW_{el} installed electric power could remain by 2030. This paper highlights the need for further subsidies for existing biogas plants. However, it does not integrate the development of supplementary capacity and does not consider the future flexibilization of existing and new built installations.

In [137] a forecast for the development of the future electricity production from biogas under continuation of the EEG 2014 framework is carried out. In this assessment a biogas plant decommissioning is also taken into account starting from 2020. A capacity increase of 100 MW_{el} per year is systematically

[25] Assuming a CHP-electric efficiency of 38%

assumed according to the expansion cap defined in the EEG 2014. By the end of 2030 a total cumulated installed capacity of 1,700 $\mathrm{MW_{el}}$ is foreseen [137]. The forecasts published in [136] and [137] solely integrate already planned events, namely capacity expansion caps under the EEG 2014 framework and plants decommissioning starting from 2020. They cannot thus be seen as complex model-based assessments.

Table 3-5 proposes a classification of the different approaches employed up to now for the analysis of future electricity production from biogas in Germany. By considering future regional developments from the plant operator perspective this thesis delivers a unique contribution. It provides new insights regarding future developments in each Federal state for different biogas plant types, sizes and under various framework conditions. It complements all past analysis which were relying on a (bio)-energy systemic approach.

Table 3.5: Modelling approaches for the analysis of future electricity production from biogas in Germany

	Evaluation at the German national level			**Evaluation at the regional Federal states level**	**Total costs minimization**	**Total profit maximization**
	From the energy system perspective	From the bioenergy system perspective	From the plant operators perspective	From the plant operators perspective		
[133]						
[134]						
[122]						
[135]						
[136]						
[137]						
This work						

3.5 Summary

In this chapter the current situation and legal framework conditions for biogas in Germany have been described highlighting the central role of the EEG subsidy schemes for the electricity produced. In the framework of a literature review existing studies regarding the analysis of current and future electricity production from biogas have been assessed. Especially the content and methodology applied in these studies have been described in detail and the scientific contribution of the present work has been emphasized. The two models proposed in this thesis intend thus to bridge a knowledge gap between existing studies. The simulation model aims to provide a continuous economic evaluation of biogas plant sizes in Germany under variable and differentiated biomass input. This continuous profitability analysis currently does not exist and complements all existing discrete evaluations already carried out for German biogas plants. The optimization model characterizes the evolution of German biogas plant capacity at the Federal State level and from a plant operator's perspective up to the year 2030. It further takes into account different plant types and subsidy frameworks. This modelling perspective aims to deliver new insights for future electricity production from biogas in comparison to past assessments which are based on a systemic approach.

4 A simulation model for the analysis of current electricity production from biogas in Germany

Increasing energy crop costs and frequently changing subsidy schemes strongly impact the development of German biogas plants. These evolving framework conditions are the source of complexity and the economic analysis of biogas installations thus appears to be a difficult task for plant operators. In this context simulation models are a suitable tool for optimal plant design and operation. In particular one of the key-problem that can arise when planning a biogas plant concerns the determination of the most profitable plant size to be built. Biogas plant operators aim to build, operate and maintain plant sizes giving a maximal operating profit. Biogas plant sizes are defined by the installed electric capacity in $\mathrm{kW_{el}}$ and intuitively increase with the valorized biomass input mass flow. The plant revenues in $\mathrm{ct/kWh_{el}}$ are generally lower for large-scale installations than for small ones mainly due to size effects. The electricity production costs (in $\mathrm{ct/kWh_{el}}$) also remain generally lower for large-scale plants than for small-scale installations. Consequently, the determination of the most profitable plant sizes is complex and requires the use of decision support tools. This chapter has thus the objective to describe the simulation model developed for the economic analysis of currently existing biogas plants.

In section 4.1 a general introduction to simulation models is presented highlighting their scope, the system boundaries and level of detail. Currently existing simulation software and programs applied to process engineering are briefly described and categorized according to the type of problem that they intend to solve. The objectives and general methodology related to the simulation model developed are then presented in section 4.2. In section 4.3 the simulation model built with the help of the software SuperPro Designer and the different methodological steps are described. A first step consists of calibrating the biogas plant and is then followed by a process simulation under a variable and differentiated biomass input mass flow. This simulation step delivers correlations between the installed electric power and the valorized biomass mass flow. These correlations provide the basis for a further economic analysis presented in chapter 7.

4.1 General introduction to simulation models

Models should assist the decision process of various stakeholders using knowledge-based and systematic methods [138]. The general objective of the models has to be defined in an initial step. Especially the level of detail, the scope and system boundaries are of crucial importance. Possible assessments can be covered by highly aggregated models on the global economy up to models of single plants or processes. The models linked to the global economy are set up to answer completely different research questions than the more technical models on the process level. The simulation models correspond to the highlighted model classes in Figure 4-1. Input data from higher aggregation levels, such as feedstock costs characterizing bioenergy carriers, are taken into account. Similarly, data from more disaggregated levels such as process parameters are also considered.

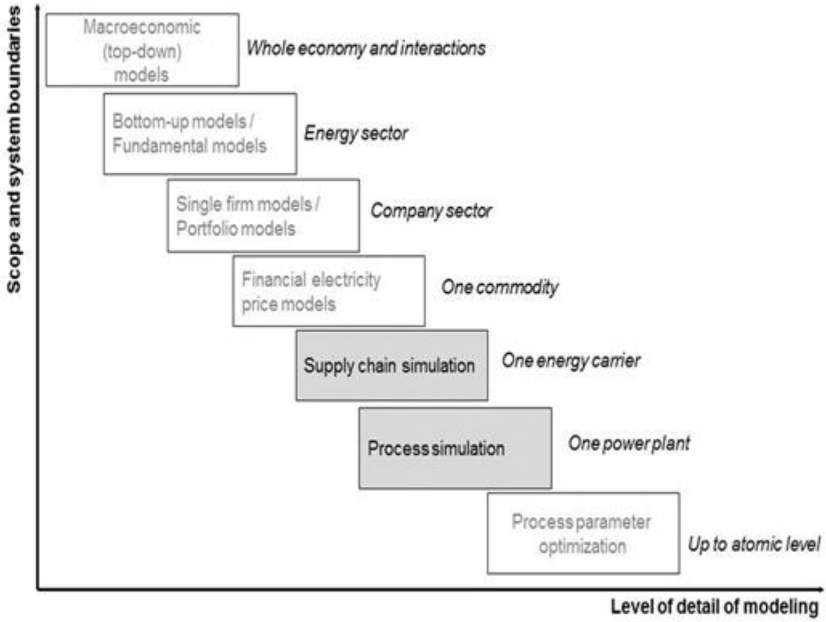

Figure 4.1: Scope, system boundaries and level of detail [138]

Due to the scope and diversity of questions it is clear that one single method or one model cannot answer all research questions. There is no “single” model of a biomass supply chain, and thus there is no “best” methodological approach. Modelling tools are generally developed for quite specific types of systems (e.g., static/dynamic). These modelling platforms consider the requirements of specific users, e.g., from a mechanical engineering, chemical engineering or economic point of view. A brief description of current simulation software and programs is shown in Table 4-1.

Table 4.1: Current simulation languages and software (author's own representation)

Type of model	Description	Examples
Problem-oriented-language	Suited to solve simulation problems but with a high complexity	PASCAL, C++, JAVA
Simulation language	Similar to high level languages	SIMULA
Specific simulation systems language	Databases are available for specific models with specific field applications. The problem is described through an interactive graphic interface or through a script language.	ASPEN PLUS, ASPEN DYNAMICS, ASPEN CUSTOM MODELLER (ACM), IPSEPro, PROSIM, SuperPro Designer, …
Parameterized simulation system	The simulation tool is only suited for a restricted type of structures. Some model parameters can be modified and parameterized.	All the above-mentioned tools coupled with additional applications

4.2 Objectives and general methodology

This section aims to describe the main objectives and methodology relative to the analysis of current electricity production from biogas in Germany. For this purpose, a simulation model, developed with the help of the software Super Pro Designer, is described and applies to three reference biogas plant types. These plant types correspond to the valorization of energy crops and manure in co-digestion process (EM plants[26]), of energy crops (E plants) and biowaste (B plants) in mono-digestion. The main objective of this simulation model is to identify most profitable plant sizes under a variable and

[26] EM plant sizes between 0 and 75 kW_{el} correspond to installations valorizing exclusively manure in mono-digestion processes. For larger sizes the co-digestion of manure with various energy crops is assessed (see section 6.2.1).

differentiated biomass feedstock input mass flow. The preliminary task is to model all the involved conversion processes (biomass pre-treatment, biogas production, digestate treatment as well as heat and electricity production) under a fixed biomass input mass flow. The anaerobic digester is modelled and calibrated by specifying a digester volume, a residence time as well as by defining the biochemical reactions occurring in the reactor. Stoichiometry and methane formation rates are further determined and described in section 4.3.2.4.

Once the whole biogas plant is calibrated a simulation of the plant's energetic behaviour is carried out assuming a variable biomass input mass flow m_i. For each variation step i the corresponding biogas output volumetric flow Y_i and further the electric power $P_{el,i}$ are determined. These technical correlations represent the basis for a further economic evaluation integrating costs and revenues input data and leading to the determination of specific operating profits in each simulation step. The results are further represented in the form of characteristic "specific operating profit versus installed electric power" diagrams (see section 7.2) which leads to the identification of the most profitable plant sizes. The economic analysis is carried out in chapter 7 by considering for each plant type two different electricity subsidy schemes namely EEG 2012 and EEG 2014. A costs versus revenues assessment for the most profitable plant sizes combined with a sensitivity analysis aims to identify the main profitability drivers for each plant type. The most profitable plant sizes are technically assessed by determining global plant energetic efficiencies. Based on the model results strategic recommendations for policy makers and plant operators are finally formulated.

Figure 4-2 sets out the main methodological steps employed in the framework of the simulation model.

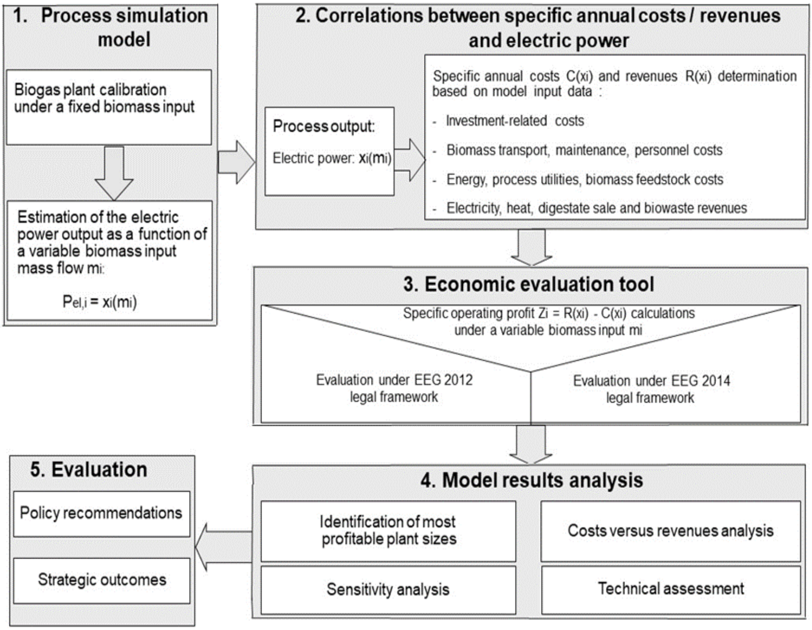

Figure 4.2: Main methodological steps employed for the analysis of current electricity production from biogas in Germany (own representation)

4.3 Process simulation with the help of SuperPro Designer

4.3.1 Description of the simulation software SuperPro Designer

The software chosen for the process simulation is SuperPro Designer, which is a modular type computer program and allows steady state calculations. This software offers the possibility to design biogas plants in particular by modelling anaerobic digesters. An integrated solver controls all parts of the simulation such as input and output data, flow chart analysis and model iterations. Databases store the main physical and chemical properties of approximately 370 chemical species. To achieve a flowsheet simulation with SuperPro Designer several steps are required. It is firstly necessary to specify the type of operation involved in the process (batch or continuous). Then the process flow chart can be modelled by choosing the equipment parts involved (process icons). In order to initialize the process, the operating conditions and design parameters[27] have to be specified for each equipment and for each input flow (plant calibration). In the following the modelling assumptions concerning each process step of the biogas installations are described.

4.3.2 Biogas plant calibration

4.3.2.1 Biomass feedstock characterization

In the present simulation model, the biomass elementary composition is defined according to [139]. The substrate to be valorized is thus defined as "biomass" and represented by a generic chemical formula $CH_{1.8}O_{0.5}N_{0.2}$.

4.3.2.2 Biomass transport, delivery and storage

The energy crops management step starts with the transport from the cultivation area to the biogas plant location. The transport of energy crops and/or manure is carried out with the help of agricultural trucks. The transported energy crops are then stored in bunker silos where the ensilage process takes place. During this process, the energy crops are subject to a mass loss specified at about 12% according to [140]. Manure is mixed with energy crops in order to obtain a mash. In the case of biowaste, the transport takes place from the biowaste collection point to the biogas plant location and is carried out with the help of trucks. The biowaste is further loaded in a storage tank before the pre-treatment step.

[27] Design parameters concern e.g., the equipment size, temperature, pressure, input mass flow, volume, power or recycling loops.

4.3.2.3 Biomass pre-treatment and loading

In the case of energy crops and/or manure valorization, the mixed biomass feedstock (mash) is pre-heated before entering into the digester. The process temperature has a decisive influence on the degradation efficiency and on the biogas quality. In the case of agricultural plants, the mixed solid is heated at a temperature of 38°C specified in SuperPro Designer interface and corresponding to a mesophilic process temperature. A screw conveyer is used to bring the solid biomass to the blending storage tank. The blending tank is modelled as a vessel with an agitator to simulate the biomass storage for a certain period here assumed as 10 h. Some heat transfer operation units (heat exchangers) are then necessary to warm up the substrate to the mesophilic digestion temperature. The biowaste pre-treatment starts with the shredding step and is followed by the separation of metal and impurities. These pre-treatment steps generate a global biowaste mass loss specified at 8% of the transported biowaste mass [141].

After this operation the biowaste mass flow is mixed with water during a hydrolysis reaction. The hydrolysed biowaste mash is further pre-heated to a specified temperature of at least 70°C. This aims in particular to satisfy the epidemiologic and phytohygienic criteria related to biowaste installations (see Table 2-2). The pre-heated biowaste feedstock is finally loaded into the fermenter where the anaerobic digestion process can start.

4.3.2.4 Biogas production process modelling

The objective of this section is to describe the model that has been developed with the help of SuperPro Designer in relation to the biogas production process. Biogas is produced by the fermentation of biomass feedstock under the action of bacteria. The biomass residence time in the fermenters is given by Eq. 4.1.

$$\tau = \frac{V_W}{\dot{V}_o} \tag{4.1}$$

With:

V_W: fermenter working volume in m^3

$\dot{V}_o$: input material volumetric flow entering the digester (in m^3/h)

The anaerobic digester is modelled as a well-mixed reactor [142]. Several models in the literature exist and aim to mathematically describe anaerobic digestion processes. A general and extensive review of these models can be found in [143]. In the case of this work a simplified model, the Buswell model, characterizing the biogas formation from anaerobic digestion pro-cesses has been used (Eqs. 4.2, 4.3 and 4.4) [144].

$$C_cH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + nNH_3 + sH_2S + (c-x)CO_2 \quad (4.2)$$

with $\quad x = 1/8 \times (4c + h - 2o - 3n - 2s) \quad (4.3)$

and $\quad y = 1/4 \times (4c - h - 2o + 3n + 3s) \quad (4.4)$

In the present work, the substrate is $\mathrm{CH_{1.8}O_{0.5}N_{0.2}}$ and is further transformed into methane, carbon dioxide and ammonia through Eq. 4.5 which represents the simplified biogas formation equation.

$$CH_{1.8}O_{0.5}N_{0.2} + 0.45H_2O \rightarrow 0.53CH_4 + 0.47CO_2 + 0.2NH_3 \quad (4.5)$$

It is further assumed that the biomass fermentation reaction follows a first order kinetic reaction. According to this kinetic reaction the volumetric methane flow rate $\mathrm{Y_{CH_4}}$ (in $\mathrm{m^3/h}$) can be expressed through Eq. 4.6.

$$Y_{CH_4} = \frac{v_{Biomass}}{v_{CH_4}} \cdot k \cdot \frac{\rho_{Biomass}}{\rho CH_4} \cdot V_W \quad (4.6)$$

With:

k: methane formation rate to be determined (in h^{-1})

$\rho_{Biomass}$: biomass density in input of fermenter (in kg/m^3)

ρ_{CH_4}: methane density (in kg/m^3)

V_W: working volume (in m^3)

v_{CH_4}: stoichiometric coefficient for CH_4in Eq. 4.5

$v_{Biomass}$: stoichiometric coefficient for the biomass in Eq. 4.5

Furthermore $\mathrm{Y_{CH_4}}$ can be expressed as a function of the biomass feedstock specific methane yields mentioned in the German Biomass Ordinance (Eq. 4.7) [145]:

$$Y_{CH_4} = ß \cdot \dot{m}_{Biomass} \tag{4.7}$$

With:

$\dot{m}_{Biomass}$: feedstock input mass flow (in kg/h)

β: feedstock specific methane yield mentioned in the German Biomass Ordinance (in ${m^3}_{Methane}$ / $kg_{Substrate}$)

By combining Eq. 4.6 and Eq. 4.7, the methane formation rate k can be expressed as a function of the biomass input mass flow (Eq. 4.8).

$$k = \frac{v_{CH_4} \times \rho_{CH_4} \times ß}{V_W \times v_{Biomass} \times \rho_{Biomass}} \cdot \dot{m}_{Biomass} \tag{4.8}$$

Eq. 4.8 can be further simplified by introducing the residence time defined in Eq. 4.1 (Eq. 4.9):

$$k = \frac{v_{CH_4} \cdot \rho_{CH_4} \cdot ß}{\tau \cdot v_{Biomass}} \tag{4.9}$$

The methane formation rate can be finally determined for each plant type by using following numerical values (Table 4-2)

Table 4.2: Numerical values of the employed parameters for the determination of the methane formation rates k

Constant	Definition	Numeric values
$\nu_{Biomass}$	Stoichiometric coefficient for the biomass in Eq. 4.5 (-)	1.0
ν_{CH4}	Stoichiometric coefficient for CH_4 in Eq. 4.5 (-)	0.53
ρ_{CH4}	Methane density (kg.m^{-3})	0.72 [146]
β	Biomass feedstock input specific methane yield (m^3/kg)[28]	EM plant: 0.0916 E plant: 0.1085 B plant: 0.0738
τ	Residence time in anaerobic digester (h)	Agricultural plants: 1,920 (i.e. 80 days) [147] Biowaste plants: 600 (i.e. 25 days) [148]

In each plant type, the numerical values of the methane formation rates are mentioned in Table A-2 of the Appendix and are specified in SuperPro Designer interface. This aims to calibrate the fermenters according to the specific methane yields mentioned in Table 6-1.

The annual biogas production Yi can finally be estimated, assuming a fixed methane content μ in the biogas produced (Eq. 4.10). For each feedstock, the μ value is specified according to the methane contents mentioned in Table 6-1.

$$Y_i = \frac{Y_{CH_4}}{\mu} \tag{4.10}$$

[28] The values for each plant type have been determined based on the specific methane yields mentioned in Table 6-1.

4.3.2.5 Modelling of the heat and electricity production from biogas

After the anaerobic digestion process, the biogas mass flow amount Y_i is burned in a Combined Heat and Power system (CHPs). The CHPs is represented here by a single stage gas turbine because SuperPro Designer offers no straightforward possibility to model a gas engine. The gas turbine system is made of a centrifugal gas compressor coupled to a gas expansion unit and in between a combustion chamber. Biogas is mixed and burnt in the combustion chamber simultaneously with air. The air volume flow stream enters the combustion chamber at a temperature of 90 °C and under a pressure of 50 bar. The temperature inside the combustion chamber is 1,200 °C [149]. The methane combustion reaction with oxygen is defined by Eq. 4.11:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4.11}$$

The reaction enthalpy for methane equals to -55,643 kJ/kg and corresponds to an exothermal reaction. Finally, the model of the gas turbine has been adapted to that of a CHP gas engine by considering the electric and thermal efficiencies mentioned in [150].

4.3.2.6 Modelling of the digestate treatment unit

In the case of agricultural plants, the digestate issued from the fermentation is assumed to be directly used on soil as fertilizer so that no treatment process is required. The digestate produced by the biowaste fermentation is treated by a decanter centrifuge in order to obtain a solid digestate mass representing 50% of the raw digestate according to [141]. The solid digestate is further valorized in a post-rotting process in order to obtain a solid compost mass flow which represents 30% of the biowaste input mass flow [141].

4.3.3 Process simulation

After the biogas plant calibration the next step consists of determining the evolution of the electric power $P_{el,i}$ (output variable) as a function of the biomass feedstock mass flow $\dot{m}_{o,i}$ (input variable). Figure 4-3 represents the different mass and energy flows that characterize each simulation step i. Detailed flowsheet examples issued from SuperPro Designer interface and related to the modelling each of the plant type are further mentioned in Figures A-1, A-2, A-3 and A-4 of the Appendix.

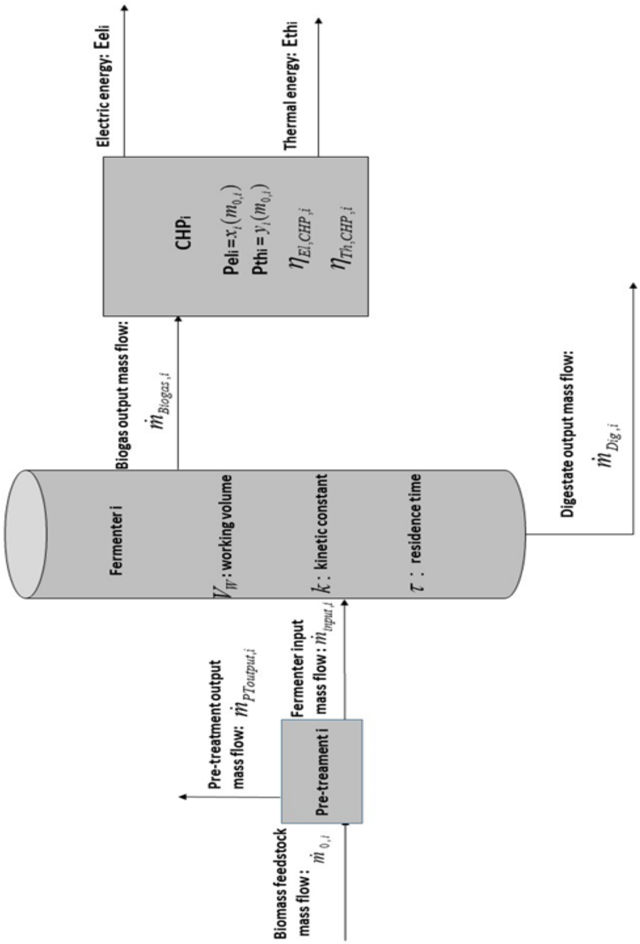

Figure 4.3: Schematic representation of the mass and energy flows in each simulation step i

In each simulation step i, the installed electric power $\mathrm{P}_{\mathrm{el,i}}$ can be expressed as a function of the biomass feedstock mass flow $\dot{\mathrm{m}}_{0,\mathrm{i}}$ according to Eq. 4.12:

$$P_{el,i} = \frac{ß \cdot H_{g,CH_4} \cdot \eta_{El,CHP,i}}{OH} \cdot \dot{m}_{0,i} \tag{4.12}$$

With:

- β: feedstock specific methane yield mentioned in the German Biomass Ordinance (m^3/t)

- H_{g,CH_4}: Methane gross calorific value set at 9.97 kWh/m^3 according to [151]

- $\eta_{El,CHP,i}$: CHP electric efficiency set as a function of the installed electric power $P_{el,i}$ according to a correlation derived from [150]

- $\dot{m}_{0,i}$: biomass feedstock mass flow (t/a)

- OH: plant operating hours (h)

By combining Eq. 4.9 and 4.12 a more detailed correlation between P_{el} and $\dot{m}_{0,i}$ is obtained and involves all specified parameters under Super Pro Designer interface (Eq. 4.13):

$$P_{el,i} = \frac{k \cdot \tau \cdot v_{Biomass} \cdot H_{g,CH_4} \cdot \eta_{El,CHP,i}}{v_{CH_4} \cdot \rho_{CH_4} \cdot OH} \cdot \dot{m}_{0,i} \quad (4.13)$$

The linear relation obtained between $P_{el,i}$ and $\dot{m}_{0,i}$ according to Eq. 4.13 is represented in Figure 4-4 in the case of the co-digestion of energy crops with manure (EM plant[29]).

[29] The two further correlations characterizing E and B type plants can be found in Figures A.5 and A.6 of the Appendix.

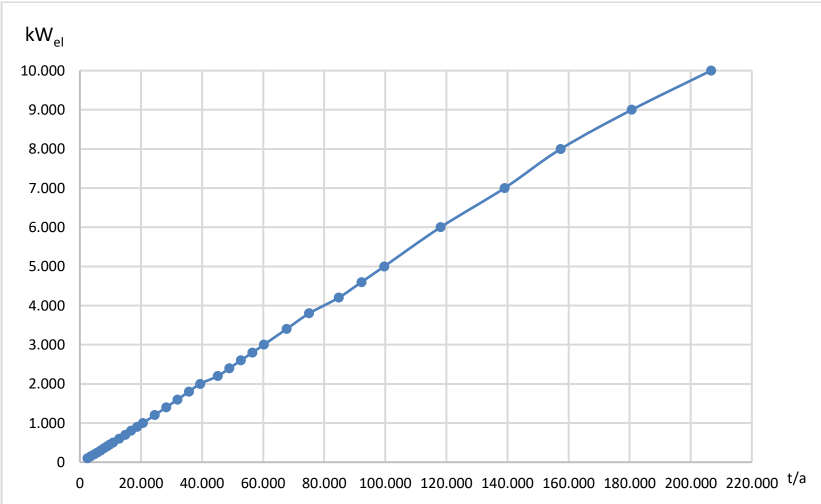

Figure 4.4: Correlation between the CHP-electric power and the biomass input mass flow

4.4 Summary

Due to the frequently evolving legal framework conditions as well as to volatile energy crops and electricity prices, the economic assessment of biogas plants represents a difficult task for biogas companies and plant operators. In particular challenges remain in the identification of the most economically attractive plant sizes. Simulation models offer a suitable tool for estimating the profitability for various plant sizes and types. For a given plant type, the objective is to identify the most profitable plant sizes by assuming a variable and differentiated annual biomass input mass flow. In this chapter a model aiming at the operative simulation of the three main biogas plant types valorizing energy crops, biowaste and manure is presented. For this the process simulation software SuperPro Designer is employed. The simulation variable corresponds to the annual biomass input mass flow. All main steps of the biogas supply chain going from the biomass feedstock transport up to heat, electricity and digestate production are modelled. The anaerobic digesters are calibrated according to specific biogas yields defined by the German Biomass Ordinance. As a result of the simulation, correlations between the installed electric power (output variable) and the annual biomass input mass flow are thereby derived for each of the three plant types. These correlations represent the basis for a further economic analysis realized in chapter 7.

5 An optimization model of future German electricity production from biogas

An unstable economic context characterizes the German biogas industry with in particular volatile energy crops and electricity prices as well as frequently evolving framework conditions. For this reason, the analysis of future electricity production from biogas as well as the forecasting of mid-term capacity developments are of considerable assistance to biogas plant operators. Due to their recurrent use in the framework of the energy system analysis, optimization models represent a well-adapted solution for assessing the evolution of the future German biogas system. The objective of these models is to provide plant operators and decision-makers with valuable insights regarding future developments for biogas in Germany. Optimization models should further contribute to identifying and quantifying the main economic drivers. In this chapter an optimization model developed in the programming language GAMS (General Algebraic Modeling System) is presented and has the objective to analyse the evolution of future capacity and electricity production from biogas in Germany. A general introduction to optimization models applied in particular to energy system analysis is first carried out in section 5.1. In section 5.2 the general methodology employed for the analysis of future electricity production from biogas in Germany is detailed. This analysis is based on a regional linear mixed-integer optimization model which is described in section 5.3. This model aims at maximizing the total profit over all plant sizes, the whole time period and all Federal States combined. It further provides a forecast of regional capacity and electricity production at the Federal State level analysed in chapter 8.

5.1 A general introduction to optimization models

Decision- and policymakers have to cope more and more with complex issues regarding the design of current and future energy policy at different levels (municipality, regional, national or international). Optimization models can assist them in shaping future energy systems in an optimal way that corresponds to the best alternatives given technical, economic and environmental constraints. Optimization models are used in almost all areas of decision-making, notably engineering design, and financial portfolio selection. In the formulation of the optimization problem, an objective function should be specified as a mathematical function involving certain variables and potentially involving several constraints. In the context of an energy system analysis four main categories of optimization models can be distinguished according to [152]: linear, non-linear, mixed integer linear or stochastic.

Linear optimization models correspond to the case where the objective function and all the constraints are linear functions of independent variables. If one of these functions is non-linear, then the optimization is considered as non-linear. If at least one of the independent variables of the linear optimization problem is linked to integer values, then the optimization problem is considered as a mixed integer linear problem (MILP). Stochastic programming represents a valuable approach for modelling optimization problems that involve uncertainties. More precisely stochastic optimization models try to find robust solutions able to cope with a group of uncertain parameter values [153]. Most of the energy system models are linked to linear optimization models involving an objective function for cost minimization or profit maximization [154]. The main objective of energy system models is to establish an optimal energy supply structure given certain framework conditions. The energy system analysis should provide support to decision-makers in the field of energy policy and research. The scale of the system being considered can be global, national, regional or even a single household [155]. It can concern the development of a single technology (e.g., a biogas plant) or a portfolio of all available technologies (e.g., all existing renewable energy conversion technologies) in the context of technical, environmental and/or economic framework conditions. In the next section the objective and general methodology for the analysis of future German biogas plants development based on an optimization model is described.

5.2 General objective and methodology

The main objective of German biogas plant operators is to run and maintain reliable and profitable installations over their whole lifetime, which generally corresponds to 20 years (EEG subsidy time period). For this a robust forecast of future costs and revenue development is required so that the operators can maximize their plant operating profit. The general model objective is thereby to identify which biogas plant types and sizes appear to be the most economically attractive for plant operators on a mid-term horizon (i.e., up to 2030).

In addition, the regionalized model results should show in which Federal States future capacity developments occur considering different EEG subsidy schemes. For this a resource-oriented approach is required that takes into account the current and future technical biomass total potentials. A regional model is thereby developed up to the year 2030 at the German Federal State level. Three reference plant types representing the large majority of installed German plants are analysed. The anaerobic digestion of either energy crops or biowaste, or the co-digestion of energy crops and manure characterize these plant types. Both of the subsidy schemes related to EEG 2012 and EEG 2014 are taken into account in the calculations in the framework of explorative scenarios. These scenarios assess the future development of German biogas plants assuming that the legal frameworks EEG 2012 or EEG 2014 remain unchanged over the whole time period i.e., up to 2030. Finally, the model results are analysed and evaluated in terms of policy recommendations and strategic outcomes. Figure 5-1 summarizes the general methodology employed for the analysis of future electricity production from biogas in Germany.

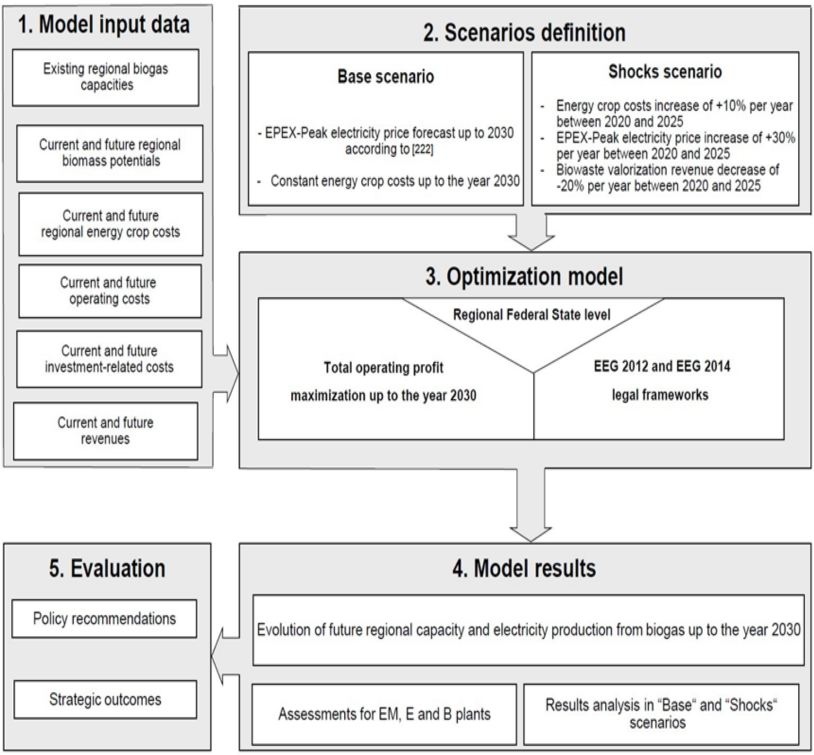

Figure 5.1: Main methodological steps employed for the analysis of future electricity production from biogas in Germany (author's own representation)

In the model input data determination phase the currently existing biogas plant[30] capacity is first estimated for each Federal State and installation type.

[30] In § 3 Nr. 1 of the EEG 2009, the definition of a biogas plant is given and refers to the totality of all functional and technical components dedicated to the electricity production from biogas (e.g., CHP, fermenter, gas storage, digestate storage tank, biomass feedstock pre-treatment unit) [101]. This broad definition is further taken into account in this work and it is also assumed that several

For this purpose, a biogas plant database is built. In addition, literature data concerning existing biomass potentials at the Federal State level is used. In a second step investment-related costs, operating costs including in particular regional energy crop costs and revenues are calculated based on literature and plant operator's data. This techno-economic data, described in chapter 6, feeds the model core structure developed in the programming language GAMS, which contains an objective function and model constraints. The objective function aims to maximize the total operating profit by plant type, for all Federal States aggregated, over the whole time period and all plant sizes. A first constraint corresponds to the limitation of future capacity expansion by regional biomass potentials dedicated to electricity production from biogas. A second constraint concerns the limitation of the electric capacity that could be built for each plant type, in a given year for all Federal States combined (capacity expansion cap defined by the EEG legal frameworks). The model results thereby provide an economically optimal development plan of new built biogas capacity up to the year 2030, seen from the plant operator point of view. In addition to this analysis the sensitivity of future capacity developments to a strong variation of three main market drivers for biogas plants in Germany is assessed. The main profitability drivers firstly correspond to energy crop costs, and to revenues derived from the EPEX-Peak electricity sale received by plant operators in the framework of the electricity direct marketing. The third driver concerns the biowaste fee revenues which are linked to the valorization of biowaste into biogas and further into renewable energy.

CHP units connected to the same biogas production plant (anaerobic digester) have to be seen as a single plant.

5.3 Objective and structure of the optimization model

In order to realize a forecast of new built biogas plants for electricity production up to the year 2030 at the German Federal State level a mixed-integer linear optimization model is developed. The objective is to determine in each Federal State and for three separated biogas plant types (EM, E and B) a development plan of new built electric capacities (in $\mathrm{MW_{el}}$). An objective function is firstly defined in Eq. 5.1 and represents the core of the optimization model. This objective function corresponds to the maximization of the total operating profit (in €) over the whole period, for all plant sizes and all Federal States combined. This aims to ensure an eco-nomically optimal development for German biogas plants up to the year 2030. The objective function contains the annual specific revenues and electricity production costs (in $\mathrm{ct/kWh_{el}}$) that are determined year on year up to 2030 for each plant size and in each Federal State (see sections 6.6 and 6.7). Plant annual operating hours OH are set as a constant and corresponding to 8,000 h/a in base-load operation (see Section 6.2.2.). A variable $\mathrm{X_{i,t,r}}$ is defined and corresponds to existing capacities ($\mathrm{kW_{el}}$) for a given plant size i, in year t and in the Federal State r. A discount rate α_t of 6% per year is applied to all specific cost and revenue flows up to 2030, for each plant size and in each Federal State.

$$Max(Z) = Max[\sum_{r=1}^{16} \sum_{t=1}^{16} \sum_{i=1}^{49} \alpha_t \cdot OH \cdot X_{i,t,r} \cdot (rev_{i,t,r} - epc_{i,t,r})] \tag{5.1}$$

In addition to the objective function Eq. 5.2 models the recursive capacity evolution from year t-1 to year t and integrates a capacity expansion variable $\mathrm{X_{i,t,r}^{Exp}}$ as well as a decommissioning parameter $\mathrm{X_{i,t,r}^{Decom}}$ for plants older than 20 years. This equation allows the solver to build new capacities year on year in selected Federal States.

$$X_{i,t,r} = X_{i,t-1,r} + X_{i,t,r}^{Exp} + X_{i,t,r}^{Decom} \qquad \forall\ i,t,r \tag{5.2}$$

Additional constraint equations concern the annual limitation for each plant type and in each Federal State of future capacity expansion by biomass potentials dedicated to electricity production from biogas $A_{t,r}$ (Eq. 5.3). This ensures that no capacity can be further built if the corresponding biomass potentials are not sufficient.

$$\sum_{i=1}^{49} OH \cdot X_{i,t,r} \leq A_{t,r} \qquad \forall\ t,r \qquad (5.3)$$

A second constraint models the annual capacity expansion cap defined in the framework of the EEG 2012 and EEG 2014 (Eq. 5.4). This capacity expansion limitation ensures that not all the plant sizes are built in the first year of the time period due to a full valorization of biomass potentials.

$$\sum_{r=1}^{16} \sum_{i=1}^{49} X_{i,t,r}^{Exp} \leq W_t \qquad \forall\ t,r \qquad (5.4)$$

Under the EEG 2012 framework the annual capacity expansion cap has been set for each plant type following an historical growth rate of 6% for the years 2012 to 2014[31] according to [156], [157] and [158]. In the context of the EEG 2014, the Federal Government defined an annual capacity expansion cap of 100 MW_{el} in order to better drive and control future capacity developments [159]. In the present work this annual capacity expansion limit has been equally distributed between biowaste plants and agricultural plants. Finally, Eq. 5.5 ensures a mixed-integer capacity expansion for all the buildable capacity unit sizes P in each year and region r. In each plant size i, year t and

[31] Years prior to 2012 have not been taken into account because there was a strong increase in German biogas plants development over that period. This strong expansion was mainly due to the very favourable legal framework for agricultural plants employing energy crops and manure in the context of EEG 2006 and 2009. Since the year 2012, the Federal Government considers that the biogas sector is mature enough to be integrated into the German electricity market. This integration should be achieved with fewer subsidies and using new mechanisms like the market and the flexibility premium defined by the electricity direct marketing model. The EEG 2012 thus caused a slowdown in German biogas plant development due to the introduction of these new mechanisms. It appears then more realistic to set an annual maximum capacity rate up to 2030, taking into account this paradigm shift and without considering the effect of the years before 2012.

region r, a mixed-integer variable y is employed and represents the number of new built plants.

$$X_{i,t,r} = y_{i,t,r} \cdot P_i \qquad \forall \text{ i,t,r} \qquad (5.5)$$

5.4 Summary

The use of optimization models appears as well adapted to the analysis of various energy systems of different aggregation levels and scopes. In the framework of this thesis the energy system considered concerns the whole German biogas plant park. The objective of the regional optimization model developed is to provide a forecast for the evolution of future plant capacity as well as for future electricity production from biogas up to the year 2030. For this an objective function is defined aiming at maximizing the total profit over all plant sizes, the whole time period and all Federal States combined. Several constraints such as the limitation of future capacity expansion by biomass potentials and by caps defined under the EEG legal framework are also specified. The modelling approach is then resource-based meaning that the evolution - and the limitations - of future biomass potentials impacts the development of biogas plant capacities. Furthermore, the model assumes that the biogas plant operator’s objective is to maximise profit over the installation’s lifetime

6 Model input data determination

This chapter aims to describe the input data that has been employed for both the simulation and the optimization models. In each model two separate assessments, under the EEG 2012 and the EEG 2014 legal frameworks, have been carried out. The model input data refers then to the base year 2013 for the assessment done under the EEG 2012 framework. In the case of an analysis under the EEG 2014 framework, the base year 2015 has been selected. In section 6.1 the system boundaries characterizing the analysed biogas plants are set. In section 6.2 an overview of all required input data including a general description of methodology is given. The underlying assumptions and methodology for the determination of each data set are described in detail in sections 6.3 to 6.7. Technical input data consists of biomass properties, plant operation mode, existing biogas plant capacity as well as current and future biomass potentials for electricity production (sections 6.2, 6.3 and 6.4). Economic input data corresponds to the cost and revenue positions of a biogas plant project and is described in sections 6.5, 6.6, and 6.7. In section 6.8 an assessment of uncertainties and a plausibility check of the specified input data is carried out. This chapter ends with a summary (section 6.9).

6.1 System boundaries

Before performing an economic assessment of a biogas plant, it is necessary to firstly define the system that has to be analysed. The system considered is represented in Figure 6-1 and corresponds to the whole biogas supply chain from resource harvesting and transport up to electricity and heat production including digestate valorization.

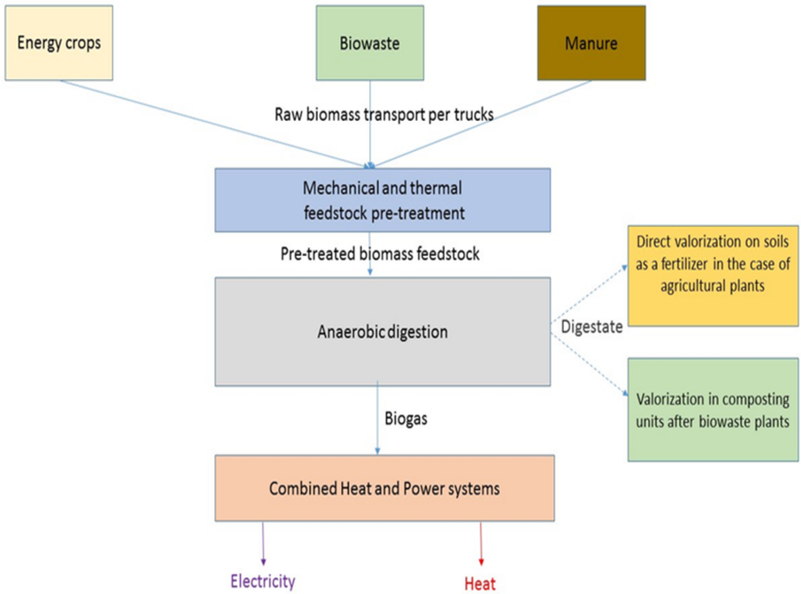

Figure 6.1: System boundaries (author's own representation)

The substrates are firstly harvested and cultivated in the case of energy crops or collected and stored in the case of bio-waste and manure. The transportation stage of cultivated or collected biomass feedstocks to the biogas plant follows. On the plant site the biomass feedstocks can be mechanically or thermally pre-treated before the fermentation. After the anaerobic digestion process the output streams (heat, electricity and digestate) leave the biogas plant. In the case of electricity, the system boundaries are set at the transmission station so that the costs for transformers and cables are included in the economic evaluation. The heat produced does not all leave the biogas plant and can be reused for heating the anaerobic digesters or be valorized through external heat sinks.

For agricultural plants it is assumed the raw digestate is used for free by farmers. For biowaste plants the solid digestate, treated by a compost operation unit, is systematically sold as compost. The transport of solid digestate to potential digestate sinks is not integrated into the system boundaries. Finally, the acquisition step of the plant site location is also considered in the economic calculations and included in the investment for civil engineering. One should differentiate between an already existing property, a partially referenced property and a not yet reference property. For the economic evaluation existing properties will be assumed and are supposed to be already equipped with connection to water, electricity, gas, district heating and be easily accessible (road access). In the next section the methodology for deter-mining the techno-economic input data for both the simulation and optimization models is presented.

6.2 Overview of the required input data for the simulation and the optimization models

6.2.1 Substrate and process definition

As mentioned in section 3.2 energy crops, manure and biowaste represent the main substrates employed in biogas plants by mono- or co-digestion plants. In particular the number of co-digestion plants using energy crops and manure rapidly increased between the years 2000 and 2008 [160]. Therefore, three reference biogas plants valorizing these feedstock types are assessed in the present work.

The first plant type (EM plant) corresponds to the valorization of energy crops with manure in co-digestion process as well as to the mono-digestion of manure. EM plants with an installed power smaller or equal to 75 $\mathrm{kW_{el}}$ are assumed to exclusively valorize manure in mono-digestion processes. For an installed power greater than 75 $\mathrm{kW_{el}}$ EM plants are assumed to use a biomass feedstock input mix containing 58% maize silage, 20% manure, 10% grass silage, 10% cereal silage and 2% cereal grains. E plants are characterized by an input mix of 58% maize silage, 20% grass silage, 20% cereal silage and 2%

cereal grains. The valorized maize silage and cereal grains mass share are thus in line with the specific cap of 60% set for these feedstocks under EEG 2012 [161]. Finally, B plants exclusively valorize biowaste in mono-digestion processes. The energetic properties of all employed feedstocks are given in the Table 6-1.

Table 6.1: Assumed biomass feedstocks properties [145], [162], [163]

Employed feedstocks	Methane yield ($m^3_{methane}$ / $t_{Feedstock}$)	Methane content in biogas (in %)	Biogas yield (m^3_{Biogas} / $t_{Feedstock}$)
Maize silage	106	52	204
Grass silage	100	53	189
Cereal silage	103	53	194
Cereal grains	320	54	593
Manure	17	55	31
Biowaste	73.8	60	123

In the case of agricultural plant types, maize silage, grass silage, cereal silage and cereal grains are selected due to their high biogas yield and also due to their high degradability. As mentioned in [79], these biomass types also represent by the end of the year 2014 the most common energy crop feedstocks in German biogas plants. Animal effluents like pig manure are often located in the proximity of agricultural biogas plants and are assumed to be available for free. The valorization of manure into biogas aims at reducing methane emissions and thus shows environmental benefits as described in [164]. In the present work biowaste feedstocks are assumed to come from German household kitchens and gardens and can be easily transformed into biogas by micro-organisms through anaerobic digestion processes. Finally, the digestate issued from the fermentation is assumed to be directly used on soil as fertilizer in the case of agricultural plants and treated to be further sold as a compost in the case of biowaste plants.

6.2.2 Operator models, plant operating hours and flexibility

In the present work the following operator models are considered respectively under the EEG 2012 and EEG 2014 frameworks (Figure 6-2).

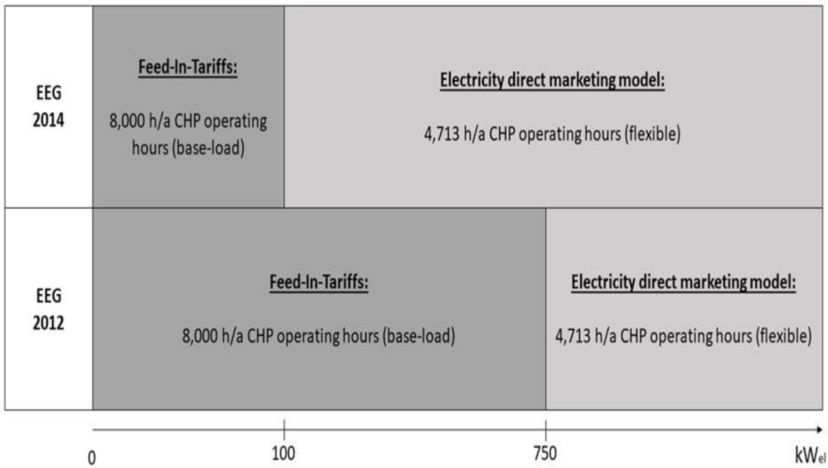

Figure 6.2: Considered operator models under EEG 2012 and EEG 2014 legal frameworks

According to a study from the German biomass research centre the average operating hours for biogas plants running in baseload in Germany has been estimated in 2014 at about 7,886 h/a [165]. This figure is derived from a questionnaire involving 567 biogas plants from which 284 were in the power range 151-500 kW_{el} and were operated for 8,033 h/a in baseload. In the present work the operating hours for baseload capacity have been systematically set at 8,000 h/a for all concerned plant sizes.

The operating hours $\mathrm{OH}_{\mathrm{Flex}}$ for flexible capacity have been determined according to Eq. 6.1:

$$E_{Full-Load} = E_{Base-Load} + E_{Part-Load} \tag{6.1}$$

With:

$E_{Full-Load}$: Energy amount in full-load operating mode

$E_{Base-Load}$: Energy amount in baseload operating mode

$E_{Part-Load}$: Energy amount in part-load operating mode

Eq. 6.1 can be further expressed as follows (Eq. 6.2):

$$\frac{P_{El,Base-Load}}{\eta_{CHP,Base-Load}} \cdot FLH = \left(\frac{P_{El,Base-Load}}{\eta_{CHP,Base-Load}} + \frac{P_{El,Flexible}}{\eta_{CHP,Flexible}}\right) \cdot PLH \tag{6.2}$$

With:

$P_{El,Base-Load}$: Electric power in baseload operating mode

$P_{El,Flexible}$: Flexible electric power in part-load operating mode

$\eta_{CHP,Base-Load}$: Electric CHP efficiency in baseload operating mode

$\eta_{CHP,Flexible}$: Electric efficiency for flexible CHP in part-load operating mode

FLH: full-load hours (8,760 h/a)

PLH: part-load hours for flexible capacity

The part-load hours for flexible capacity PLH are derived from Eq. 6.2 (Eq. 6.3):

$$PLH = \frac{\frac{P_{El,Base-Load}}{\eta_{CHP,Base-Load}}}{\frac{P_{El,Base-Load}}{\eta_{CHP,Base-Load}} + \frac{P_{El,Flexible}}{\eta_{CHP,Flexible}}} \cdot FLH \tag{6.3}$$

For a given plant size, the flexible CHP capacity has been set at 80% of baseload capacity which leads to simplifications in Eq. 6.4. In the analysis mentioned in [166] a doubling of the baseload CHPs is taken into account in order to obtain flexible capacity. The conservative assumption of the present work should however be balanced against the fact that all considered existing and future new built plant involved in the electricity direct marketing are supposed to be systematically transformed into flexible capacities.

$$PLH = \frac{FLH}{1 + 0.8 \cdot \frac{\eta_{CHP,Base-Load}}{\eta_{CHP,Flexible}}} \cdot FLH \qquad (6.4)$$

As mentioned in Figure A-15 of the Appendix baseload and flexible CHP electric efficiencies are correlated to the CHP electric power [150]. More precisely the ratio $\frac{\eta_{\mathrm{CHP,Base-Load}}}{\eta_{\mathrm{CHP,Flexible}}}$ remains constant at a value of 1.073 for all baseload and corresponding flexible electric CHP capacities. The annual full-load hours FLH are equal to 8,760 hours. Thereby constant annual operating hours for all new built flexible capacity have been estimated at about 4,713 h/a. The flexibilization of existing baseload CHPs requires supplementary flexible CHP gas engines but also new gas storage. The supplementary gas storage volume due to the flexibilization of existing CHP is systematically determined for each plant size by using the calculator of the Federal Office for Agriculture of Thuringia (TLL) [167]. An example calculation can be found in Table A-3 of the Appendix for a plant equipped with an existing CHP of 1,000 $\mathrm{kW_{el}}$ and a gas storage with a volume of 4,000 m^3.

6.2.3 Techno-economic input data

Beside data characterizing the biomass feedstocks and the plant operation mode, information regarding the estimation of existing plants, the determination of current and future biomass potentials, annual costs and revenues for the biogas plants operation is necessary. For the simulation model all positions concerning revenues, operating and investment-related costs are estimated in each simulation step and lead to the calculation of specific operating profits. The simulations are performed in the framework of EEG 2012 and EEG 2014 respectively for the base years 2013 and 2015.

In the case of the simulation model the results are assessed nationally by considering an average value of the regional energy crop costs that has been determined in section 6.6.1.7. The revenues and costs that have been estimated in the simulation model also feed the optimization model for the base years 2013 and 2015. They are further forecasted up to the year 2030 with the help of annual evolution rates. Regional energy crop cost contributions (in $\mathrm{ct/kWh_{el}}$) are determined in each Federal State in section 6.6.1.9 and are further integrated in the optimization model. Thereby specific operating profits can be derived year on year for each plant type, size and region.

The specification of the existing biogas plant capacity for the base years 2013 and 2015 also represents an important information that has to be fed into the optimization model. The determination of existing plants in each Federal State is a starting point for the estimation of future capacity development concerning the whole German biogas plant park. These developments are driven by the evolution of regional biomass electrical potentials up to the year 2030 specified for each of the three reference plant types (EM, E and B). Figure 6-3 sums up the necessary input data for both the simulation and optimization models.

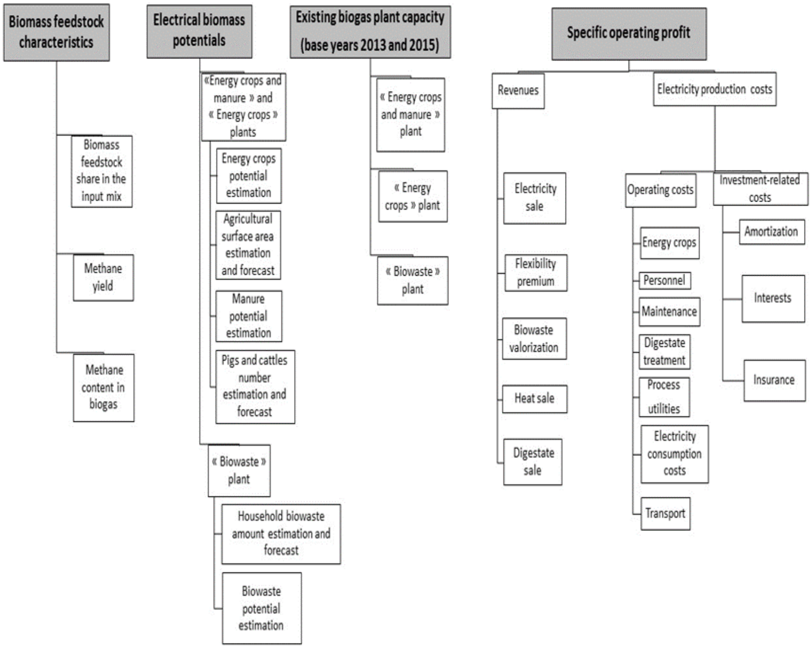

Figure 6.3: Classification of the required model input data

6.2.4 General methodology for the model input data determination

The methodology and the literature sources that have been employed for the determination of all technical and economic input data are summed up in Table 6-2. The model input data is determined on the basis of questionnaires sent to plant operators, according to published information or derived from methodological assumptions. In particular total capital investment has been estimated by using the Multiplier Value Method (section 6.5.1) and energy crop costs have been quantified in each Federal State on the basis of regional biomass hectare yields (section 6.6.1).

Table 6.2: Literature sources and methodology employed for the models input data determination

	Description	Methodology employed / Data source
Technical input data	Biomass feedstock properties	Literature data from [145], [161], [162], [163]
	Operating hours for flexible CHP	Based on: Specific plant operator models (section 6.2.2) Calculation tool from the Federal Office for Agriculture of Thuringia (TLL) [167]
	Supplementary gas storage volume	
	Existing biogas plant capacity	Biogas plant database (web-based research)
	Biomass potentials for electricity production	Potentials estimation and forecast based on literature data (section 6.4)
Economic input data	Total capital investment	Estimation based on literature data and according to the Multiplier Value Method (section 6.5)
	Additional investment (flexibilization)	Based on: Specific plant operator models (section 6.2.2) Calculation tool from Federal Office for Agriculture of Thuringia (TLL) [167]
	Energy crop costs	Calculations are carried out at the Federal State level according to literature data and based on regional hectare yields (section 6.6.1).
	Biomass feedstock transport costs	Based on literature data (section 6.6.2) Specific transport costs models are defined for biowaste according to various collections zones (section 6.6.2.3)
	Electricity consumption costs	Based on literature data (sections 6.6.3, 6.7.3., 6.7.4 and 6.7.5)
	Process utilities costs	
	Digestate treatment costs	
	Revenues from heat sale	
	Revenues from digestate sale	
	Revenues from biowaste valorization	
	Personnel costs	Derived from questionnaires sent to plant operators
	Maintenance costs	Based on literature data (sections 6.6.3, 6.7.1 and 6.7.2) and on the defined plant operator models (sections 6.2.2)
	Revenues from electricity sale	
	Flexibility premium and supplement	

In the next section, the methodology used to determine each input data set is described in detail. Firstly, existing biogas plant capacity is estimated (section 6.3). In a second step current and future technical biomass potentials are evaluated and forecasted at the Federal State scale up to the year 2030 (section 6.4). A final step focuses on the estimation and forecast of current and future revenues and costs for each of the three plant types (sections 6.5, 6.6. and 6.7).

6.3 Estimation of existing biogas plant capacity

In order to evaluate future biogas capacity development up to the year 2030 a starting point is the estimation of the existing plants park at the Federal State scale and according to the three reference installation types. In a first step a database gathering 1,323 installations in Germany is built using a web-based research of German companies operating biogas plants. The database contains for each plant the feedstock type employed, namely energy crops, manure or biowaste in mono- or in co-digestion plants and the installed electric power. In a second step this database is statistically evaluated according to the three plant types: the energy crops and manure plants (type "EM"[32]), the energy crops plants (type "E"[32]) and the biowaste plants (type "B"). The apportionment rates of existing capacities according to these three plant types are given in Table 6-3.

In a third step the database is further discretized into 49 power ranges along the electric capacity bandwidth [0:20,000 kW_{el}] as described in Figure 6-4. It appears that most of existing biogas plants in the database are located in the power range [100:500 kW_{el}] followed by the range [500:1,000 kW_{el}]. Plants smaller than 75 kW_{el} and larger than 5,000 kW_{el} currently play a marginal

[32] Agricultural EM and E plant types also include the valorization of agricultural residues such as cereals straw, grain maize straw and harvest residues.

role in the capacity mix. This repartition is in line with the observed situation by the end of 2012 [168].

In a fourth step the plant typology and capacity repartition obtained for the 1,323 installations in the database are scaled-up to the whole German biogas plant park, which amounts to about 7,366 installations for a total installed capacity of 3,091 MW_{el} at the end of 2012 [156]. Finally, a regionalization of the installed capacity is carried out for each of the three plant types at the level of the German Federal States according to repartition keys derived from [156] and [157]. The regional plant repartition shows that more than half of German biogas plants are located in Lower-Saxony, Bavaria and Baden-Württemberg. No plants dedicated to electricity production from biogas exist in the Federal States of Berlin, Hamburg and Bremen.

Table 6.3: Estimated capacity repartition according to the three defined plants EM, E and B

Plant type	Employed feedstocks	Plant capacity apportionment rates (%)
Energy crops and manure plant (type “EM”)	Valorization of energy crops and manure in co-digestion	60.39
Energy crops plant (type “E”)	Valorization of energy crops in mono-digestion	33.14
Biowaste plant (type “B”)	Valorization of biowaste in mono-digestion	6.47

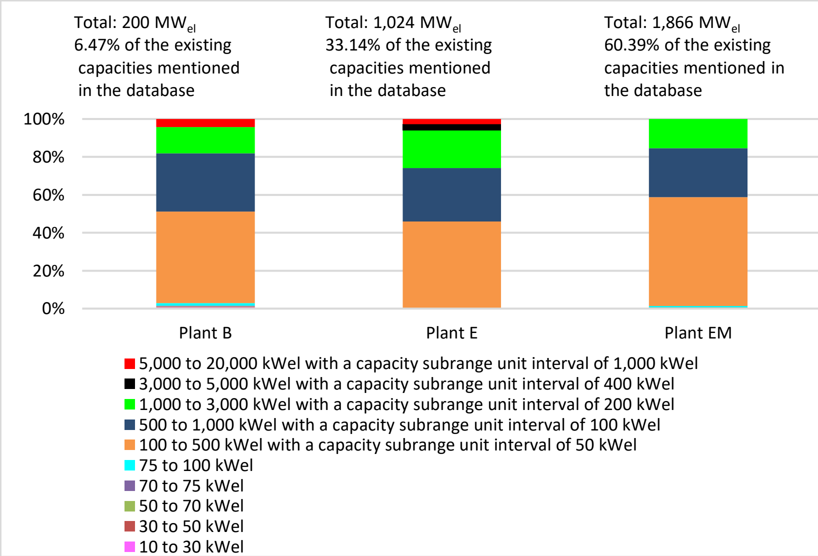

Figure 6.4: Capacity repartition for the existing biogas plant types at the end of the year 2012

In the framework of the optimization model, it is systematically assumed that all existing plants impacted by electricity direct marketing are concerned by flexibilization. This applies to plants with a capacity larger than 750 kW_{el} under EEG 2012 (year 2013) and superior to 100 kW_{el} under EEG 2014 (year 2015). According to the biogas plant database about 733 MW_{el} and 2,743 MWel existing capacities are then subject to flexibilization respectively under the EEG 2012 and EEG 2014 operator models. Each of these capacities are then further split into baseload installations and plants that are already flexible, by using repartition rates derived from [169] and [170][33]. Table 6-4 sums up the capacity repartition obtained under EEG 2012 and EEG 2014.

[33] Under EEG 2012 the total capacity subject to flexibilization can be divided into 96.7% baseload installations and 3.3% flexible plants. Under EEG 2014 base-load capacity represents 64.15% of the total capacity whereas 35.85% are linked to already existing flexible plants.

In the next section annual biomass potentials for energy crops, manure and biowaste dedicated to electricity production from biogas are determined for each Federal State up to the year 2030.

Table 6.4: Existing capacity concerned by flexibilization under EEG 2012 and EEG 2014 operator models

	EEG 2012 operator model (year 2013)	EEG 2014 operator model (year 2015)
Total existing capacity concerned by flexibilization (MW_{el})	733	2,743
Existing base-load capacity subject to further flexibilization (MW_{el})	709	1,759
Already existing flexible capacity (MW_{el})	24	984

6.4 Estimation of current biomass potentials and evolution up to 2030

6.4.1 Estimation of current biomass potentials for electricity generation

The use of renewable energy carriers in order to deliver electric, thermal and chemical energy can be estimated with the help of potentials. In the literature the potentials are split into the theoretical, technical, economic and deducible one [48], [171]. The theoretical potential corresponds to the upper boundary of energy delivery and describes the theoretical, physical usable energy supply which is available in a certain region and at a certain time point. It can be for example the global current energy contained in energy crops mass in Germany if the country is set as a physical boundary. Due to certain technical, structural, ecological, economic and administrative constraints, this theoretical potential can only be partially used. The technical potential represents the share of the theoretical potential which can be used given technical restrictions. The technical potential is often used as a key indicator for investment or political decisions in the field of renewable energies. The boundaries are set by the limitations of the employed technologies. Further potential limits are defined by geographical, ecological and legal framework conditions. Therefore, technical potentials can be defined depending on time and space. For example, the efficiency of a conversion technology generally increases with time and the potentials depends on the existence, for instance, of natural protection zones. In the case of bioenergy, the technical potential represents the possible contribution of a certain area at a certain time point to cover an energy requirement. As various biomass conversion technologies and various framework conditions can be applied to a certain area it is possible to obtain different potential value levels for the same area.

The economic potential describes the part of the technical potential that can be used given economic restrictions. A variety of parameters have an influence on this potential (e.g., depreciation, interest) which is then more time and space dependent than the technical potential. As there are numerous possibilities to ensure the profitability of a plant, several economic potentials exist. As economic restrictions are permanently evolving (e.g., costs of renewable electricity production, changes in tax system, CO_2 certificate trading) it is not possible to determine the economic potential exactly and precisely. Finally, the deducible potential is a limitation of the economic potential and is set by considering additional restrictions like production capacities, administrative limitations or pre-existing plants. The study published in [132] and described in section 3.4.2 provides an analysis of technical biomass potentials for the main feedstock employed i.e., energy crops, biowaste and manure. This study has been used in the present work for the determination of potentials dedicated to electricity production from biogas. Technical biomass potentials are converted into potentials for electricity generation assuming an average CHP electric efficiency of 38%

[132]. These potentials represent the maximal electricity amount produced by the valorization of technical biomass potentials dedicated to biogas production. The potentials are expressed in $\mathrm{TWh_{el}}$ and are used in a constraint equation in the optimization model (see Eq. 5.3). They ensure that no electric capacity can be further built if the corresponding biomass potentials are not sufficient.

In Germany and at the end of 2012 a total biomass potential of about 36.7 $\mathrm{TWh_{el}}$ linked to onsite electricity generation from biogas was estimated according to [132][34]. This potential is mainly located in the Federal States of Bavaria, Lower Saxony and North Rhine-Westphalia which contain more than 20 $\mathrm{TWh_{el}}$. An allocation of this total potential to the three analysed plant types is carried out for the base year 2013 by using the repartition rates mentioned in Table 6-3 (see Figure A-7 in the Appendix).

This gives a repartition of about 22.2 $\mathrm{TWh_{el}}$ for the EM plants, about 12 $\mathrm{TWh_{el}}$ for E plants and about 2.4 $\mathrm{TWh_{el}}$ for B plants. The level of the currently used biomass potentials dedicated to electricity from biogas is also relevant. As mentioned in [172] about 90% of the available biomass potential linked to energy crops for biogas is already used. This figure amounts to 50% in the case of manure or biowaste valorization [172] which indicates that development perspectives for the energetic use of biogenic waste and agricultural effluents are remaining. On the opposite the valorization pathway related to energy crops conversion into bioelectricity is almost saturated which could lead to very limited developments in some Federal States.

[34] In [132] a total potential of 99.4 TWh both relative to biogas and biomethane is mentioned. The assumption of a global electric CHP-efficiency of 38% in all Federal States leads to a total electrical potential of 37.8 $\mathrm{TWh_{el}}$. From this value 1.1 $\mathrm{TWh_{el}}$ are linked to the decentralized electricity production from bio-methane and must be subtracted in order to obtain the total electrical potential dedicated to biogas.

6.4.2 Evolution of biomass potentials for electricity generation up to 2030

As the model intends to assess German electricity production from biogas up to the year 2030, an evaluation of future biomass potentials for the three plant types “Energy crops” (E), “Energy crops and manure” (EM) and “Biowaste” (B) is necessary. In the case of agricultural plants employing energy crops but also manure it is supposed that the future evolution of the biomass potentials is mainly driven by the evolution of agricultural surface areas [173], [174]. More precisely the historical evolution of agricultural areas be-tween 1992 and 2014 at the scale of the German Federal States stands for the basis of a forecast carried out up to the year 2030. A general decreasing trend in the surface area evolution is observed, especially in the Federal States of Bavaria, Low-Saxony and North Rhine-Westphalia, where the potentials are mainly located. For biowaste plants it is assumed that future potential developments are correlated to the evolution of household biowaste amounts [175]. According to the German Witzenhausen Institute for Waste, Environment and Energy, a saturation of the use of waste from industry and commerce is already observed. Thereby future developments concerning this biowaste category may be limited. On the contrary, potentials for household biowaste should expand strongly up to the year 2030 [175]. Table 6-5 provides an overview of the assumptions that have led to the determination of future biomass potentials for the years 2013, 2020 and 2030. The results of the potentials estimation and forecast at the Federal State level and for each of the three installation types are mentioned in Figures A-8 and A-9 in the Appendix.

Table 6.5: Employed assumptions for the determination of current and future biomass potentials

	2013 (base year)	2020	2030
Evolution of total agricultural areas in Germany (million ha) [173]	18.48	17.8	16.78
Evolution of cattle and pig numbers (million) in Germany [174]	36	36	36
Evolution of household biowaste amount (million t) [175]	4.5	7	8.3

6.5 Specific investment-related costs

The required economic data for both the simulation and optimization models are the specific revenues and specific costs of electricity production for each plant type (in $\mathrm{ct/kWh_{el}}$). They are determined year on year and all Federal States combined. Specific annual costs of electricity production epc can be split into specific investment-related costs $\mathrm{c_{inv}}$ and the specific operating costs $\mathrm{c_{op}}$ (Eq. 6.5) [176].

$$epc = c_{inv} + c_{op} \tag{6.5}$$

In the following, the methodology and assumptions used to estimate the different cost positions for $\mathrm{c_{inv}}$ and cop is described.

The specific investment-related costs are fixed costs derived from the total capital investment TCI in the biogas plant. Investment-related costs consist of depreciation, imputed interest and insurance costs. They are proportionally linked to the total capital investment [177]. Depreciations D are assumed to be linear over the lifetime t of the investment - 20 years for buildings and 10 years for technical components - and are determined according to Eq. 6.6.

$$D = \frac{TCI}{t} \tag{6.6}$$

Imputed interest is derived from the total capital investment TCI and from the rate of interest j[35] according to Eq. 6.7 and assuming a residual value equal to zero.

$$Int = \frac{TCI}{2} \cdot j \tag{6.7}$$

Finally, insurance costs are estimated at 0.5% from the total capital investment according to [178], [179]. In the next section the methodology employed for the estimation of the total capital investment is described in detail.

6.5.1 Total capital investment estimation

The starting point for the total capital investment estimation is to collect equipment acquisition costs from questionnaires sent to German biogas plant operators. Acquisition costs can be divided into expenditure for plants and machines and also include indirect expenditure for construction and engineering. More precisely acquisition costs for plants are incurred by fermenters[36], feedstock and digestate storage tanks. Acquisition costs for machines apply to CHP, feedstock delivery technology and process equipment for digestate treatment. Figure 6-5 mentions the acquisition costs that have been considered for typical sizes of each plant type E, EM and B.

[35] A rate of interest of 6% is assumed according to [75].

[36] The correlations linking fermenters acquisition costs as a function of the fermenter's volume and also as a function of the installed electric power are given in Figures A.10 and A.11 in the Appendix [105], [167], [180], [181].

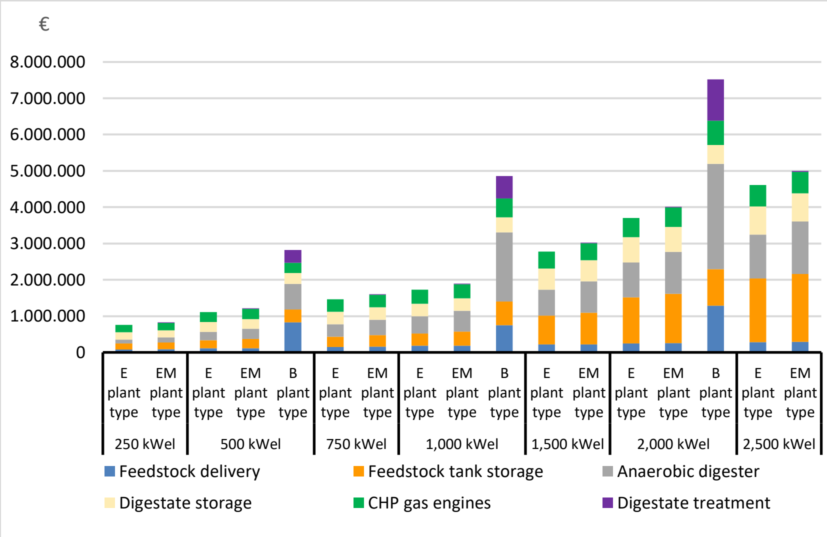

Figure 6.5: Acquisition costs structure for typical E, EM and B biogas plant sizes

The total capital investment corresponds to the fixed employed capital covering all equipment and auxiliaries related to the biogas plant. In the literature numerous methodologies lead to the estimation of the total capital investment. These methods include the Chilton method, the Holland method, and the Miller method [182], [183]. In this work the Peters and Timmerhaus method, also known as the Multiplier Values Method, has been selected [184]. The Multiplier Values Method is being more and more employed in scientific contributions, e.g., regarding the evaluation of bio-refineries or Biomass-to-Liquid processes [185], [186]. This method has been selected as it relies on the previously determined acquisition costs. In the Multiplier Values Method, the total capital investment TCI is assumed to be proportional to the sum of previously estimated acquisition costs $\mathrm{AC_i}$ according to Eq. 6.8. The proportionality coefficient M is equal to the sum of multipliers values relative to all investment positions: investments for equipment, installation, piping, instrumentation, insulation, electrical facilities, buildings, infrastructures and technical utilities.

$$TCI = \sum_{i=1}^{n} M \cdot AC_i \qquad (6.8)$$

In order to characterize anaerobic digestion processes the selected multipliers are set out in Table 6-6 and are based on the values bandwidth for microbial systems according to [187].

By applying the above multipliers to the acquisition costs mentioned in Figure 6-5 correlations linking the specific investments (in $€/\mathrm{kW_{el}}$) to the installed electric power (in $\mathrm{kW_{el}}$) can be derived and are represented in Figure 6-6 exemplary for EM and B type plants. For small-scale manure plants with an installed capacity lower than 75 $\mathrm{kW_{el}}$ the following correlation between the specific investment $\mathrm{SI_{ManurePlants}}$ and the installed electric power $\mathrm{P_{el}}$ has been applied based on the values of [116][37] (Eq. 6.9):

$$SI_{ManurePlants} = 3{,}0334 \cdot P_{el}^{-0.392} \qquad (6.9)$$

Table 6.6: Employed multipliers values for the total capital investment estimation

Investment position	Description of the investment position	E and EM plants	B plants
Total equipment acquisition costs	Selling price from commercial tenders including indirect costs (construction overhead and engineering)	1	1
Installation	Costs for the physical installation of an equipment at the biogas plant location	0.2	0.2
Piping	Pipes for steam, cooling and digestate	0.3	0.3

[37] In [116], a 30 $\mathrm{kW_{el}}$ small scale manure plant shows a specific investment of 8,000 $€/\mathrm{kW_{el}}$, whereas 6,560 $€/\mathrm{kW_{el}}$ are related to a 50 $\mathrm{kW_{el}}$ plant and 5,587 $€/\mathrm{kW_{el}}$ correspond to a 75 $\mathrm{kW_{el}}$ one.

Instrumentation	Measurement, process control, automation and metrology	0.1	0.1
Insulation	Costs for building insulation and painting	0.01	0.01
Electrical facilities	Electric systems, lighting, grid connection	0.1	0.1
Building	Buildings associated with the biogas plant. Incorporates non-electrical building services as well as safety items.	0.15	0.25
Infrastructure	Roads, parking, pathways	0.05	0.15
Technical utilities	External, process-oriented facilities required for the proper operation of a process facility (steam, water and electricity)	0.01	0.4
Total multiplier value M	Sum of the multipliers values for the above-mentioned positions	**1.92**	**2.51**

A gap in the specific investment is observed in Figure 6-6 when moving from 75 $\mathrm{kW_{el}}$ to 100 $\mathrm{kW_{el}}$, due to a technological change for plants larger than 75 $\mathrm{kW_{el}}$. Starting from 100 $\mathrm{kW_{el}}$, manure is valorized with energy crops in co-digestion plants which requires another fermenter type (dry fermentation) and generates higher specific investment than in the case of small-scale manure plants (wet fermentation).

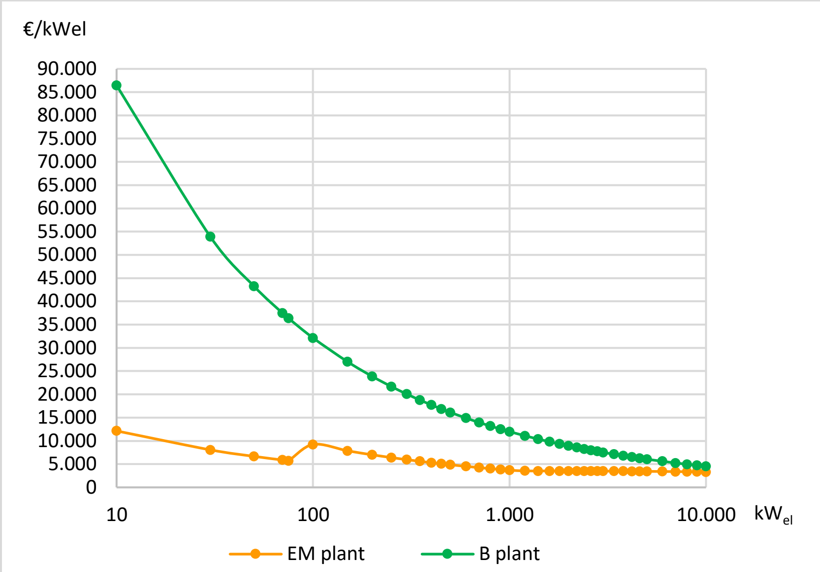

Figure 6.6: Specific investment for agricultural and biowaste plants (EM and B plants) as a function of the installed electric power

For comparison [147] mentions similar specific investment values for both biowaste and agricultural plants. Agricultural plants remain clearly less capital intensive than biowaste plants mainly due to the high level of investment in the biowaste pre-treatment process[38] and in the anaerobic digester technology[39].

6.5.2 Additional investment

Additional investment applies to flexible electricity production from biogas. It principally concerns the employed supplementary flexible CHPs and the new

[38] Biowaste pre-treatment processes generally correspond to hygienization, hydrolysis or pasteurization.
[39] The anaerobic digesters for biowaste plants often employ a dry fermentation process which is more expensive than the wet technology used in agricultural plants.

gas storage equipment. The specific investment in new CHPs can be expressed as a function of the installed electric power according to the correlation mentioned in [150]. Figure A-12 of the Appendix provides a correlation linking the investment in new gas storages to the storage working volume according to [188]. The total investment-related costs linked to the flexibilization of a 1,000 kW_{el} plant are exemplarily estimated in Tables A-3 and A-4 of the Appendix.

6.6 Specific operating costs

The annual specific operating costs apply to energy crop costs, transport costs, personnel, energy and process utilities costs, maintenance and digestate treatment costs. In the following sections the methodology and assumptions employed for each of these specific cost positions are described in detail. In particular the methodology employed for the determination and the forecast of regional energy crop costs in each Federal State is presented in detail in section 6.6.1.

6.6.1 Energy crop costs estimation and forecast

6.6.1.1 General employed methodology

As mentioned in [189] the energy crop price paid by the biogas plant operators at the gate of their installation is set in the framework of supply contracts with local farmers. The first aspect to define in a supply contract is the biomass amount delivered. For each variety of energy crops the form of the delivered biomass as cultivable areas (ha), fresh mass (t FM) or silage should be specified. The margin between minimum and maximum Dry-Matter contents should be as small as possible in order to avoid fluctuations in feedstock quality. The second point concerns the place where the biomass should be delivered. Logistical aspects are thereby defined. For example, it has to be clearly mentioned if the biomass should be harvested and transported to the plant or if the biomass is delivered under the form of silage. In the case of a silage delivery the farmer has to financially bear silage losses (minimum 10%). Another point concerns the biomass quality. The main parameters are here linked to biomass yields (in t/ha), methane yields (in m^3/t) and to fertilizer values (N- P- K- fractions).

A central information in biomass supply contracts concerns the contracting period. From the farmers perspective a short-term contract of five years has to be preferred in order to protect them from short-term high energy crop price volatility [190]. Biogas plant operators try to realize long-term contracts of about 10 years in order to maximize the financial security level of the project. The defined substrate prices are in most cases correlated to the development of other resource prices like for instance oil prices. On the farmer’s side, the costs of production of energy crops can be divided into various positions like seed costs, costs for crop protection, costs for fertilizer, variable and fixed machine costs, harvesting costs, fixed and variable storage costs, hail insurance costs, personnel costs, buildings and land rent costs.

Regarding the biogas plant profitability analysis, the cost contribution of energy crops represents more than the half of the electricity production costs from biogas and is a key parameter in the implementation of a biogas plant project [147]. Four types of agricultural feedstocks are considered in the present work and represent more than 90% of the energy crops valorized into biogas in Germany: maize silage, grass silage, cereal grains and cereal silage [79]. As the energy crop costs are set locally in the framework of the above-mentioned supply contracts a regionalization of national energy crop costs is necessary. This aspect is strengthened by the fact that regional technical parameters (e.g., specific hectare yields) are also involved in energy crop costs calculations. In the following the methodology used to estimate regional energy crop costs at the Federal State level is presented. The objective is to determine the contribution of regional energy crop feedstock costs $\mathrm{C}_{\mathrm{FeedstockCosts},2013,\mathrm{i},\mathrm{r}}$ in the total electricity production costs for the base year

2013. For this purpose, the following sequential steps have been followed and are described in detail:

- Estimation of regional mass flows for each feedstock type and in each Federal State
- Regional maize silage costs calculations by using regional mass flows and hectare yields derived from national costs data
- Regional grass silage costs calculations based on national hay costs, on reference values for nutrient and dry matter contents and on regional mass flows and hectare yields
- Regional cereals grain costs estimation derived from national costs for wheat, triticale and rye and from regional mass flows and hectare yields
- Regional cereals silage costs calculation derived from national cereals grain costs, from specific methane yields and from regional mass flows and hectare yields
- Estimation of the regional energy crop costs for the base year 2013
- Estimation of the electrical yields μ_i linked to feedstock organic dry matter and methane content in biogas, to reference methane yields and to average CHP efficiencies
- Estimation of the energy crop costs contribution into the electricity production costs from biogas in each Federal State and for each plant type in the base year 2013

6.6.1.2 Estimation of regional mass flows for each feedstock type and in each region

In a first step the calculation of each regional energy crops mass flow $M_{i,r}$ is carried out by multiplying in each Federal State the regional surface area $S_{i,r}$ dedicated to each energy crops feedstock for biogas production (in ha) by regional hectare yields $\eta_{i,r}$ (in t/ha) following Eq. 6.10

$$M_{i,r} = \eta_{i,r} \cdot S_{i,r} \tag{6.10}$$

The regional hectare yields for maize silage and rapeseed are derived from average historical values covering the year 2006 to 2010 [191] and are mentioned in Tables A-5 and A-6 of the Appendix. The regional hectare yields for grass silage correspond to average values for roughage in the years 2010 and 2011 [192] and can be found in the Table A-7 of Appendix. The term roughage covers meadows and pastures, legumes for whole plant harvest (e.g., clovers) and grass cultivation on arable land. The regional hectare yields for cereal grains mentioned in the Table A-8 of the Appendix are linked to average values for rye, winter cereals, winter wheat and triticale[40] between the years 2006 and 2010 [191]. The regional hectare yields for cereal silage are derived from the values for cereal grains (Table A-9 of the Appendix). An average corn-straw ratio of 1:1.2 and a DM-content of 87% for cereal grains and 33% for cereal silage are assumed [193]. The regional surface area $S_{i,r}$ is then determined for each energy crops feedstock type. The estimation (e.g., for maize silage) is based on the regional agricultural surface area for energy crops[41] $S_{EC,r}$ on the previously determined regional hectare yields $\eta_{i,r}$ and on the share α of each feedstock in the total national energy crops mass issued from [194] (Eq. 6.11).

$$S_{Maize-silage,r} = \frac{\alpha_{Maize-silage}}{\eta_{Maize-silage,r} \cdot \left(\frac{\alpha_{Maize-silage}}{\eta_{Maize-silage,r}} + \frac{\alpha_{Grass-silage}}{\eta_{Grass-silage,r}} + \frac{\alpha_{Cereal-silage}}{\eta_{Cereal-silage,r}} + \frac{\alpha_{Maize-grains}}{\eta_{Maize-grains,r}} \right)} \cdot S_{EC,r} \tag{6.11}$$

The calculated regional surface area $S_{i,r}$ for each energy crops feedstock type is set out in Table A-10 of the Appendix.

Regional manure mass flows $M_{Manure,r}$ employed in the EM plant type are further determined. In the present case it is assumed that the valorized manure is exclusively produced by cattles. According to German Federal Statistical Office about 12.7 million cattles are identified at the end of the year

[40] Triticale is a hybrid with wheat as the female partner and rye as the male partner.

[41] The regional agricultural surface area for energy crops is based on values from the biogas plant database described in Section 6.3.

2013 and can be split into milk cows (4.3 million) and remaining cattle (8.4 million). According to [195], [196], [162] an average specific manure production rate $Q_{Milk-cows}$ is estimated at about 19.8 m3 of manure per milk cow which leads to a milk cow manure mass at about 85.4 million t. A single remaining cattle produces about 8.3 m3 manure ($Q_{Remaining-cattles}$) which implies a manure mass dedicated to the remaining cattle of about 69.5 million t [197], [198], [162].

The total manure mass produced by German cattle amounts thus to about 154.9 million t. According to [199] about 33.2 million t cattle manure are dedicated to biogas plants which leads to a valorization factor w of 21.4% applied to each Federal State. In each Federal State r the existing milk cows and remaining cattles amount, $N_{Milk-cows,r}$ and $N_{Remaining-cattles,r}$, is estimated based on historical data for the year 2010 from [197], [198]. The results are mentioned in Table A-11 of the Appendix. The total manure mass flow $M_{Manure,r}$ in each Federal State can be therefore estimated according to Eq. 6.12 and the regional values are mentioned in Table A-12 in the Appendix.

$$M_{Manure,r} = \left(N_{Milk-cows,r} \cdot Q_{Milk-cows,r} + N_{Remaining-cattles,r} \cdot Q_{Remaining-cattles,r}\right) \cdot w \tag{6.12}$$

6.6.1.3 Maize silage costs calculation

Regional maize silage costs have been determined following an equilibrium price method. The farmer's objective is to sell a certain amount of maize silage to biogas plant operators at an equilibrium price covering at least the variable maize silage costs of production and the profit loss due alternative non-cultivated crops. According to [200] the non-cultivated crops, which have been replaced by maize silage cultivation for biogas production mainly correspond to rapeseed. The maize silage costs for plant operators are thus determined according to Eq. 6.13.

$$\underbrace{c(Maize)_{\frac{€}{t}} \cdot \eta(Maize)_{\frac{t}{ha}}}_{\text{Maize silage costs}} = \underbrace{c(Rapeseed)_{€/t} \cdot \eta(Rapeseed)_{t/ha} - c\,var(Rapeseed)_{\frac{€}{ha}}}_{\text{Net profit loss due to the rapeseed non-cultivation}} + \underbrace{c\,var(Maize)_{€/ha}}_{\text{Variable maize silage costs}} \tag{6.13}$$

With:

$c(Maize)$: Maize silage costs in €/t

$c(Rapeseed)$: Winter rapeseed costs in €/t

$c\,var(Rapeseed)$: Winter rapeseed variable costs in €/ha

$c\,var(Maize)$: Maize silage cultivation costs in €/ha

$\eta(Maize)$: Maize silage hectare yields in t/ha

$\eta(Rapeseed)$: Winter rapeseed hectares yield in t/ha

The variable costs for maize silage and winter rapeseed in €/ha have been determined based on data from [201]. According to [201] the average costs for winter rapeseed per Dry-Matter feedstock mass amounts 297 €/t_{DM}. The hectare yields (in t/ha) for maize silage are estimated in each Federal State based on the historical values observed from the year 2006 to 2010 [191].

6.6.1.4 Grass silage costs calculation

The costs for grass silage are derived from the ones for hay (average values for 2010, 2011 and 2012, according to [202]) and from reference values for nutrients and Dry-Matter contents issued from [193] (Eq. 6.14).

$$(c_{Grass})_{€/t} = (C_{Hay})_{€/t} \cdot \frac{DM_{Grass} \times N_{Grass}}{DM_{Hay} \times N_{Hay}} \tag{6.14}$$

With:

- $(c_{Grass})_{€/t}$: Grass silage costs in €/t

- $(C_{Hay})_{€/t}$: Hay producer costs in €/t

- DM_{Grass} : Grass silage dry matter content in %

- DM_{Hay}: Hay dry matter content in %

- N_{Grass} : Nutrients content in grass silage in MJ/kg_{DM}

- N_{Hay} : Nutrients content in hay in MJ/kg_{DM}

6.6.1.5 Cereal grains costs calculation

Regional costs for cereal grains correspond to average costs of wheat, triticale and rye. They have been provided by the Agricultural Market Information society (AMI) and concern the years 2009/2010, 2010/2011 and 2011/2012 [202].

6.6.1.6 Cereal silage costs calculation

Regional costs for cereal silage are derived from cereal grains costs and from average feedstock methane specific yields [162], [203] (Eq. 6.15).

$$c_{Cereal-Silage} = \frac{\dot{V}_{CH_4}\,(Cereal-Silage)}{\dot{V}_{CH_4}\,(Cereal-Grains)} \cdot c_{Cereal-Grains} \qquad (6.15)$$

With:

- $c_{Cereal-Silage}$: Cereal silage costs in €/t

- $c_{Cereal-Grains}$: Cereal grains costs in €/t

- $\dot{V}_{CH_4}\,(Cereal - Silage)$: specific methane yield for cereal silage in $m^3_{methane}$ / $t_{Cereal\ silage,oDM}$

- $\dot{V}_{CH_4}\ (Cereal - Grains)$: specific methane yield for cereal grains in $m^3_{methane}\ /\ t_{Cereal-Grains,oDM}$

6.6.1.7 Estimation of the energy crop costs for the base year 2013

The previous energy crop costs have been determined at the Federal State level for the year 2012. As the economic evaluation starts in 2013, an estimation of these costs has to also be realized for the base year 2013. The regional energy crop costs have thus been calculated according to Eq. 6.16 and the results are mentioned in Table A-13 of the Appendix

$$c_{2013,i,r} = c_{2013,i,national} \cdot \frac{c_{2012,i,r}}{c_{2012,i,moy}} \tag{6.16}$$

With:

- $c_{2013,i,r}$: regional specific costs for each feedstock i to be determined for the base year 2013 in each Federal State r (€/t)

- $c_{2013,i,national}$: national specific costs for each feedstock i determined for the base year 2013 according to [204] (€/t)

- $c_{2012,i,r}$: regional specific costs for each feedstock i determined for the base year 2012 in each Federal State r (€/t)[42]

- $c_{2012,i,moy}$: for each feedstock type, average value over all Federal State of the previously determined regional feedstock costs for the base year 2012 (€/t)

6.6.1.8 Estimation of electrical yields

In a further step the contribution of energy crop costs to the total electricity production costs should be determined. Therefore, the above-mentioned energy crop costs expressed in €/t should be converted into $\mathrm{ct/kWh_{el}}$ with

[42] Determined in sections 6.6.1.3 to 6.6.1.6.

the help of feedstock specific electrical yields in $\mathrm{kWh_{el}/t}$. For each of the energy crops feedstock the electrical yield in $\mathrm{kWh_{el}/t}$ is defined according to Eq. 6.17:

$$\mu_i = DM_i \times oDM_i \cdot (1 - L_i) \cdot v_{Biogas,i} \cdot \tau_{Methane} \cdot H_{g,Methane} \cdot e_{CHP} \tag{6.17}$$

With:

DM_i : Dry-Matter content in feedstock i (%)[43]

oDM_i : Organic Dry-Matter content in feedstock i (%)[43]

L_i : storage losses for feedstock i (%) [196]

$v_{Biogas,i}$: biogas yield for feedstock i ($m^3_{Biogas}/t_{FM,Feedstock,i}$)[43]

$\tau_{Methane}$: CH_4 content in the biogas produced from the valorization of feedstock i (%)[43]

$H_{g,Methane}$: methane gross calorific value (kWh/m^3)[44]

e_{CHP}: average CHP electric efficiency (%)[45]

The corresponding values of feedstock electrical yields are thus mentioned in Table A-14 of the Appendix.

6.6.1.9 Estimation of the energy crop costs contribution in the total electricity production costs from biogas

Following the general methodology and the assumptions made in the previous sections the contribution of the different energy crop costs to the total electricity production costs from biogas is estimated for the base year

[43] The corresponding numerical values for each feedstock are given in [162].
[44] The methane gross calorific heating value is to 9.97 $\mathrm{kWh/m^3}$ according to [151].
[45] An average CHP electric efficiency of 38% is assumed for the electrical yields determination.

2013. This contribution $C_{\mathrm{FeedstockCosts,2013,i,r}}$ can be expressed in each Federal State r as following (Eq. 6.18):

$$C_{FeedstockCosts,2013,i,r} = \sum_{i=1}^{4}\sum_{r=1}^{16}\frac{\varepsilon_{2013,i,r}\cdot p_{2013,i,r}}{\mu_i} \quad (6.18)$$

With:

$C_{FeedstockCosts,2013,i,r}$: contribution of the feedstock costs in the electricity production costs from biogas in the Federal State r (in ct/kWh_{el})

i: feedstock type

$\varepsilon_{2013,i,r}$: regional electric share of feedstock i (%)[46]

$p_{2013,i,r}$: regional specific costs for each feedstock i the base year 2013 in each Federal State r (€/t)

μ_i: electrical yields for feedstock i (kWh_{el}/t)

For each of the two agricultural biogas plants E an EM and in each Federal State r the numerical values of the energy crop costs contribution in the electricity production costs are set out in Figures A-13 and A-14 of the Appendix. In the case of E plant type, the energy crop costs contribution varies from 7.03 $\mathrm{ct/kWh_{el}}$ in the Federal State of Bavaria up to 10.88 $\mathrm{ct/kWh_{el}}$ in Brandenburg. The average energy crop costs contribution is estimated at about 9.01 $\mathrm{ct/kWh_{el}}$ for the base year 2013. The co-digestion of energy crops with manure in EM plants has the effect of lowering the costs contribution of energy crops in the electricity production costs as manure is available for free. In this case the average energy crop costs contribution for the year 2013 amounts about 7.94 $\mathrm{ct/kWh_{el}}$. The lowest costs contribution

[46] The regional electric share $\varepsilon_{2013,i,r}$ for energy crops feedstock i is defined as the ratio between the electricity flow amount Ei,r linked to a feedstock i in a region r and the total electricity amount for all energy crops in a region r.

is observed in Bavaria with 6.35 $\mathrm{ct/kWh_{el}}$ and reaches its maximum in the Federal State of Brandenburg with 9.79 $\mathrm{ct/kWh_{el}}$.

6.6.1.10 Energy crop costs forecast up to the year 2030

Forecasts for the previously determined energy crop costs contribution (in $\mathrm{ct/kWh_{el}}$) up to the year 2030 are then established for each Federal State. The high volatility relative to seed price leads to unpredictability in the energy crop costs forecasts [190]. In the forthcoming years a progressive introduction of agricultural residues in German biogas plants should occur. Simultaneously the future energy crops demand for biogas should slow-down mainly due to the subsidy cut related to energy crops valorization decided in the framework of EEG 2014. Agricultural residues are available for free on the site of the biogas plant and do not require transport costs. Their future increased use should reduce the volatility of energy crop costs. Considering all these aspects an energy crop costs stability[47] up to the year 2030 is assumed in the framework of a base scenario and in all Federal States. In addition to the analysis in the base scenario, energy crop costs shocks are carried out in the framework of a further scenario. More precisely an energy crop costs in-crease of +10% per year between 2020 and 2025 is considered (section 8.2).

6.6.2 Biomass feedstock transport costs

6.6.2.1 Energy crops transport costs

Biomass feedstock transport costs are influenced by three main parameters: the biomass type and feedstock physicochemical properties, the transport distance and the biomass collection radius. In a first step the biomass collection radius in km is defined for each of the feedstock types. In [205] a correlation between the total usable surface area for energy crops (ha) and

[47] This cost stability does not integrate the annual discount rate of 6% applied to all cost flows up to the year 2030.

the collection radius (km) from the biogas plant is provided and represented in Figure 6-7.

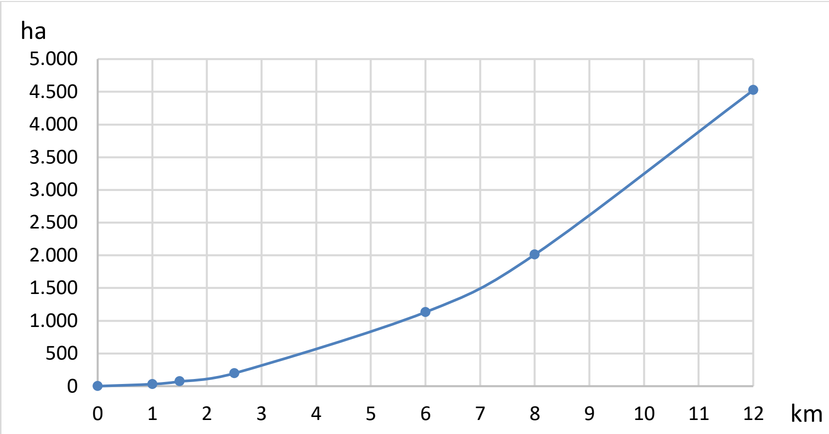

Figure 6.7: Usable surface area as a function of the transport distance [205]

Table 6-7 provides specific feedstock hectare yields and a typical feedstock mass repartition for 1 ha agricultural surface area. By combining this information with the results of Figure 6-7 a correlation between the usable feedstock mass and the transport distance can be established for each energy crops type (Figure 6-8).

Table 6.7: Specific hectare yields and mass repartition of energy crops for 1 ha surface area

	Hectare yields ($t_{Feedstock\ FM}$ / ha) [79]	Mass repartition according to [79]
Maize silage	50	73%
Grass silage	33	12%
Cereal silage	40	7%
Cereal grains	5.5	2%
Sugar beet, catch crop and miscellaneous agricultural feedstocks	65 (not taken into account in the calculations)	7% (not taken into account in the calculations)

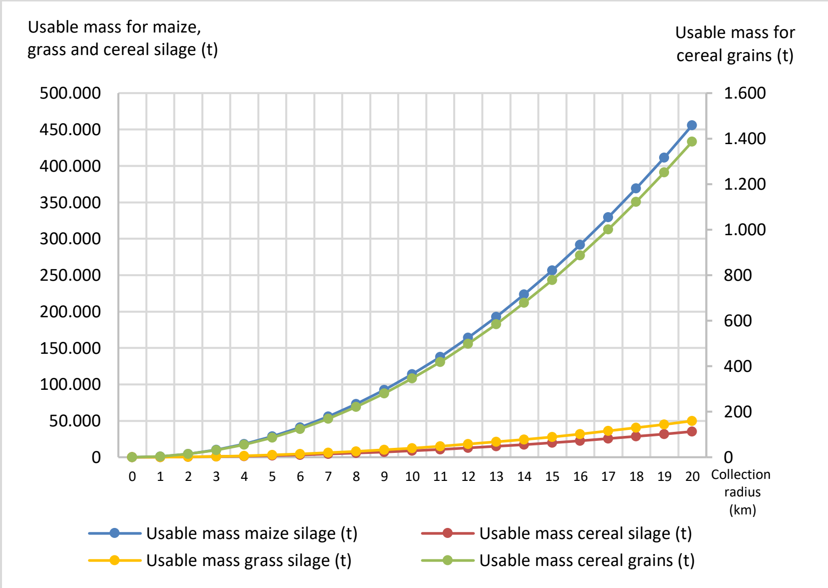

Figure 6.8: Usable mass amount for energy crops as a function of the collection radius [79], [205]

In a second step and according to [206], [207], [208] specific transport costs in €/t can be estimated as a function of the energy crops collection radius in km (Figure 6-9).

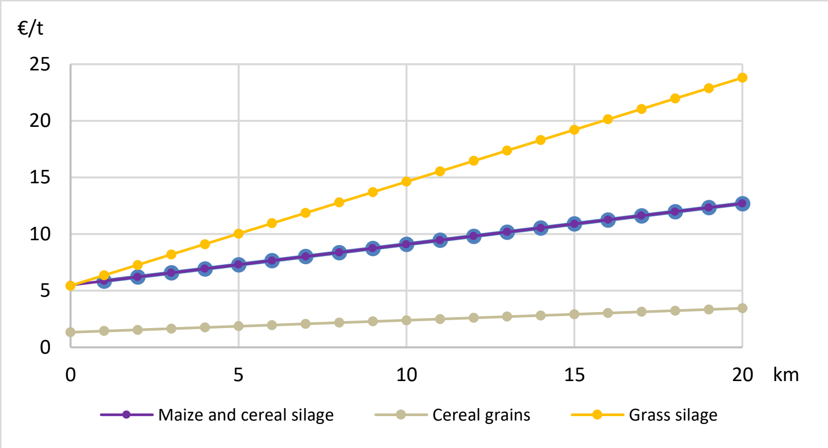

Figure 6.9: Specific biomass transport costs for energy crops as a function of the collection radius [206], [207], [208]

Only a single public study deals with the estimation of transport costs functions applied to grass silage for biogas in Germany [208]. In this study transport costs for maize silage have also been analysed and remain clearly lower than the transport costs for grass silage. This thus confirms the gap observed in Figure 6-9. For a given farm this study provides, assuming a transport distance of 5 km, grass silage costs of about 1.72 €/t and maize silage costs of about 1.02 €/t. The main driver explaining this difference seems to be linked to fixed costs. Biomass transport costs are made of variable machine costs, fixed costs and personnel costs. Total fixed costs can be split into fixed costs for machines and equipment and fixed costs for storage buildings. Fixed costs for storage buildings are similar for maize silage and for grass silage due to them having approximately the same feedstock density. The costs discrepancy can therefore be explained by the high investment in machines and equipment linked to grass silage. For grass silage specific annual depreciations of about 87.29 €/ha are already mentioned for the machines and equipment with 79.66 €/ha for tractors and 7.63 €/ha for rotary mowers [209]. In the case of maize silage, the total fixed costs amount to 82.45 €/ha

[210] which is lower than depreciations for machines and equipment relative to grass silage. The combination of the two correlations set out in Figures 6-8 and 6-9 finally provides for each feedstock type specific biomass transport costs (in €/t) as a function of the transported mass amount in t (Figure 6-10).

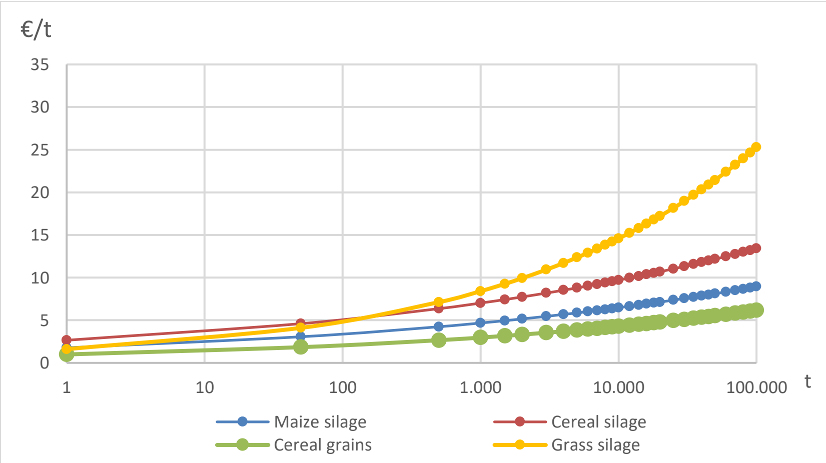

Figure 6.10: Specific biomass transport costs for energy crops as a function of the transported energy crops mass amount

6.6.2.2 Manure transport costs

As stated in section 6.6.1.2, about 12.7 million cattle and about 158,000 cattle farms were identified in Germany at the end of 2013 [211]. This corresponds to about 80 cattle per farm. Furthermore, the total manure mass produced by German cattle was estimated at about 154.9 million t in section 6.6.1.2. The cattle manure mass amount per km[48] is further determined in Table 6-8. The calculations are based on the total surface area of Germany, which is 357,000 km^2, and take into account a manure valorization factor of about 68% [212], [213].

[48] The collection radius r (in km) is linked to the surface area S (in km^2) by Eq. 6.19: $S = \pi . r^2$ (6.19)

Table 6.8: Assumptions relative to cattle manure feedstock in Germany

Number of cattle farms in Germany at the end of 2013 [211]	158,000
Germany's surface area (km^2) [212]	357,000
Number of cattle farms per km^2 in Germany	0.442
Total manure mass produced by German cattle at the end of 2013 (million t)	154.9
Manure valorization factor (%) [213]	68
Cattle manure mass amount per km in Germany (t/km)	522.9

Furthermore Figure 6-11 represents the manure transport costs as a function of the collection radius assuming a manure density of 1 kg/m^3 [214], [215].

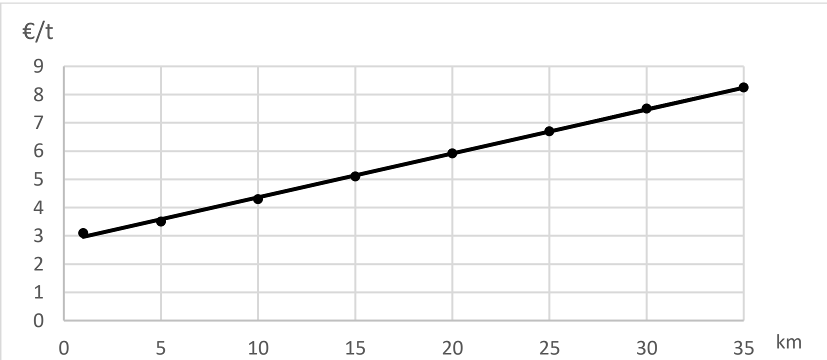

Figure 6.11: Specific manure transport costs as a function of the collection radius [214], [215]

As shown in Table 6-8, about 522.9 t of manure per km are assumed as specific manure mass amount in Germany. This value is further combined with the results of Figure 6-11. This leads to the determination of specific manure transport costs as a function of the manure amount transported (Figure 6-12).

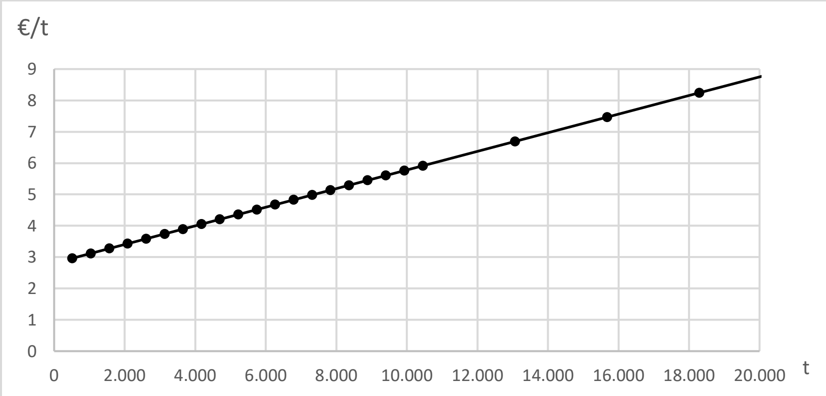

Figure 6.12: Specific manure transport costs as a function of the feedstock mass amount

6.6.2.3 Biowaste transport costs

In the case of biowaste four concentric zones are firstly defined according to various collection radiuses in km (Figure 6-13 and Table 6-9). In each zone population density (a1 to a4), biowaste per habitant amount (b1 to b4) and the maximal biowaste amount per zone ($\mathrm{m}_{1,\mathrm{max}}$ to $\mathrm{m}_{4,\mathrm{max}}$) are determined (Figure 6-13 and Table 6-9).

The population density in each zone is determined based on literature data in [216]. For each zone the biowaste per habitant amount is issued from a study published by the State Office for the Environment, Measurements and Nature Conservation of the Federal State of Baden-Württemberg (LUBW) [217].

The maximal biowaste amount contained in each zone is determined according to following equations system S1:

$$
\text{(S1)} \quad \begin{cases} m_{1,\max} = \pi \cdot a_1 \cdot b_1 \cdot 10^2 \\ m_{2,\max} = \pi \cdot a_2 \cdot b_2 \cdot (30^2 - 10^2) \\ m_{3,\max} = \pi \cdot a_3 \cdot b_3 \cdot (60^2 - 30^2) \\ m_{4,\max} = \pi \cdot a_4 \cdot b_4 \cdot (120^2 - 60^2) \end{cases}
$$

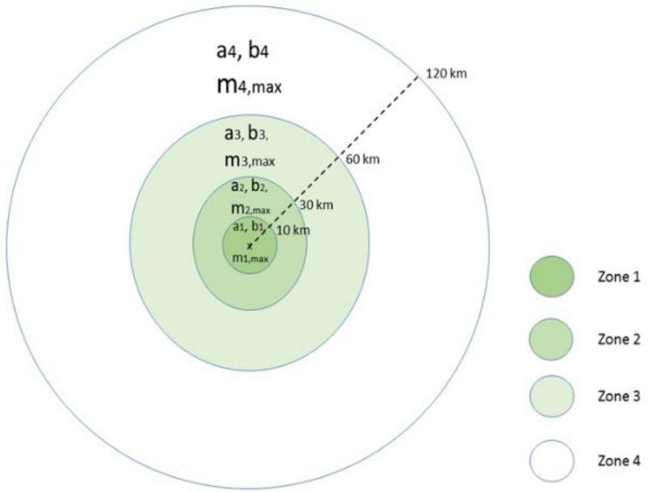

Figure 6.13: Biowaste collection zones (author's own representation)

In order to estimate the biowaste transport costs two functions are defined in Table 6-9 according to [218]. A first cost function covers the zone 1 (from 0 km to 10 km) and refers to the biowaste collection in close range and in the urban area. A second function is applied for zones 2, 3 and 4 and corresponds to a transport distance greater than 10 km in peri-urban and rural areas. Table 6-9 sums up the input data that have been assumed in order to estimate the biowaste transport costs.

Table 6.9: Collection radius, maximal amount per inhabitant and specific transport costs for biowaste

	Biowaste collection radius (km)	Population density (a_1 to a_4) in hab/km² [216]	Annually produced biowaste mass per inhabitant (b_1 to b_4) in kg/hab [217]	Calculated maximal biowaste amount per zone[49] ($m_{1,max}$ to $m_{4,max}$) in t	Specific biowaste transport costs C (€/t) as a function of the collection radius r (km)
Zone 1	0 to 10	1500	167	78,697	$C = 0.4 \cdot r + 1.5$ (6.20) [218]
Zone 2	10 to 30	300	107	80,676	$C = 0.8 \cdot r + 1.5$ (6.21) [218]
Zone 3	30 to 60	150	92.5	117,692	

In a zone i and based on the collection zones represented in Figure 6-12 the biowaste collection radius r_i can be expressed as a function of the transported biowaste amounts $m_{i,k}$ according to the following equations system (S2):

$$(S2)\quad \begin{cases} r_1 = \sqrt{\dfrac{m_{1,k}}{\pi \cdot a_1 \cdot b_1}} \\ r_2 = \sqrt{10^2 + \dfrac{m_{2,k} - m_{1,\max}}{\pi \cdot a_2 \cdot b_2}} \\ r_3 = \sqrt{30^2 + \dfrac{m_{3,k} - m_{2,\max} - m_{1,\max}}{\pi \cdot a_3 \cdot b_3}} \\ r_4 = \sqrt{60^2 + \dfrac{m_{4,k} - m_{3,\max} - m_{2,\max} - m_{1,\max}}{\pi \cdot a_4 \cdot b_4}} \end{cases}$$

[49] In a zone i the maximal biowaste amount $m_{i,max}$ is determined based on the maximal biowaste collection radius $r_{i,max}$, on the population density a_i and on the annually produced biowaste amount per inhabitant bi according to Eq. 6.22: $m_{i,\max} = \pi \cdot r_{i,\max}^2 \cdot a_i \cdot b_i$ (6.22)

By using the numerical values of Table 6-9 in each equation of (S2), correlation functions between the collection radius r_i in each zone i and the collected biowaste amount $m_{i,k}$ are obtained and represented in Figure 6-14.

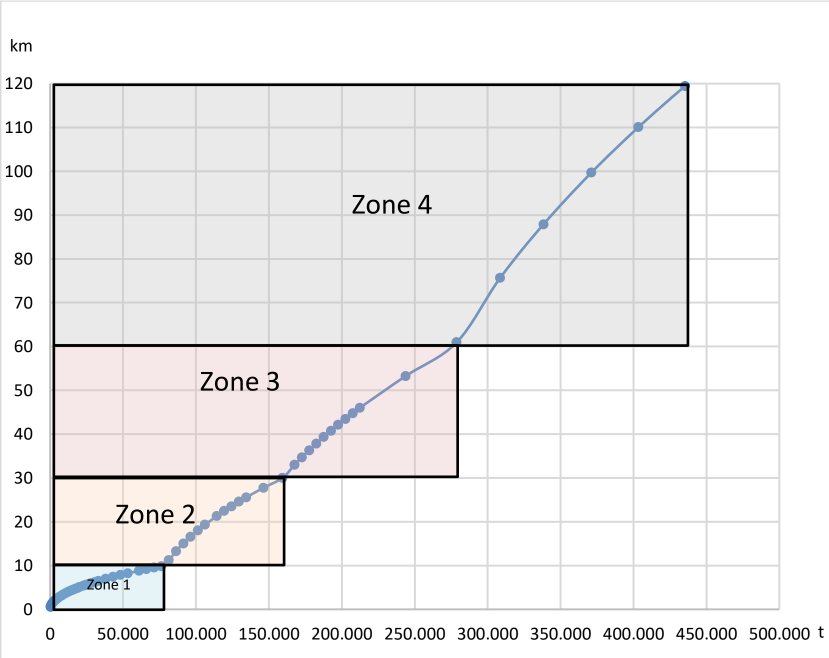

Figure 6.14: Biowaste collection radius as a function of the biowaste mass amount

Finally, by combining the results of Figure 6-14 with the costs functions of Eqs. 6.20 and 6.21 specific biowaste transport costs (in €/t) can be expressed as a function of the collected biowaste amount (in t) (Figure 6-15).

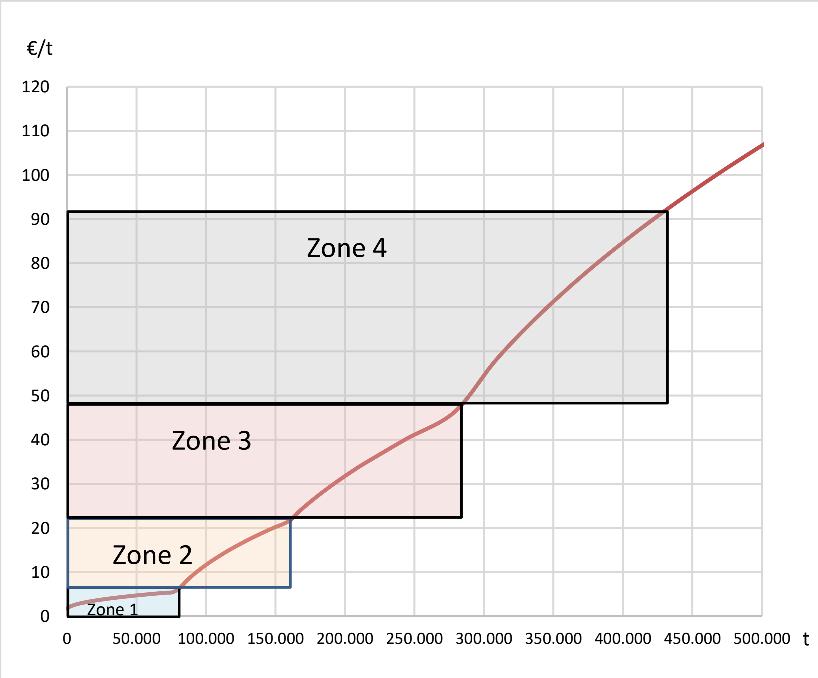

Figure 6.15: Biowaste transport costs as a function of the biowaste mass amount

6.6.3 Other operating costs

Other annual operating costs concern electricity consumption, process utilities, personnel, maintenance and digestate treatment costs. In order to estimate these costs positions the following assumptions have been made and are derived from literature sources and from biogas plant operator data (Table 6-10).

Table 6.10: Main assumptions related to electricity consumption, process utilities, personnel, maintenance and digestate treatment specific costs

	E Plant type	EM Plant type	B Plant type
Specific electricity consumption costs	Electricity price: 15.11 ct/kWh$_{el}$ in year 2013 and 15.23 ct/kWh$_{el}$ in year 2015 [12] Electricity own requirement rates in 2013: [219] - 0 to 75 kW$_{el}$: 10% - 75 to 150 kW$_{el}$: 6.9% - 150 to 500 kW$_{el}$: 7.2% - 500 to 1,000 kW$_{el}$: 7.9% - More than 1,000 kW$_{el}$: 8.7%		
Specific process utilities costs	10,000 €/a [75]		1.2 €/t for impurities elimination. Impurities correspond to 2% of the biowaste mass input which is valorized at 60 €/t [220]
Specific personnel costs	Data from biogas plant operators: Cost of 1 Full Time Employee (FTE): 30,000 €/a. 1 FTE employed from 0 to 750 kW$_{el}$ and 2 FTEs from 750 to 1,000 kW$_{el}$ From 1,000 to 6,000 kW$_{el}$: 1 supplementary FTE every 500 kW$_{el}$ From 6,000 to 10,000 kW$_{el}$: 1 supplementary FTE every 1,000 kW$_{el}$ From 10,000 to 20,000 kW$_{el}$: 2 supplementary FTEs every 1,000 kW$_{el}$		
Specific maintenance costs	Maintenance costs for existing and new CHPs in ct/kWh$_{el}$ as a function of electric power (Eq. 6.23) [150]: $C= 17.053.P^{-0.4782}$ (6.23) The maximal unit size of one CHP equals to 2,000 kW$_{el}$ (see Figure A-16 in the Appendix).		
Specific digestate treatment costs	0 €/t: digestate directly valorized on soils as a fertilizer by the farmer for its own exploitation.		44,6 €/t biowaste input [121]

In a further step Table 6-11 sums up the assumed annual evolution rate for each costs position up to the year 2030. The annual evolution for electricity consumption, process utilities, maintenance and digestate treatment costs is assumed to follow an average inflation rate set at 1% per year. According to [221] an average evolution rate of +3.6% concerning German salaries has been observed between the years 2015 and 2016. Technicians and workers are the most employed personnel category in biogas plants companies. For this reason, a lower evolution rate at about 2% has been assumed in the model as a conservative assumption for personnel costs. Investment-related costs are assumed to remain constant from a year to another. Biogas plants are supposed to represent a mature and established technology in Germany which is not subject to disruptive innovations. Finally, all biomass feedstock related costs, i.e., energy crop purchase and transport costs have been assumed as constant from a year to another. This costs stability is firstly explained by the progressive introduction of agricultural residues – available for free – in German biogas plants. Another aspect concerns the slow-down of the energy crops demand in the biogas sector due to the subsidy cut for energy crops valorization in the framework of the EEG 2014. Both of these aspects should thereby tend to stabilize future energy crop costs for biogas plants in Germany.

Table 6.11: Assumed annual evolution rates for each costs position up to the year 2030

Costs positions	Annual evolution of to the year 2030
Electricity consumption costs	+1% per year
Utilities process costs	+1% per year
Personnel costs	+2% per year
Maintenance costs	+1% per year
Digestate treatment costs	+1% per year
Investment-related costs	Assumed as constant up to 2030
Energy crop costs	Assumed as constant up to 2030 (base scenario)
Biomass transport costs	Assumed as constant up to 2030

6.7 Revenues estimation and forecast

Revenues for the operation of German biogas plants are issued from the sale of the electricity fed into the grid, from the valorizable heat sale issued from biogas combustion in CHPs, from the sale of the digestate as a fertilizer or compost and from the biowaste valorization into biogas.

6.7.1 Revenues from electricity sale

Based on the two operator models described in Figure 6-2 in section 6.2.2 following revenues are defined for the electricity sale (Table 6-12).

Furthermore, a flexibility supplement at 40 $€/kW_{el}$ aims to cover the investments in supplementary CHPs and gas storages.

Revenues from the FIT are assumed to decrease by 2% per year. In the case of the direct marketing model, it is assumed that plant operators sell the electricity produced at a price corresponding to the yearly average of monthly EPEX electricity prices in Peak time. According to [12] the average EPEX-Peak electricity price was 43.13 $€/\mathrm{MWh_{el}}$ for the year 2013 and 35.09 $€/\mathrm{MWh_{el}}$ for 2015. The evolution of these annual prices up to 2030 is based on a forecast from EWI Prognos and GWS published in 2014 [222]. The monthly average EPEX-Base electricity prices used for the calculation of the market premium are derived from the BDEW[50] annual report [12]. Average prices have been considered for the years 2013 and 2015 and amounted to 37.78 and 31.68 $€/\mathrm{MWh_{el}}$ respectively.

Table 6.12: Operator models for the calculation of electricity revenues

Model type	Model description
Model A according to EEG 2012	FIT without electricity direct marketing up to an installed power of 750 kW_{el}
	Electricity direct marketing with market AND flexibility premium for an installed power larger than 750 kW_{el}
Model B according to EEG 2014	FIT without electricity direct marketing up to an installed power of 100 kW_{el}
	For installations with an installed capacity larger than 100 kW_{el}, the electricity sale revenues can be split into: - A subsided part linked to 50% of the installed capacity - The 50% remaining capacity obtain revenues corresponding to the electricity sales price at the monthly average EPEX SPOT electricity price

[50] German Association of Energy and Water Industries

	Furthermore, a flexibility supplement at 40 €/kW_{el} aims to cover the investments in supplementary CHPs and gas storages.

6.7.2 Flexibility premium and supplement

The assumptions employed for the calculation of the flexibility premium in the context of EEG 2012 are mentioned in Table A-3 and A-4 of the Appendix. As a result, a constant value of 1.13 ct/kWh_{el} for each plant size over the electric capacity bandwidth [0:20,000 kW_{el}] is obtained. Under EEG 2014 framework the flexibility supplement amounts 40 $€/kW_{el}$ which corresponds to about 0.85 ct/kWh_{el}.

6.7.3 Revenues from heat sale

Beside electricity, heat represents another useful product of biogas combustion. It can be valorized in local heat sinks and in order to cover the plant's own thermal requirements. Taking into account monitoring reports published by the German biomass research center, external heat utilization rates to external heat sinks at levels of 56% and 57% are assumed respectively for the years 2012 and 2014 [223], [224]. The thermal own requirements rates set out in Table 6-13 are also taken into account [225], [226].

Table 6.13: Thermal own requirements rates for the years 2013 and 2015 [225], [226]

	Year 2013	Year 2015
0 to 70 kW_{el}	57%	52.1%
71 to 150 kW_{el}	36.4%	42.3%
151 to 500 kW_{el}	25%	27.3%

501 to 1,000 kW_{el}	23.9%	24%
More than 1,000 kW_{el}	16.9%	18.4%

Regarding economic aspects, the Working Group for Heat and Heating Economics published a price comparison for district heating in Germany. In 2011, the average district heating price in Germany was estimated at about 7.6 ct/kWh_{th}[227]. In [119] revenues for external heat sale and use of 5 ct/kWh_{th} were assumed. In the present work and for all biogas plants analysed, a value of 4 ct/kWh_{th}[51] is taken into account as conservative assumption. Assuming a future development of the market for renewable heat in Germany an annual increase of 2% per year up to 2030 has been further considered for the revenue from the external heat sale.

6.7.4 Revenues from digestate sale

Digestates can represent another source of revenues for biogas plant operators through the sale as fertilizer in the case of agricultural plants or as a compost for a biowaste plant. In the case of agricultural plants, no revenues related to the digestate sale are taken into account, as the digestate is supposed to be directly valorized by the farmer on his own land. For biowaste plants, revenues linked to the compost sold mainly depend on N-, P- and K-contents and prices and can vary strongly from one Federal State to another. In [228], an average compost price of 6 €/t for N- P- and K- is given for the area of Westfalen-Lippe, located in the Federal State of North Rhine-Westphalia. As no study mentioning regional compost prices currently exists, this value of 6 €/t is applied to all the Federal States. Finally, an annual

[51] The average revenue from heat sale is mentioned in ct/kWh_{th} and must be converted into the specific electric functional unit in ct/kWh_{el}. For this, mathematical functions linking thermal and electric yields to the electric capacities are determined according to values mentioned in Figure A.15 of the Appendix [150].

increase of 1% per year for the revenues from the digestate sale has been assumed up to 2030.

6.7.5 Revenues from biowaste valorization

Plant operators can receive, in addition to the electricity, heat and digestate revenues, municipal fee revenues for the valorization of biowaste into biogas. These fee revenues should in principle cover the costs associated with the digestate composting process, which follows the anaerobic digestion. The level of these revenues is very heterogeneous and can vary between 20 and 100 €/t [229]. It often remains confidential information, which is rarely published by plant operators. These specific revenues are moreover not directly linked to the plant location so that a regionalization at the Federal State level is currently not possible. Considering all these uncertainties factors an average fee revenue level of 60 €/t for the valorization of biowaste is assumed for all Federal States. Revenues for biowaste valorization are also assumed to increase by 2% per year up to 2030. This can be justified by a supposed increasing valorization of biowaste in biogas plants in the future.

6.8 Model input data uncertainties and plausibility

The main objective of model assumptions is to approximate as accurately as possible the economic and physical reality of the planning, construction, operation and maintenance of a biogas plant. Therefore, potential uncertainties concerning the employed numerical assumptions should be pointed out. A strong input data uncertainty can considerably impact the profitability calculations as well as further strategic decisions on a mid-term horizon. In this section a review of all the technical and economic uncertainties affecting biogas plants in Germany is carried out. Plausibility checks further ensure that the specified model input data is in line with reality.

Technical uncertainties apply to biomass feedstock parameters, operating hours for baseload and flexible CHPs, to the supplementary gas storage volume as well as to the existing biogas plant capacity and to biomass potentials for electricity production. Biomass feedstock parameters such as the methane yields and the methane content in the biogas produced are derived from standard literature data which limits data uncertainties. In the case of agricultural plants (E and EM) the feedstock shares in the biomass input mix have been set taking into account the maize silage and cereal grains cap introduced under EEG 2012 framework (60% maximal mass share in the total input mix). The defined apportionment of feedstock mass is considered as representative enough of standard agricultural biogas projects. Nevertheless, in practice the feedstock mass share can vary from one type of plant to another. In particular feedstock availability plays a major role in the input mix.

The assumed base-load hours, i.e., 8,000 h/a, appear to be quite representative of real plants [165]. The calculated operating hours for flexible capacity are however subject to uncertainty. In the present work the systematic approach of flexibility leads to a bias in the economic evaluation. In practice every single plant has its own operation and flexibility strategy. In this work most profitable plant sizes are thus determined under ceteris paribus conditions applied to flexibility. This enables a systemic assessment of all plant sizes and types.

Technical uncertainties linked to the estimation of current and future biomass potentials for electricity production at a regional scale are pointed out. These potentials are derived from a single literature source according to [132]. This source represents the only study quantifying, for each feedstock, regional technical biomass potentials dedicated to electricity production from biogas in Germany. Ideally a comparison with other assessments – if available – could have reduced the uncertainty level for this parameter.

A plant and size typology for existing biogas capacities has been determined on the basis of a data base containing 1,323 plants which is a representative sample of the whole plant park (about 8,900 plants by 2015). In this sample the capacity and plant distribution obtained has then been scaled up to the level of the whole biogas plant park, which appears as a suitable approach. The uncertainty level concerning the existing biogas plant portfolio remains then relatively low.

Economic uncertainties are linked to the estimation of electricity production costs and revenues in each biogas plant type and size. From the costs side, the first uncertainty concerns the calculation of regional energy crop costs. In the calculations, national average biomass feedstock costs have been first determined according to [204], [230] and further regionalized with the help of regional hectare yields and regional mass flows. These two last parameters have been established by a literature review and should thus only be seen as standardized values. Further parameters such as local soil quality, weather conditions, nutrient cycles, intensity of use of pesticides and cultivation techniques employed also have an impact on the hectare yields level. They could not however be assessed in the present work due to a lack of available regional data.

Furthermore, no study currently exists dealing with the systematic estimation of regional feedstock costs for maize silage, grass silage, cereal silage and cereal grains involved in German biogas plants. Methodological own assumptions have thus been made in order to determine each feedstock cost at a regional level (e.g., assumptions concerning the maize silage costs as a function of rapeseed costs or the relation between costs for cereal grains and cereal silage).

Moreover, effects of the international agricultural commodities markets are not taken into account which can lead to uncertainties. Indeed, the seed prices, for instance for corn and wheat, are set at the MATIF Commodities Exchange in Paris and represent a major driver for the energy crop costs paid by the biogas plant operator at the gate of anaerobic digesters. The high volatility of these prices leads to unpredictability in the energy crop costs forecasts. Regional energy crop costs have been assumed to remain stable up to the year 2030. This costs stability is firstly explained by the progressive introduction of agricultural residues – available for free – in German biogas plants. Another aspect concerns the assumed slow-down of energy crops demand in the biogas sector due to the subsidy cut for energy crops valorization in the framework of EEG 2014. Both of these aspects should therefore tend to stabilize future energy crop costs for biogas plants in Germany. The determined regional energy crop costs contribution for EM and E plant type remain in a cost bandwidth going from 6.35 to 10.87 $\mathrm{ct/kWh_{el}}$ (see section 6.6.1.9). Real data from the biogas measurement program II shows in Figure 3-11 that most of the electricity productions costs for agricultural plants vary between 15 and 20 $\mathrm{ct/kWh_{el}}$. The cost bandwidth for energy crops is then in line with real data as the energy crops cost generally represent between 40 and 60% of the total electricity production costs [231]. This validates the plausibility of the determined values for the regional energy crop costs contribution.

The second uncertainty concerns the estimation of plant specific investment and especially the assumed Multiplier Values. These values are derived from [187] and apply to microbial systems which represent a suitable modelling for biogas plants. Nevertheless, the multipliers determined correspond to an average of bandwidth values and can only be seen as approximations. A validation of the specific investment calculated is however possible based on a discrete evaluation of single biogas plants. In [232] several specific investments for biowaste and agricultural plants are mentioned. A biowaste plant located in Wicker and with an installed electric power of 1,300 $\mathrm{kW_{el}}$ is characterized by a total capital investment of about 16.4 € million which corresponds to a specific investment at about 12,600 $\mathrm{€/kW_{el}}$. Similarly, the biowaste plant in Alzey-Worms valorizes household kitchen biowaste and shows specific total investment of about 13,900 $\mathrm{€/kW_{el}}$ for a 900 $\mathrm{kW_{el}}$ installed capacity. In [117] specific investment of about 18,700 €/kWel is found for a 312 $\mathrm{kW_{el}}$ installation and in [118] a 1 $\mathrm{MW_{el}}$ plant shows specific investment at about 12,280 $\mathrm{€/kW_{el}}$. These specific investment values are in line with the correlation specified for biowaste plants in the simulation and optimization models (Figure 6-16). However, a larger data sample would be necessary in order to fully validate the estimated investment for biowaste plants. Only a few studies concerning the economic assessment of biowaste installations are available in the literature and data from plant operators is rarely published.

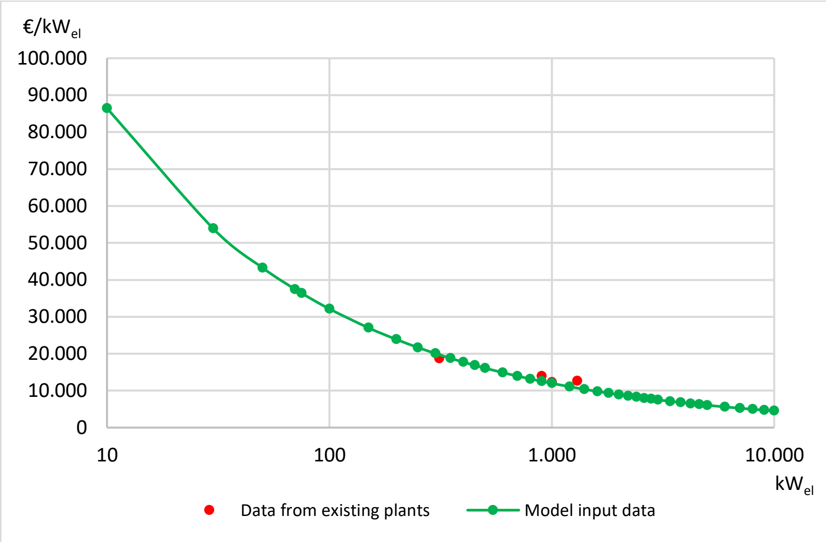

Figure 6.16: Specific investment for biowaste plants according to model input data and to data from existing plants [117], [118], [232]

The specific acquisition costs for agricultural plants can be compared to real values provided by German plant operators for 55 installations in the framework of the “Biogas Measurement Program II” [125]. The specific acquisition costs involved in the model data for agricultural biogas plants are in line with the values derived from the “Biogas Measurement Program II” (Figure 6-17).

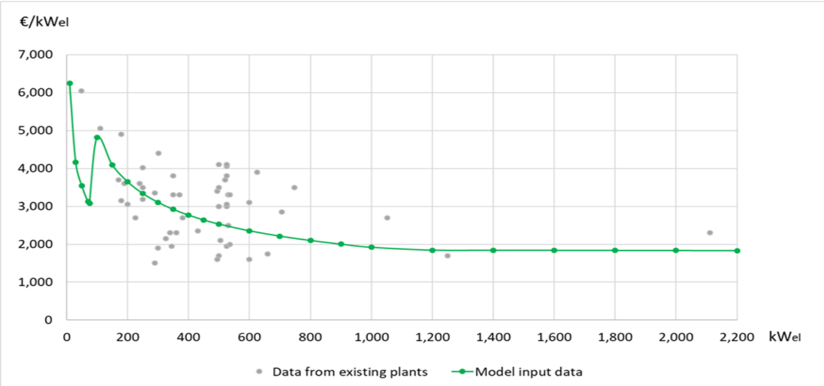

Figure 6.17: Specific acquisition costs for agricultural EM plants[52] according to model input data and to data from existing plants [125]

Additional investment-related costs result from investment in supplementary CHPs and gas storages. These costs are determined using correlations issued from [150] and [188]. Another uncertainty on the costs side concerns those for digestate treatment in biowaste plants. An average value of 44.6 €/t has been used according to [121] but in reality, this cost position can vary between 20 and 80 €/t. In order to quantify the impact of this volatility on plant profitability a sensitivity analysis has been realized in section 7.4.3 and includes the digestate treatment costs as one of the main profitability drivers. The correlations relative to biomass transport costs as a function of transport distance are drawn from literature data and can be found in [206], [207], [208], [215] and [218], which validates their plausibility and reduces the level of data uncertainty.

Costs for process utilities (use of water or anti-foam) are drawn from plant operator data and estimated as constant at about 10,000 €/a for all plant sizes and all plant types [75]. This simplification generates data uncertainty but has a low impact on plant profitability as the share of process utilities costs in

[52] Explanations justifying the visible gap observed in the acquisition costs when moving from 75 kW_{el} to 100 kW_{el} are available in section 6.5.1.

total electricity production costs is not significant. Personnel costs have been set according to plant operator data at a unitary FTE cost of 30,000 €/a. The number of FTE employed is further directly correlated to the plant capacity range. In practice it also depends on the fermentation and digestate treatment process complexity and is difficult to generalise. For this reason, the correlation between personnel costs and plant size involves uncertainties.

Maintenance costs for CHP are estimated as a function of the total installed electric power according to the correlation of ASUE mentioned in [150]. The number of maintained CHP units as a function of installed power is specified in Figure A-16 of the Appendix (own assumptions). A CHP unit size of 2,000 $\mathrm{kW_{el}}$ is assumed over the whole plant capacity bandwidth [0:20,000 $\mathrm{kW_{el}}$]. In practice a systematization and generalization of maintained CHP unit numbers as a function of total installed power appears to be difficult as it varies between plant operators. Thereby the correlation linking maintenance costs to installed electric power is subject to uncertainty. Finally, electricity consumption costs are determined on the basis of electricity own requirement rates [219]. The values assumed for electricity prices are 15.11 $\mathrm{ct/kWh_{el}}$ for 2013 and 15.23 $\mathrm{ct/kWh_{el}}$ for year 2015 according to [12]. Therefore, the specified input data regarding this cost position appears plausible and is subject to a low level of uncertainty.

In the present work it has been assumed that plant operators involved in the direct marketing model sell the produced electricity at a price corresponding to the yearly average of monthly EPEX electricity prices in Peak time. For the base year 2013, a price of 43.13 €/$\mathrm{MWh_{el}}$ has been taken into account and corresponds to the yearly average of all monthly EPEX electricity prices observed in peak time [12]. Similarly for the year 2015 the average EPEX price for the electricity sold is about 35.09 €/$\mathrm{MWh_{el}}$ in Peak time [12]. For comparison in [233], the revenue structure of 500 $\mathrm{kW_{el}}$ agricultural plant is detailed under the EEG 2014 framework. The electricity direct marketing model is considered there and three levels for the EPEX electricity price are assumed: 40, 50 and 60 €/$\mathrm{MWh_{el}}$. The EPEX price for the electricity sold thus represents a major uncertainty. The impact of this uncertainty is however quantified with the help of a sensitivity analysis in section 7.4. The calculation of the flexibility premium and supplement has been done according to the legal definitions of EEG 2012 and EEG 2014, which minimizes the uncertainty level for this revenue position. Eq. 3.2 has been used for the plants evaluated under EEG 2012 whereas 40 $€/kW_{el}$ is assumed according to EEG 2014 framework.

Another uncertainty concerns the level of municipal fee revenues for biowaste valorization into biogas. Only few assessments are available in the literature for this revenue position, which can vary between 0 and 120 €/t. An average value of 60 €/t has been assumed for all the calculations. The influence of this uncertainty has been further quantified using a sensitivity analysis realized for biowaste plants in section 7.4.3. Revenues from digestate sale are subject to a low uncertainty level as they have been derived from literature data in [228]. A last economic uncertainty concerns the valorization of the heat produced by the CHPs on the biogas plant location site. The revenues for heat sale considerably influence plant profitability and depend on the presence of local heat network infrastructures as well as on potential sinks (e.g., buildings located in the proximity of the plant). The revenues specified for heat sale are however in line with values from literature study according to [119]. In sections 7.4.2 and 7.4.3 a sensitivity analysis realized for E and B plants integrates the impact of a strong variation of heat sale revenues on the specific operating profit. This quantifies the degree of uncertainty for this revenue position. All required techno-economic data is summed up in Table 6-14 according to its uncertainty level[53]. The sensitivity analysis realized in section 7-4 quantifies the major uncertainties impacting plant profitability.

[53] In Table 6.14 the green colour corresponds to data with very low uncertainty level, whereas data with a more important uncertainty level are marked in orange. This classification aims to characterize the degree of uncertainty for all techno-economic input data.

Table 6.14: Uncertainty levels for all models input data

		Uncertainty level	Comment
Technical Uncertainties	Biomass feedstock properties		The uncertainty level results here from the systematic approach followed in this work. In practice plant specific operation strategies involving specific technical parameters should be considered.
	Operating hours for flexible CHP		
	Supplementary CHP size and gas storage volume		
	Existing biogas plant capacity		
	Biomass potentials for electricity production		The potentials have been derived from [132]. This source represents the only study quantifying, for each feedstock, regional technical biomass potentials dedicated to electricity production from biogas in Germany. Ideally a comparison with other assessments - if available - could have reduced the uncertainty level for this parameter.
Economic Uncertainties	Total capital investment		The impact of this uncertainty on profitability is quantified by a sensitivity analysis in section 7.4.
	Additional investment (flexibilization)		
	Energy crop costs		The impact of this uncertainty on profitability is quantified by a sensitivity analysis in section 7.4.
	Biomass feedstock transport costs		
	Electricity consumption costs		
	Process utilities costs		
	Personnel costs		
	Maintenance costs		The impact of these uncertainties on profitability is quantified by a sensitivity analysis in section 7.4.
	Digestate treatment costs		
	Revenues from electricity sale		
	Flexibility premium and flexibility supplement		
	Revenues from heat sale		The impact of these uncertainties on profitability is quantified by a sensitivity analysis in section 7.4.
	Revenues from biowaste valorization		
	Revenues from digestate sale		

Further uncertainties which are not involved in the input data perimeter should be pointed out. The first one relates to the legal frameworks that have been analysed. A continuation of the EEG 2012 and EEG 2014 legal frameworks up to the year 2030 has been taken into account in the optimization model in order to carry out the forecasts. In practice new legal frameworks will be enacted in the next ten years and then impact the development of biogas in Germany. Another uncertainty concerns the effects of potential disruptive innovations notably related to fermenters and to CHPs. Disruptive innovations could lead to an increase of plant efficiencies and to major electricity production costs decrease. These effects have not been integrated in the present work. It has been assumed that existing technologies for biogas production and valorization are well-established and mature so that they will not be displaced by new technologies.

6.9 Summary

This chapter describes the methodology and assumptions used for determining the input data for both the simulation and optimization models. In a first step the existing German biogas plant park has been estimated by the end of the year 2012. A discretization of the existing capacities into three plant types (EM, E and B) and 49 plant sizes has been realized. The second step of the model input data determination concerns the estimation of current and future potentials for electricity generation relative to each of the three above mentioned plant types. Existing potentials have been evaluated at the Federal State level and for each plant type on the basis of literature data. Future potentials for agricultural plants are directly correlated to the evolution of agricultural surface areas whereas future biowaste potentials are closely linked to the evolution of household biowaste mass amounts. Data related to existing biogas plant capacity is used by the optimization model which is described in chapter 5. In a further step costs and revenues input data is determined. Costs data is divided into investment-related costs and operating costs. The determined investment-related costs in $\mathrm{ct/kWh_{el}}$

consist of depreciations[54], imputed interests and insurance costs. Operating costs can be split into various positions and are expressed in €/t or in ct/kWh_{el} depending on if the cost position is linked to a mass or to an energy flow. Operating costs positions concern regional energy crop costs[55], biomass feedstock transport costs, as well as energy, process utilities, personnel, maintenance and digestate treatment costs. Revenues accrue from electricity, heat and digestate sales as well as from biowaste valorization. In the case of electricity sales two plant operator models are taken into account according to FIT subsidies from the EEG or following the electricity direct marketing model. Revenue assumptions for heat and digestate sales and for biowaste valorization are taken from literature data. In section 6.8 all uncertainties regarding model input data are pointed out. The main technical uncertainties concern the biomass feedstock properties, operating hours for flexible CHP, as well as supplementary CHP size and gas storage volume. Cost uncertainties mainly apply to investment-related, energy crop and digestate treatment costs. Revenue uncertainties mainly concern the EPEX price level for the electricity sold in the framework of the direct marketing model. Other revenue uncertainties are related to income from heat sales and biowaste valorization. The impact of the main cost and revenue uncertainties on plant profitability is further quantified using a sensitivity analysis in section 7.4.

[54] Depreciations have been linearly derived from the total capital investment over the whole investment lifetime. The total capital investment was estimated with the help of the Multiplier Values Method and relates to all main equipment acquisition costs.
[55] A dedicated methodology for estimating regional energy crop costs in each Federal State was developed and is presented in section 6.6.1.

7 Model-based analysis of current electricity production from biogas in Germany

The objective of this chapter is to present and analyse the results of the simulation model concerning current electricity production from biogas in Germany. The simulation model aims to identify the most profitable biogas plant sizes under various legal frameworks. These installations correspond to the plants showing the highest specific operating profit determined under a variable and differentiated biomass input mass flow. In section 7.1 correlations linking the electricity production costs and revenues to the installed electric power are established. They result from the combination of technical correlations obtained by the process simulation model in chapter 4 with the economic input data specified in chapter 6. In a further step correlation involving specific operating profits as a function of the installed electric power are then derived in section 7.2 under the legal frameworks of the EEG 2012 and EEG 2014. In each case the most profitable plant sizes are identified. The costs and revenues structure of these plant sizes is then assessed in section 7.3. A further sensitivity analysis realized in section 7.4 aims to identify and quantify the main profitability drivers. In section 7.5 a technical assessment of the most profitable plant sizes is carried out and has for objective to determine for each installation biological and global energetic efficiencies all along the biogas supply chain. A discussion of the methodology and results follows in section 7.6 emphasizing pros and cons of the simulation model employed. Based on the model results policy recommendations and strategic outcomes are then formulated for biogas plant operators and decision-makers in section 7.7. Chapter 7 ends with a summary in section 7.8.

7.1 Costs and revenues functions

The economic model input data described in chapter 6 is combined with the correlations derived from the process simulation in chapter 4. This provides costs and revenues functions linking each specific cost and revenues position, expressed in ct/kWh_{el}, to the electric installed power in kW_{el} (Figures 7-1 and 7-2). The results are shown for EM plants and analysed in the following. The results for E and B plants are mentioned in Figures A-17, A-18, A-19, A-20, A-21 and A-22 of the Appendix. Regarding the investment-related costs a first domain going from 0 to 75 kW_{el} can be defined and corresponds to small installations valorizing manure in mono-digestion processes. A gap in the specific investment-related costs is observed when moving from 75 kWel to 100 kW_{el}, due to a technological change for plants larger than 75 kW_{el}. Starting from 100 kW_{el}, manure is therefore valorized with energy crops in co-digestion plants which requires another fermenter type and generates higher specific investment[56]. Due to scale effect, a strong decrease of the specific investment-related costs occurs from 100 to 1,000 kW_{el}. Starting from about 2,000 kW_{el}, a stabilization is observed mainly due to the fact that supplementary fermenters and CHPs are required[57]. Specific maintenance costs for both baseload and flexible CHPs decrease for plant sizes up to 2,000 kW_{el}. For larger sizes costs stabilize as supplementary CHP gas engines are employed.

The evolution of specific personnel costs is characterized by size effects in each of the power ranges [0:75 kW_{el}] and [100:20,000 kW_{el}]. In the power range [0:75 kW_{el}] personnel costs correspond to 4% of the total capital investment according to [234]. Additional costs for laboratory analyses at 1,000 €/a are further considered [234].

In the case of EEG 2014 flexibilization costs of 40 €/kW_{el} apply starting from an installed capacity of 150 kW_{el}. These costs remain constant up to 20,000

[56] For more information see the evolution of the specific investment in Figure 6.6.
[57] The maximal unit size for one CHP is set in the present work at 2,000 kW_{el}.

kW_{el} at a value of about 1.13 ct/kWh_{el}. No biomass feedstock costs are related to small-scale manure plants inferior to 75 kW_{el} as no energy crops and only manure is valorized into biogas. Average energy crop costs of about 7.07 ct/kWh_{el} are taken into account starting from 100 kW_{el}[58] and remain stable all along the capacity bandwidth. Energy crop costs are then supposed to not be linked to the plant size but rather to the plant location, i.e., to the Federal States. This regionalization is further integrated in the optimization model developed at the Federal State level.

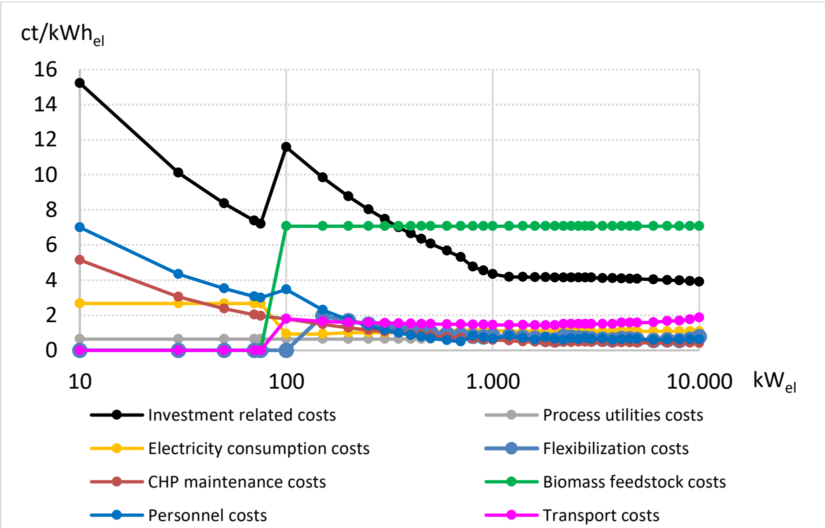

Figure 7.1: Specific annual costs for EM plants as a function of the electric power for the base year 2015 and under EEG 2014

The specific revenues for electricity sale can be divided into the EEG-subsidies, the EPEX monthly average and the EPEX-Peak electricity sale price accrued from electricity direct marketing. Their evolution is represented in Figure 7-2. For small-scale manure plants with an installed power between 0

[58] This energy crop costs value represents the average of all regional energy crop costs determined for the base year 2015 for EM plants (see section 6.6.1.9).

and 75 $\mathrm{kW_{el}}$ no direct electricity marketing model is considered. Plant operators thus receive a constant revenue level of 23.53 $\mathrm{ct/kWh_{el}}$ for the produced electricity according to [106]. For plants larger than 75 $\mathrm{kW_{el}}$ the subsidy cut for energy crops and manure applies. This explains the strong variation for the specific electricity sale revenues visible on Figure 7-2. The electricity direct marketing model applies starting from 100 $\mathrm{kW_{el}}$ with an EPEX-Peak electricity price at about 43.13 $\mathrm{€/MWh_{el}}$ and a monthly average EPEX-Base electricity price at about 31.68 $\mathrm{€/MWh_{el}}$ [12]. Specific revenues from heat sale slightly increase with the plant size. Thermal own requirements decrease with the plant size which implies an increase of the valorization rate for the produced heat and consequently of the specific heat sale revenues. Specific revenues for digestate sale are assumed to remain stable at 6 €/t according to [228]. The conversion of this value in $\mathrm{ct/kWh_{el}}$ implies a slight revenue decrease as the plant size increases. This is justified by an increase in plant electric efficiency with plant size [150]. Finally, the flexibility supplement amounts to 40 $\mathrm{€/kW_{el}}$ for plants larger than 150 $\mathrm{kW_{el}}$ and remains stable as the operating hours of flexible installations stays constant at about 4,713 h/a.

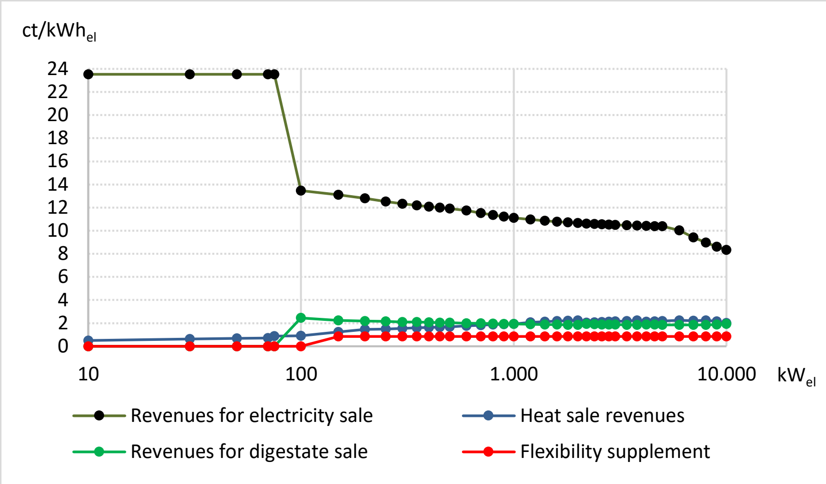

Figure 7.2: Specific annual revenues for EM plants as a function of the electric power for the base year 2015 and under EEG 2014

The evolution of total specific revenues and total specific electricity production costs is represented in Figure 7-3. This leads to the identification of profitability and unprofitability domains[59]. “Breakeven points” are determined in cases where specific revenues are equal to the electricity production costs. The results of Figure 7-3 show that for EM plants specific electricity production costs remain higher than the specific revenues starting from 75 kW_{el}. No profitable operation for the EM plants is possible above this capacity size.

59 A profitability domain corresponds to the case where specific revenues are higher than specific electricity production costs. An unprofitability domain refers to the case where specific electricity production costs are higher than revenues.

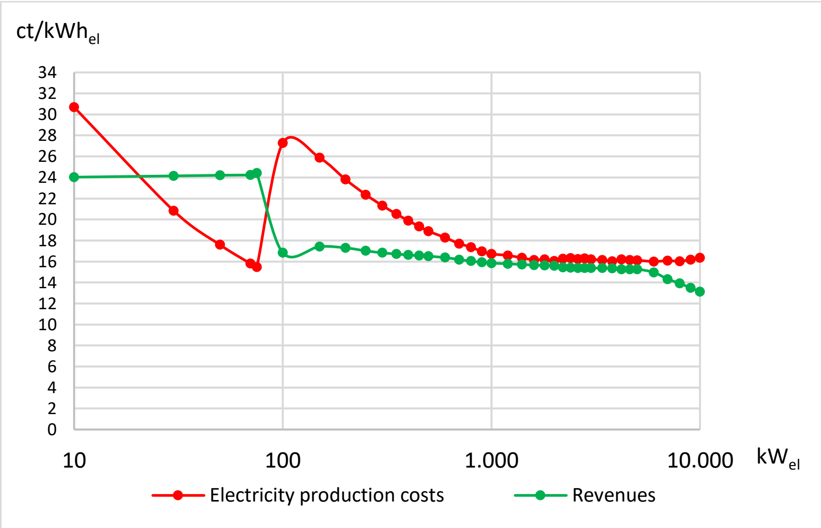

Figure 7.3: Specific electricity production costs and revenues for EM plants as a function of the electric power for the base year 2015 and under EEG 2014

7.2 Identification of most profitable plant sizes

Based on the previously described input data and methodology, the model results are presented under EEG 2012 and EEG 2014 frameworks. In each case the evolution of the specific operating profit as a function of the installed electric power is shown. Most profitable plant sizes can be identified and correspond to the highest specific operating profit values. The costs and revenues structure for the most profitable plant sizes is then assessed. In addition, sensitivity analyses quantify in each case the impact of the main fundamental drivers on biogas plants profitability.

7.2.1 Results under the EEG 2012 framework

The results under the EEG 2012 framework are illustrated in Figure 7-4. Small-scale manure plants, with an installed electric power lower than 75 kW_{el}, appear there as the most profitable option. This plant type shows the highest specific operating profit at about 10.85 ct/kWh_{el}. For plant sizes up to 900 kW_{el} the co-digestion of energy crops with manure systematically leads to the highest profitability. Starting from 900 kW_{el} biowaste plants turn out to be the most economically attractive option. A maximal specific operating profit at about 9.29 ct/kWh_{el} for a 3,000 kW_{el} installation is thereby reached. Finally, the valorization of energy crops in mono-digestion plants remains the least profitable alternative. The operating profits are in that case less than 4 ct/kWh_{el} and become negative above 7 MW_{el} of installed electric power.

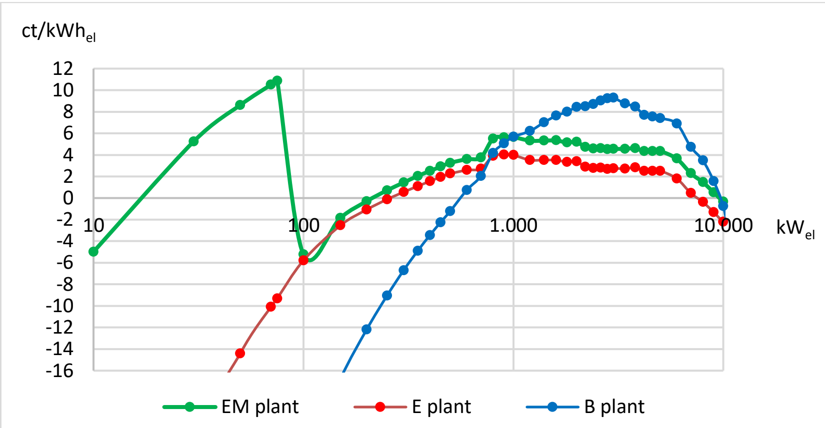

Figure 7.4: Plant specific operating profit as a function of the electric power for the base year 2013 and under EEG 2012

7.2.2 Results under the EEG 2014 framework

Under EEG 2014 energy crops and manure co-digestion plants display the highest specific operating profits up to an installed power of 550 kW_{el} (Figure

7-5). For larger capacities biowaste plants become the most profitable installation type. A maximal specific operating profit at about 6.54 $\mathrm{ct/kWh_{el}}$ for a 3,000 $\mathrm{kW_{el}}$ plant is reached in this case. Manure plants, smaller than 75 $\mathrm{kW_{el}}$, do remain the most economically attractive installation type with a corresponding maximal operating profit of about 8.95 $\mathrm{ct/kWh_{el}}$. Agricultural plants larger than 75 $\mathrm{kW_{el}}$ using energy crops with manure in co-digestion or employing energy crops in mono-digestion processes are then analysed. These plants appear as unprofitable over the whole capacity bandwidth, i.e., from 0 to 20,000 $\mathrm{kW_{el}}$. This unprofitability mainly results from the energy crops subsidy cut which was defined in the framework of EEG 2014.

Figure 7.5: Plant specific operating profit as a function of the electric power for the base year 2015 and under EEG 2014

As a result of the simulation model following most profitable plant types and sizes can be identified (see Table 7-1).

Table 7.1: Most profitable plant types and sizes under EEG 2012 and EEG 2014 frameworks

	Plant type	Most profitable size (kW_{el})	Corresponding specific operating profit (ct/kWh_{el})
EEG 2012	Plant B	3,000	9.29
	Plant EM	75 (small manure plants)	10.85
	Plant E	900	4.01
EEG 2014	Plant B	3,000	6.54
	Plant EM	75 (small manure plants)	8.95
	Plant E	2,000	-0.97

From EEG 2012 to EEG 2014 a profit loss of -2.75 ct/kWh_{el} is observed for the most profitable B plant size. This is mainly due to lower electricity sale revenues observed in the year 2015 than in 2013. A drastic profitability loss of -4.98 ct/kWh_{el} is observed from the EEG 2012 to EEG 2014 for E plants due to the energy crops subsidy cut enacted by the German Federal Government. Finally, a slight profitability loss of -1.9 ct/kWh_{el} between the two EEG versions applies to small manure plants characterized by a size of 75 kW_{el}. This installation type remains however profitable with a specific operating profit close to 9 ct/kWh_{el} under EEG 2014. The results show that the EEG 2014 framework is generally less economically favourable than the version of 2012.

7.3 Costs and revenues structure

The most profitable plant sizes for each installation type are economically assessed in the framework of a costs versus revenues analysis. For a given plant type and size all specific costs and revenues positions involved are detailed and compared with each other. This enables the identification of major costs and revenues drivers impacting the plant profitability. The results are shown below for each plant type exemplarily under the EEG 2014 legal framework.

7.3.1 Energy crops and manure plants

Under EEG 2014, the most profitable capacity size for EM plants is 75 $\mathrm{kW_{el}}$. Investment-related costs are in that case the main driver in the total electricity production costs with a contribution at about 7.2 $\mathrm{ct/kWh_{el}}$ (Figure 7-6). The other main costs positions are personnel, electricity consumption and CHP maintenance costs. These costs positions have been estimated at about 3 $\mathrm{ct/kWh_{el}}$, 2.67 $\mathrm{ct/kWh_{el}}$ and 1.96 $\mathrm{ct/kWh_{el}}$ respectively on the basis of the correlations in Figure 7-1. Costs for utilities only play a minor role with a contribution lower than 1 $\mathrm{ct/kWh_{el}}$. About 96% of the total revenues comes from electricity sale and is estimated at about 23.53 $\mathrm{ct/kWh_{el}}$ The other revenue position corresponds to heat sale estimated at about 0.88 $\mathrm{ct/kWh_{el}}$. Total electricity production costs for the most profitable EM plant size amount to 15.47 $\mathrm{ct/kWh_{el}}$ and the corresponding specific operating profit is determined at a value of 8.95 $\mathrm{ct/kWh_{el}}$.

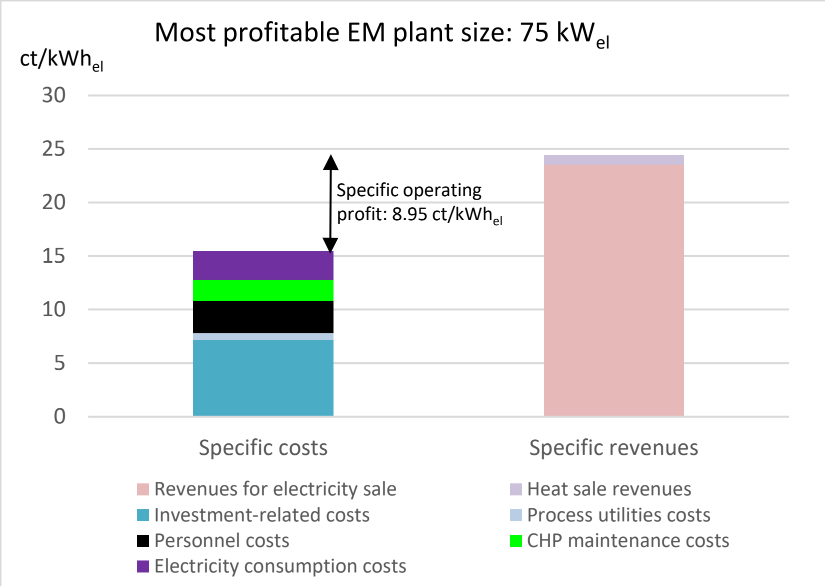

Figure 7.6: Costs versus revenues for the most profitable EM plant size under EEG 2014

7.3.2 Energy crops plants

In the case of energy crops mono-digestion the main costs positions are represented by the biomass feedstock costs (8.05 $\mathrm{ct/kWh_{el}}$) and by the investment-related costs (3.93 $\mathrm{ct/kWh_{el}}$) (Figure 7-7). The costs for utilities, personnel, maintenance, biomass transport and the costs for flexible electricity production only play a minor role in the economic balance. From the revenues side the main contributors are the electricity sale with about 10.62 $\mathrm{ct/kWh_{el}}$ and the heat sale generating a specific revenue of 2.25 $\mathrm{ct/kWh_{el}}$. Revenues for digestate sale and from the flexibility supplement have a low influence on the plant profitability. The electricity production costs for the most profitable plant size are estimated at about 16.19 $\mathrm{ct/kWh_{el}}$. A corresponding negative specific operating profit is therefore observed at a level of -0.97 $\mathrm{ct/kWh_{el}}$.

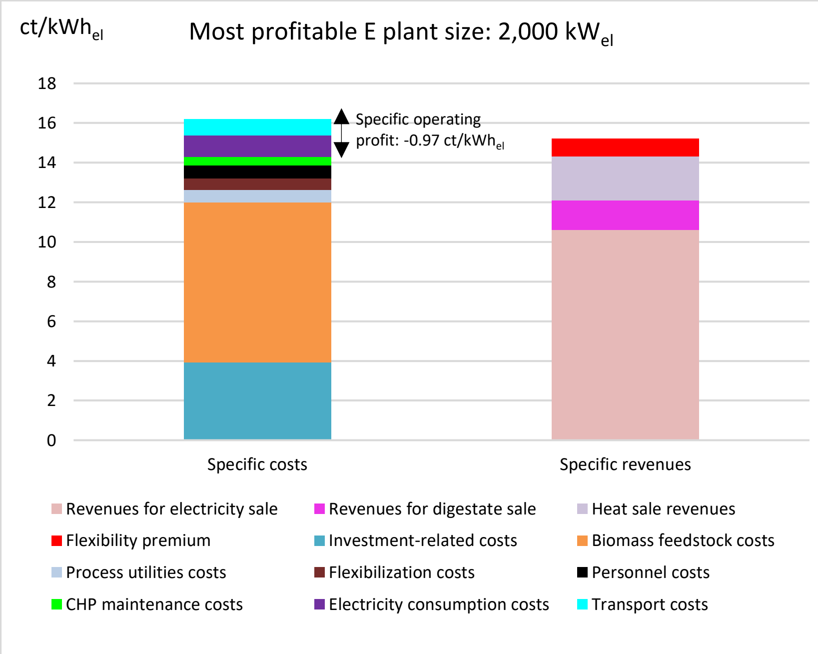

Figure 7.7: Costs versus revenues for the most profitable E plant size under EEG 2014

7.3.3 Biowaste plants

As shown in Figure 7-8, the electricity production costs for the most profitable biowaste plant size are mainly driven by the digestate treatment costs (11.89 ct/kWh_{el}) and by the investment-related costs (8.54 ct/kWh_{el}). The costs positions for maintenance, process utilities, electricity consumption, personnel, biomass transport and for flexible electricity production only play a minor role. The main revenues positions concern the fee revenue for biowaste valorization into biogas (17.62 ct/kWh_{el}) and electricity sale (10.6 ct/kWh_{el}). Revenues from compost and heat sale and from the flexibility premium only have a small influence on the plant profitability. The electricity production costs for the most profitable biowaste plant size amount approximatively to 25.64 ct/kWh_{el}. A corresponding specific operating profit of about 6.54 ct/kWh_{el} is determined.

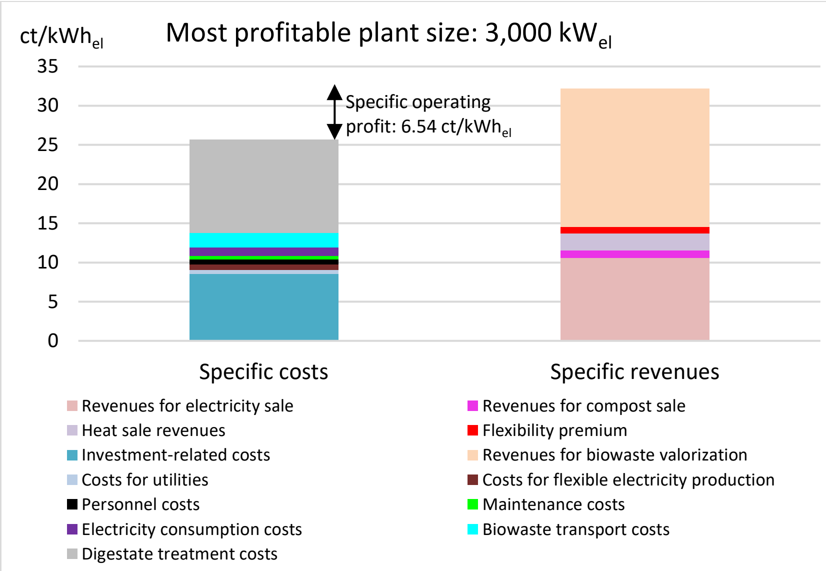

Figure 7.8: Costs versus revenues for the most profitable B plant size under EEG 2014

7.4 Sensitivity analysis

A sensitivity analysis aims to quantify the impact of a variation of the main cost and revenue drivers on biogas plant profitability. The results are represented for each plant type in Figures 7-9, 7-10 and 7-11. The specific operating profit values are represented on the ordinate-axis as a function of the variation rate of main profitability drivers on the abscissa-axis (in %).

7.4.1 Sensitivity analysis for energy crops and manure plants

The impacts of a variation of main profitability drivers on EM plant profitability are visible in Figure 7-9. The revenues from the electricity sale and the investment-related costs have the highest influence. For example, a decrease of about -20% of the revenues for the electricity sale leads to a profit-ability loss of about 4.8 ct/kWh_{el}. An increase of 40% of the investment-related costs leads to a profitability loss of almost 3 ct/kWh_{el}.

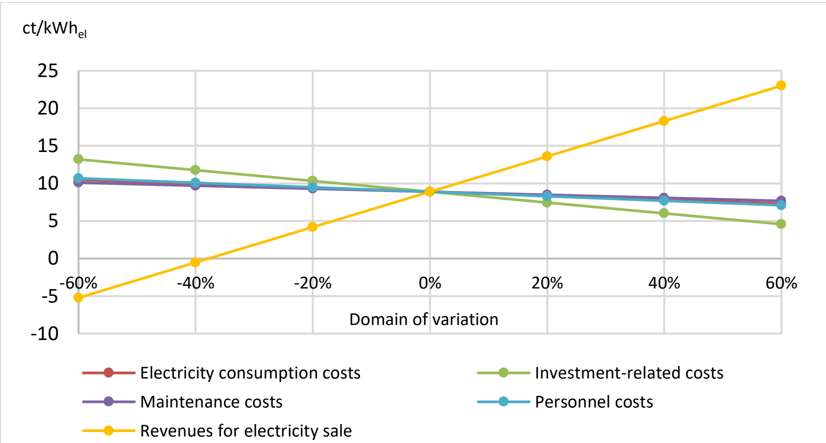

Figure 7.9: Sensitivity analysis for the most profitable EM plant size under EEG 2014

7.4.2 Sensitivity analysis for energy crops plants

For the most profitable E plant size an increase of about 30% of the EPEX-Peak electricity price leads to a profitable situation. Similarly, a decrease of -13% of the energy crop costs generates a positive specific operating profit. Finally, if the investment-related costs decrease by about -20%, then the E plant becomes profitable (Figure 7-10).

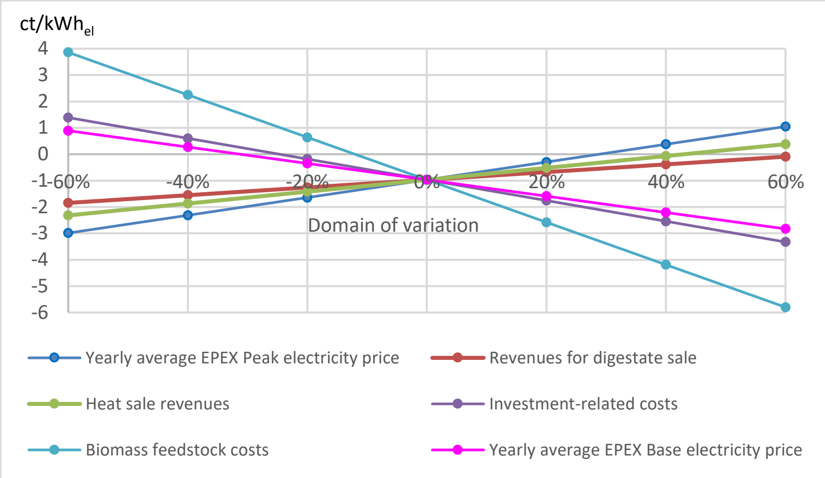

Figure 7.10: Sensitivity analysis for the most profitable E plant size under EEG 2014

7.4.3 Sensitivity analysis for biowaste plants

The profitability of biowaste plants is mainly driven by revenues for biowaste valorization, by the investment-related costs and by digestate treatment costs. A decrease of about 38% in the revenues for biowaste valorization would lead to unprofitability. If the investment-related costs are lowered by about -40% then the biowaste plant benefits from a specific operating profit increase of about 3.4 $\mathrm{ct/kWh_{el}}$. Finally, an increase of about 55% of the digestate treatment costs would create an unprofitable situation (Figure 7-11).

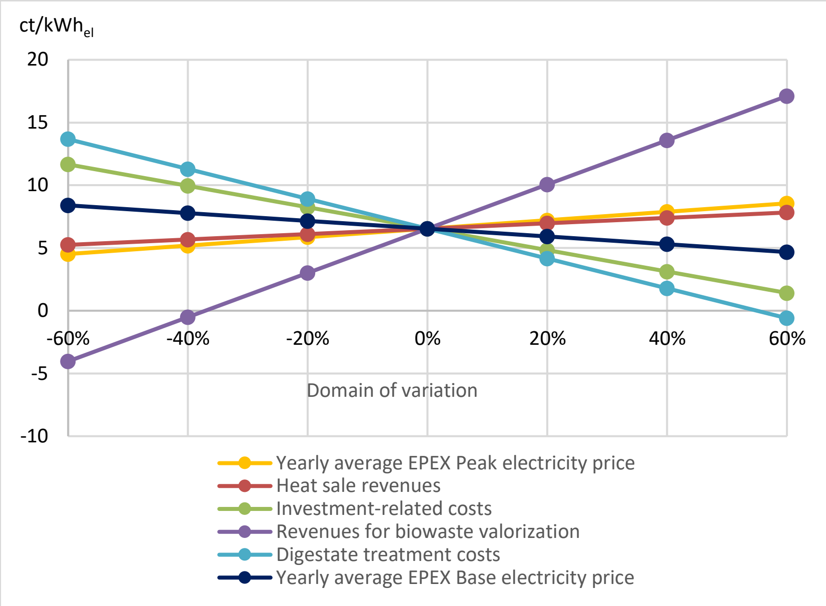

Figure 7.11: Sensitivity analysis for the most profitable B plant size under EEG 2014

7.5 Technical assessment

The aim of this section is to assess the energetic efficiency of the most profitable biogas plant sizes that have been previously analysed. In the planning and design phases of a biogas installation project the plant energetic efficiency calculation appears to be an important step. It enables the identification of energetically optimal plant concepts. For this the biological efficiency, related to the anaerobic digesters, and the fuel efficiency have to be determined. The chemical energy amounts contained in the biomass feedstock and in biogas are first estimated. This estimation is based on feedstock lower heating values drawn from literature data and on the input and output mass and volume flows from the simulation model. The biological efficiency, characterizing the energetic efficiency of the anaerobic digestion process, is then determined following Eq. 7.1.

$$\eta_{Biol} = \frac{E_{ChemBiogas}}{E_{ChemFeedstock}} = \frac{\dot{V}_{Biogas} \cdot H_{g,Biogas}}{\dot{m}_{Feedstock} \cdot H_{l,Feedstock}} \tag{7.1}$$

With:

$E_{ChemBiogas}$: chemical energy contained in the produced biogas (kWh)

$E_{ChemFeedstock}$: chemical energy contained in the biomass feedstock (kWh)

$\dot{V}_{Biogas}$: annual biogas output volume flow (m^3/a)

$H_{g,Biogas}$: biogas gross calorific value (kWh/m^3)

$\dot{m}_{Feedstock}$: annual biomass feedstock input (t/a)

$H_{l,Feedstock}$: biomass feedstock lower heating value (kWh/t)

In the case of the most profitable EM plant size employing about 10,270 t/a of manure in mono-digestion the biogas produced amounts about 0.32 million m^3/a and a biogas gross calorific value of 5.48 $\mathrm{kWh/m}^3$ [60] is assumed. The lower heating value for manure is estimated at about 0.72 MJ/kg according to [235] on the basis of 70.3% moisture content. For the most profitable biowaste plant size, about 9.19 million m^3 biogas is produced annually from the fermentation of 74,750 t/a of biowaste and the biogas gross calorific value amounts in that case to 5.98 $\mathrm{kWh/m}^3$ biogas. The biowaste lower heating value is estimated at about 5 MJ/kg i.e., 1,389 kWh/t [236]. At the gate of the fermenter about 35,421 t agricultural feedstock are

[60] The biogas gross calorific value is derived from the one of natural gas (9.97 $\mathrm{kWh/m}^3$) and from the methane content in biogas. The methane content assumed for each feedstock can be found in Table 6.1.

transformed annually into 7.78 million m^3 biogas in the most profitable E plant size. The biogas gross calorific value amounts there to 5.28 $\mathrm{kWh/m}^3$ and the energy crops lower heating has been estimated at about 6.61 MJ/kg[61] i.e. 1,836 kWh/t.

The fuel efficiency in then given by Eq. 7.2:

$$\eta_{Fuel} = \frac{EL_{Brutto} - R_{el,own} + Q_{useful}}{E_{chem,Biogas}} \qquad (7.2)$$

With:

- EL_{Brutto}: Gross electricity amount (kWh_{el})

- $R_{el,own}$: electrical own-requirements (kWh_{el})

- Q_{useful}: useful CHP-heat (kWh_{th})

- $E_{chem,Biogas}$: chemical energy contained in the burned biogas (kWh)

The following electric and thermal efficiencies, and external heat use rates are further assumed for the most profitable sizes according to [150], [224], [226] (Table 7-2).

[61] The fermenter input mix of the most profitable E plant size is made up of 20,544 t/a maize silage, 7,084 t/a grass silage, 7,084 t/a cereal silage and 708 t/a cereal grains. The energy crops lower heating values correspond to 6.7 MJ/kg for maize silage [237], 6.1 MJ/kg for grass silage [238], 6.2 MJ/kg for cereal silage [239] and 13.1 MJ/kg for cereal grains [240].

Table 7.2: Assumed electric and thermal efficiencies and external heat use rates [150], [224], [226]

Plant Type	Most profitable plant size	Electric CHP efficiencies[62]	Thermal CHP efficiencies	Electric own requirements	Thermal own requirements	Rate for external heat use
EM	75 kW_{el}	34.47%	51.76%	6.1%	42.3%	57%
B	3,000 kW_{el}	Existing: 42.4% New flexible: 39.47%	41%	7.1%	18.4%	57%
E	2,000 kW_{el}	Existing: 42.69% New flexible: 39.75%	40.65%	7.1%	18.4%	57%

The gross electricity amount is determined for base-load existing CHPs with 8,000 full-load hours per year and for the new flexible CHPs running about 4,713 h/a[63]. The useful heat corresponds to the share of the produced heat which is finally used by external heat sinks (and not for plant own requirements).

The global efficiency of each plant can be thus derived from Eq. 7.3:

$$\eta_{Global} = \eta_{Biol} \cdot \eta_{Fuel} \tag{7.3}$$

Table 7-3 sums up the results from the energetic assessment for the most profitable plant sizes.

[62] Electric CHP-efficiencies for most profitable plant sizes have been determined based on the values set out in Figure A-15 in the Appendix for both existing base-load and new flexible capacities.

[63] Flexible CHP are assumed to run at 4,713 h/a according to the value given in Table A.3 in the Appendix.

Table 7.3: Results from the energetic assessment of agricultural and biowaste plants

Plant type	Input feedstock mass (t/a)	Biogas volume flow (million m^3/a)	Electricity and useful heat amount	Plant size (kW_{el})	Biological efficiency (%)	Fuel efficiency (%)	Global plant energetic efficiency (%)
EM	10,270	0.32	Gross electricity production 0.6 GWh_{el} Useful heat amount 0.29 GWh_{th}	75	85.4	49.4	42.2
B	74,750	9.19	Gross electricity production 23.34 GWh_{el} Useful heat amount 10.59 GWh_{th}	3,000	52.9	58.7	31
E	35,421	7.78	Gross electricity production 15.56 GWh_{el} Useful heat amount 7 GWh_{th}	2,000	63.2	52.2	32.9

The results of Table 7-3 related to the technical assessment of most profitable plant sizes indicates that small-scale manure installations are the most energetically efficient plants. These outcomes should be however considered with caution as the energetic plant concept can strongly vary from an installation to another (e.g., regarding heat valorization strategies or energy own requirements). For comparison in [241] a 500 kW_{el} biogas plant valorizing maize silage and wheat shows a global energetic efficiency of about 39%. In [242] a 760 kW_{el} plant using biowaste with sewage sludge has a global energetic efficiency of about 32%. Finally, in [243] a 250 kW_{el} agricultural plant employing maize in mono-digestion has a global energetic efficiency estimated at about 20%.

7.6 Discussion of methodology and results

7.6.1 Methodology

The objective of the simulation model is to identify the most profitable biogas plant sizes under a variable and differentiated biomass feedstock input. In order to achieve this an economic assessment coupled to a process simulation is carried out. After a calibration step of all components of the biogas plant a simulation of plant profitability is realized under a variation of the biomass input mass flow. This enables the identification of plant sizes showing the highest specific operating profit values (defined as the most profitable plant sizes). This simulative approach has pros and cons which are analysed in detail in the following.

Positive aspects concerning the methodology employed are firstly linked to fermenter calibration. Before launching the simulations, fermenters were calibrated by specifying methane formation rates for each plant type in the SuperPro Designer interface. These rates lead to specific biogas yields in line with the values defined in the German Biomass Ordinance and used in order to determine the EEG subsidies. Consequently, the underlying model for biogas production corresponds to the economic reality defined by the German Biomass Ordinance. A second aspect concerns the choice of the simulation variable represented by the biomass input mass flow. Biomass input mass flows are generally the main entry parameter for a basic biogas plant design. They have a direct influence on the biogas plant size and consequently on the installation profitability. They represent thus an adequate simulation variable in order to identify most profitable biogas plant sizes. The economic assessment was carried out by considering specific operating profits as a profitability indicator. Specific operating profits represent a valuable economic indicator for analysing the profitability of a biogas plant on a given year. They can then easily lead to the identification of the most economically attractive installations. Complementarily to the economic assessment a sensitivity analysis was carried out and clearly identifies and quantifies the main profitability drivers in each plant type. The performed sensitivity analysis assesses the robustness of the plant profitability and represents then a valuable approach for integrating input data uncertainties in the economic evaluation.

Disadvantages linked to the employed simulation model should however be pointed out. A first aspect refers to the biogas production modelling which is in reality not only dependent on biochemical reactions and kinetics occurring in the anaerobic digester. The impact of process inhibitions, such as over-acidification or scum build-up, should also be taken into account. These aspects are however specific to each digester and cannot be systematized in the present work. The process simulation is further done under steady state, i.e., not time dependent. A subsequent work could consist of modelling the anaerobic digestion process under dynamic and time-dependent conditions. Process regulation systems and the temporal evolution of the bacteria community inside the fermenter could thus be integrated into the simulation model. Existing models of anaerobic digestion processes, such as the Anaerobic Digester Model 1, could be further implemented into the present process simulation [244]. This would enable the estimation of the biogas yield as a function of substrate elementary composition and milieu conditions. For this purpose, the specified reaction kinetic constants should however be validated by biological experiments for instance.

The results of the simulation model enable a systemic economic assessment of three different biogas plant types under a variable biomass input mass flow. However, this systematization must be carried out with caution as each single plant is defined in practice by a specific operation plan. Strictly speaking each single existing plant in Germany should be economically evaluated. This would confirm or invalidate the correlations determined here between the specific operating profit and plant sizes. Nevertheless, access to information regarding the specific operating profit of existing German biogas plants remains very difficult. A high level of confidentiality is observed among German biogas plant operators who generally will not deliver economic information. The calculations have been further realized under ceteris paribus conditions. From a simulation step to another certain specific costs and revenues have been assumed as constant. These positions concern the specific energy crop costs and the specific fee revenues for biowaste valorization (expressed in €/t). Specific energy crop costs vary from one Federal State to another but are not correlated to biogas plant size or to valorized biomass amount in the present model. Specific biowaste fee revenues are fixed at a constant level of 60 €/t for each plant size and in all Federal States. In practice, these ceteris paribus conditions do not apply as each single biogas plant is characterized by own specific energy crop costs and by own biowaste fee revenues dependent on local market conditions. Another aspect concerns the EPEX-Peak electricity price level that has been used in the case of electricity direct marketing. For the year 2013 it is assumed that the plant operators sell the electricity produced for 43.13 $€/MWh_{el}$[12]. A sales price of about 35.09 $€/MWh_{el}$ is further assumed for the year 2015 [12]. In practice the EPEX prices level for the sold electricity is depending on plant operator's strategy and cannot be systematized. This is the source of a data uncertainty which is taken into account in a sensitivity analysis realized in section 7.4. Figure 7-12 sums up the pros and cons regarding the methodology employed for the analysis of current electricity production from biogas in Germany.

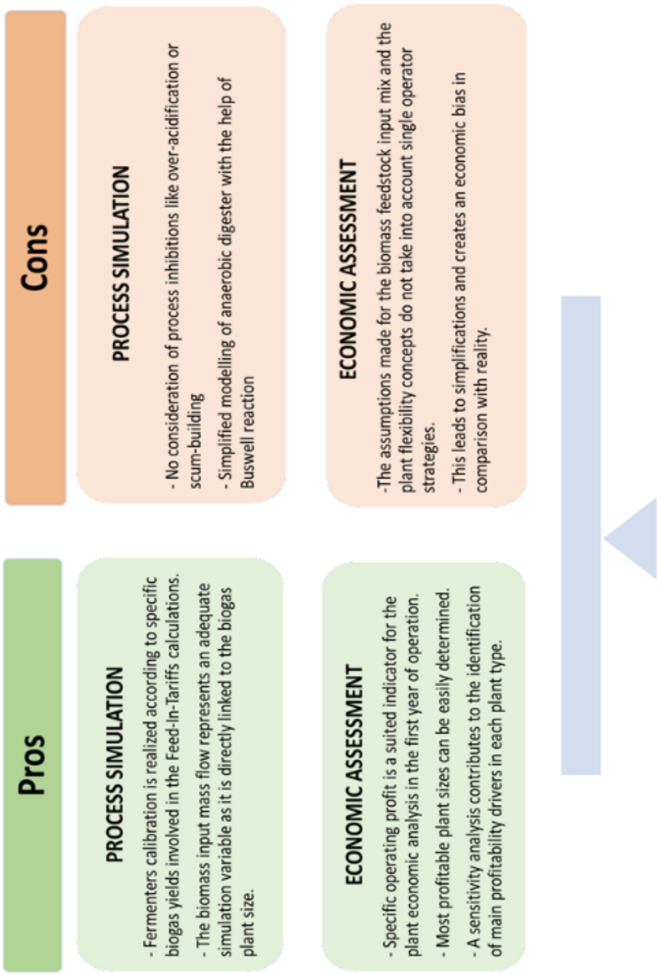

Figure 7.12: Pros and cons regarding the methodology employed for the analysis of current electricity production from biogas in Germany

7.6.2 Validation and critique of results

A validation of the model results can be carried out by comparing the observed specific operating values with literature data. From 0 to 75 $\mathrm{kW_{el}}$ small-scale manure plants appear as the most profitable installation type both under EEG 2012 and EEG 2014 framework. According to model results a 75 $\mathrm{kW_{el}}$ manure plant displays a specific operating profit of about 8.89 $\mathrm{ct/kWh_{el}}$ under EEG 2014 framework. This high profitability level is in line with literature data. A specific operating profit of about 9.5 $\mathrm{ct/kWh_{el}}$ is estimated in [116] which is close to the model results. For small-scale to mid-scale plant sizes going from 75 to 800 $\mathrm{kW_{el}}$, agricultural plants appear as the most profitable option. In particular EM plants employing energy crops and manure are the most economically attractive which highlights the economic benefits of co-digestion. These results are in accordance with the observed past development of biogas in Germany.

The political willingness has been to strongly develop agricultural co-digestion plants through the energy crops and manure bonuses included in the subsidies up to EEG 2012. For plant sizes up to 800 $\mathrm{kW_{el}}$ the specific operating profits observed are coherent with the literature data. In [245] specific operating profits for agricultural and biowaste plant types are determined under EEG 2009 and for the year 2010. The specific operating profit of a 300 $\mathrm{kW_{el}}$ agricultural co-digestion plant valorizing energy crops and manure amounts there to about 4 $\mathrm{ct/kWh_{el}}$. In the present work EM plants with a size of 300 $\mathrm{kW_{el}}$ show a specific operating profit of about 1.5 $\mathrm{ct/kWh_{el}}$ under the EEG 2012 framework. The difference observed between the two values can be explained by an important energy crop costs increase between the year 2010 and the year 2013. In [246] a maize silage cost of 25 €/t is assumed whereas a much higher cost at 35.9 €/t is considered in the present work for the year 2013.

For plant sizes larger than 550 $\mathrm{kW_{el}}$ biowaste valorization appears to be the most profitable option. No literature study mentioning specific operating profits for mid-scale to large-scale biowaste plants currently exists. In particular a difficulty remains concerning the estimation of total revenues for large-scale biowaste plants which are mainly driven by revenues from the biowaste valorization into biogas. This last information is often kept confidential by biowaste plant operators. Nevertheless, the observed profitability can be justified by analysing the main costs and revenues positions given the valorized biowaste amount. Contrary to agricultural plants biowaste installations benefit from a fee revenue for the feedstock valorization into biogas.

The biowaste mass amount also generates costs for the treatment of the produced digestate. As shown by the sensitivity analysis in section 7.4.3 the revenues from the biowaste valorization and the digestate treatment costs represent the main plant profitability drivers. In the model calculations 60 €/t was assumed for the biowaste valorization revenues whereas 44.6 €/t should be taken into account for the digestate treatment costs. Revenues for biowaste valorization are then higher than digestate treatment costs which implies that profitability increases with the plant size. The results reveal however a profitability decrease starting from 3,000 $\mathrm{kW_{el}}$ plant sizes. This can be explained by major biowaste transport costs increase as mentioned in Figure A-20 of the Appendix. In the case of large-scale biowaste plants the effects of the costs for biowaste transport and for the digestate treatment are then stronger than the effect of the bio-waste valorization revenues.

The economic analysis of EEG 2014 plants smaller than 150 $\mathrm{kW_{el}}$ can be compared to that done for EEG 2017. Indeed, under EEG 2017, biogas plants with capacity smaller than 150 $\mathrm{kW_{el}}$ are not involved in the tendering procedure [112]. These plant sizes benefit from Feed-In-Tariffs up to 100 $\mathrm{kW_{el}}$ and then from the electricity direct marketing model up to 150 $\mathrm{kW_{el}}$. Figure 7-13 compares the revenue levels from electricity sales for each of the three plant types under both EEG 2014 and EEG 2017. In all plant types a very slight decrease is observed between EEG 2014 and EEG 2017. Just as under EEG 2014, the EEG 2017 framework offers economically attractive framework conditions for plant sizes smaller than 75 kW_{el} valorizing manure in mono-digestion. On the other hand, the economic situation still remains unprofitable for plants smaller than 150 kW_{el} using energy crops and/or biowaste.

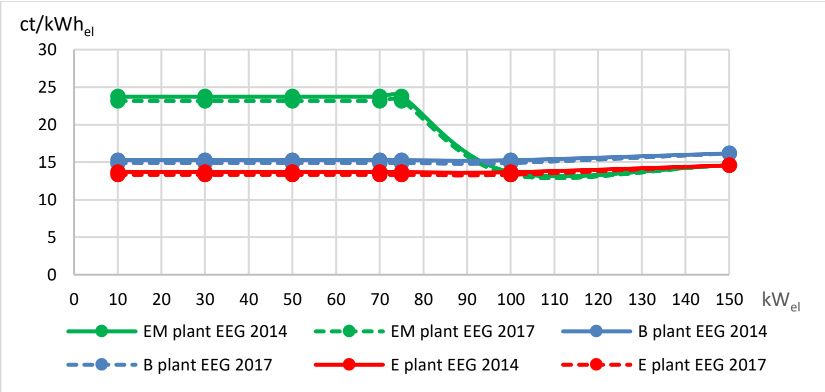

Figure 7.13: Comparison of revenues from the electricity sale in each plant type under EEG 2014 and EEG 2017 subsidy schemes for installations smaller than 150 $\mathbf{kW_{el}}$

In summary the model results for agricultural biogas plants in Germany appear to be plausible under both past and present legal framework conditions. In the case of biowaste plants the trend observed corresponds to economic reality. The profitability of biowaste plants is favorably influenced by biowaste mass flow increases up to a certain critical point[64]. For biowaste mass flows larger than this amount profitability decreases due to strongly increasing transport costs. For plants smaller than 150 kW_{el} the new EEG 2017 legal framework has only a very slight negative impact on profitability compared with the results observed under EEG 2014.

[64] This critical biowaste mass flow is estimated at about 81,250 t/a for a 3,000 kW_{el} plant size.

The model results should of course not be used as a substitute for detailed profitability assessment considering in particular real data and taking into account plant specific operation concepts.

7.7 Model outcomes evaluation

7.7.1 Policy recommendations

In light of the model results policy recommendations can be formulated for decision-makers as well as for local and national authorities. A first recommendation concerns revenue for biowaste plants. The results of the present work show that biowaste plants with installed power inferior to 550 kW_{el} are still unprofitable. In order to contribute to the development of small decentralized biowaste installations, revenue for biowaste plants should be increased. The construction and operation of small decentralized biowaste plants can improve the sustainability and acceptability of biogas in Germany[65]. A possibility for a revenue augmentation would consist in increasing the revenues related to biowaste valorization at the gate of the biowaste plants. These specific fee revenues, expressed in €/t, are paid by municipalities to biogas plant operators. The fee revenues level should at least cover the costs for the digestate treatment in composting units. In the present work fee revenues at about 60 €/t have been used in all calculations. An increase of this value would generate a profitable situation for small to mid-scale biowaste plants. For this a better implication of municipal stakeholders involved in biowaste plants projects is necessary. Local and decentralized biowaste valorization strategies should thereby be developed in order to contribute to the creation of a circular bioeconomy.

[65] The valorization of biowaste into biogas does not compete with critical pathways such as the food value chain. A “food versus fuel” debate can therefore be avoided which is not the case for agricultural plants. Moreover biowaste installations generally show a lower greenhouse gas potential than the agricultural plants [164].

The subsidies cut applied to energy crops in the framework of EEG 2014 slows down the development of agricultural plants. More precisely all agricultural plants larger than 75 $\mathrm{kW_{el}}$ appear to be unprofitable under the EEG 2014 framework. The profitability of agricultural plants could be further improved if agricultural residues were valorized (e.g., from wheat straw or corn). These residues are available for free and are directly located on the site of the biogas plant so that no or limited transport costs would appear in the economic balance. A recommendation would be thus to develop agricultural plants based on residues. This would also avoid “food versus fuel” competition.

The last policy recommendation concerns small-scale manure plants with installed electric power lower than 75 $\mathrm{kW_{el}}$. The conservation in the framework of EEG 2017 of the subsidy level for these plants appears as a positive aspect and must be maintained in the future. According to the results of the simulation model the most profitable biogas plants are of this installation type with a size of 75 $\mathrm{kW_{el}}$. This plant category only valorizes manure in mono-digestion processes so that no competition with the food supply chain occurs. Environmental benefits are further generated due to manure anaerobic digestion [164]. Therefore, the future development of small-scale manure plants should continue to be politically fostered and encouraged.

7.7.2 Strategic outcomes

Some other considerations apart from the effectiveness of German energy policy measures can be formulated. They concern the strategical planning, operation and maintenance of biogas plants. The planning phase of a biogas plant must take into account the presence of heat sinks in the proximity of the construction site. The heat produced by CHP-units is not systematically valorized which leads to process inefficiency and to an unprofitable economic balance. In particular biowaste plants should be preferentially built in semi-urban or urban areas in the proximity of important heat sinks like municipal buildings, schools or swimming pools. Agricultural plants, generally located in rural area, should be connected if possible, to heat networks in order to distribute the heat produced to remote heat sinks.

The identification of optimal marketing channels for the digestate produced, e.g., through sale as fertilizer or compost, generates supplementary revenues. For this, sustainable and robust local value chains should be established in particular in the context of circular bio-economies. A third aspect concerns the flexible and strategic operation of biogas plants. Adequate feedstock and gas storage management could lead to the operation of “smart” biogas plants. In these plants a storage tank for the biomass input feedstock would allow the production of biogas according to heat and electricity demand and price. Similarly, the storage of the biogas produced enables the operation of flexible and demand-oriented CHP units. This would allow plant operators to burn the biogas produced in the CHP-unit in order to produce electricity in times of high prices. The implementation of adequate flexibilization strategies would then lead to a maximization of the revenues from electricity sale.

On the costs side a major aspect concerns the definition of successful biomass feedstock purchase strategies especially for agricultural plants employing energy crops. As mentioned in [75] energy crop costs contribute to more than half of the electricity production costs and represent a major profitability driver for agricultural biogas plants. The high volatility characterizing, among others, wheat and maize silage prices is a source of uncertainty for biogas plant operators. Hedging strategies have to be applied in order to minimize the risks level. The negotiation of feedstock delivery contracts between farmers and plant operators should therefore integrate this price volatility [189].

Maintenance and personnel costs could be minimized through mutualization effects. For example, in the case of agricultural plants personnel and maintenance costs can be drastically reduced if the farmer operates and maintains his biogas plant himself. This can be the case for small-scale manure plants but more rarely for larger installations. Due to the complexity of operating of a biogas plant these synergy effects are however not systematic and farmers must often rely on external companies. Therefore, training courses and continuing education programs should be offered to farmers for instance in the field of process engineering, microbiology or energy economics. This would increase their autonomy and further reduce the operating costs of their biogas installations. In the case of biowaste plants mutualization effects can also occur if a fermenter is added on the site of an existing composting unit. The personnel employed on the composting plant site could then be used for the operation and the maintenance of the supplementary biogas plant. This would contribute to reduce personnel costs. Optimization of the plant energy consumption coupled with strategic purchase of the required electricity could further significantly lower the energy costs and thus improve the plant's economic balance.

Optimization of the biomass logistic supply chain especially regarding transport costs minimization further reduces variable costs. In order to minimize transport costs, the numbers of tractors employed e.g., in agricultural plants, and the maximal collection radius should be carefully defined. In agricultural plants a maximum collection radius of 20 km is generally assumed. Larger distances lead to a strong increase of specific transport costs which impacts plant profitability. Similarly, biowaste plant operators should properly define the maximal collection radius of the feedstock employed. Usually, biowaste collection and transport only occurs in urban or peri-urban areas with distances up to 120 km from the plant location site.

A last aspect concerns process microbiological inhibitions like scum formation or over-acidification which can occur in anaerobic digesters. They have a negative impact on the biogas production and also on the plant's economic balance. In [247] these inhibitions have generated a loss of about 3 $\mathrm{ct/kWh_{el}}$ on the specific operating profit for a 760 $\mathrm{kW_{el}}$ biowaste plant. The use of anti-foam and a good understanding of microbiological processes can limit inhibitions and thus maximize biogas production.

7.8 Summary

The economic model input data detailed in section 6 leads to correlations between the cost/revenues and the installed electric power for each of the three assessed plant types (section 7.1). The results analysed in section 7.2 reveal a paradigm shift concerning the profitability of agricultural biogas plants type. These installations are assessed as profitable under EEG 2012 and show positive specific operating profits on the capacity bandwidth [250:7,500 $\mathrm{kW_{el}}$]. Under the EEG 2014 framework all agricultural plant sizes larger than 75 $\mathrm{kW_{el}}$ show negative operative profits and are thus identified as non-profitable. This can be explained by the subsidy cut applied to energy crops valorization under this legal framework.

Biowaste plants are the most profitable option under EEG 2014 for plant sizes starting from 550 $\mathrm{kW_{el}}$. Small-scale manure plants with an installed power of 75 $\mathrm{kW_{el}}$ represent the most attractive option with specific operating profits higher than 8 $\mathrm{ct/kWh_{el}}$ in both EEG 2012 and EEG 2014 legal frameworks. Most profitable plant sizes are further identified in each plant type. For example, under the EEG 2014 framework the most profitable biowaste plant size relates to installations with an electric power of 3,000 $\mathrm{kW_{el}}$. The costs and revenues structure of the most profitable sizes is analysed in section 7.3 and completed by a sensitivity analysis in section 7.4. In the case of the agricultural EM type plants, the main profitability drivers are the EPEX-Peak electricity price and the energy crop and investment-related costs. The profitability of biowaste plants is mainly influenced by revenues from biowaste valorization, by investment-related costs and by digestate treatment costs. A technical assessment of the most profitable biogas plant sizes is realized in section 7.5 in addition to the economic analysis. Biological and global energetic efficiencies are determined all along the biogas supply chain. The results show that small-scale manure plants display the highest global energetic efficiency due to a high biological efficiency superior to 85%. On the contrary the low biological efficiencies characterizing energy crops and biowaste mono-digestion plants lead to lower global energetic efficiencies.

The methodology and results of the simulation model are then discussed in section 7.6. Pros and cons are highlighted concerning the modelling approach and a plausibility control validates the obtained results which are in line with current policy for biogas in Germany. The model results lead then to the formulation of policy recommendations and strategic outcomes in section 7.7. Increasing valorization fee revenues for small to mid-scale biowaste installations would facilitate the development of decentralized biowaste plants and further generate local circular bio-economies. A fostered development of manure-based installations would contribute to more sustainable electricity production from biogas as these plant types offer economic but also environmental benefits. Operating costs minimization and revenue maximization measures are further presented as strategic outcomes for plant operators.

8 Model-based analysis of future electricity production from biogas in Germany

The objective of this chapter is to analyse the results of the optimization model relative to the evolution of future biogas capacity and electricity production from biogas up to the year 2030 in Germany. In section 8.1 the results are presented in the framework of a base scenario characterized by the model input data described in chapter 6. The mid-term evolution of electric capacity and electricity production are first shown at the Federal State level for all plant types aggregated. In a second step the new built capacity and the number of new built plants for each installation type are presented. Further scenarios are assessed in section 8.2. They quantify the impact of a strong variation of three main profitability drivers, i.e., the EPEX-Peak electricity price, energy crop costs and biowaste valorization revenues on future capacity developments. The methodology employed and results are then discussed in section 8.3. Finally, the model results are used to formulate policy recommendations and strategy outcomes for plant operators and policymakers in section 8.4. Chapter 8 ends with a summary in section 8.5.

8.1 Model results analysis in base scenario

In the results presentation, the biogas plant capacities are divided into new built and existing base-load capacities distributed over the Federal States (coloured bars), as well as into existing and new built flexible capacities (black dotted bars). Base-load existing and new built capacities correspond to biogas plants running 8,000 hours per year with a constant and non-flexible electricity production. Flexible existing and new built capacities aim at a demand-oriented electricity production from biogas and are running about

4,713 hours per year in part-load (see Table A-3 in the Appendix). According to the operator models defined in Figure 6-2 flexibility applies to capacity larger than 750 kW_{el} under EEG 2012. In the case of the EEG 2014 framework flexibility concerns plants having a capacity larger than 100 kW_{el}.

8.1.1 Results at the Federal State level

As shown in Figure 8-1 and under the EEG 2012 framework, baseload capacity should continuously increase, starting from about 3,832 MW_{el} at the end of 2016 up to about 4,211 MW_{el} in 2020 (see the coloured bars). The main capacity developments should take place in the Federal States of Lower-Saxony and North Rhine-Westphalia. Starting from 2020 a general decrease for base-load capacity is observed mainly due to the decommissioning plan for biogas plants older than 20 years. These plants are thereby not subsidized by the EEG framework anymore, which leads to unprofitability. The global decommissioning plan would concern a total capacity of about 2,319 MW_{el} at the end of 2030. Finally, a global capacity of about 3,771 MW_{el} is observed by 2030 of which 2,015 MW_{el} concerns baseload installed capacity, 708 MW_{el} arise from the flexibilization of existing capacities in the year 2012 and 1,047 MW_{el} relate to the flexibilization of new built capacity (see the black dotted bars in Figure 8-1). At the end of the year 2030 the installations should mainly be located in Lower-Saxony and North Rhine-Westphalia with respective capacity of about 486 MW_{el} and 369 MW_{el}.

Under EEG 2014 and as shown in Figure 8-1, base-load capacity should slightly increase from about 3,664 MW_{el} at the end of 2016 up to about 3,830 MW_{el} in 2020, especially in the Federal States of Lower-Saxony and North Rhine-Westphalia (see the coloured bars). Starting from the year 2020 a generalized base-load capacity decrease is observed in all Federal States mainly due to the decommissioning process of biogas plants older than 20 years. At the end of 2030 a total electric capacity of about 3,966 MW_{el} is observed. From this amount 1,905 MW_{el} come from baseload installed capacity, 1,759 MW_{el} are derived from the flexibilization of existing capacity in the year 2014 and finally

302 MW_{el} are issued the development of new built flexible capacity (black dotted bars in Figure 8-1).

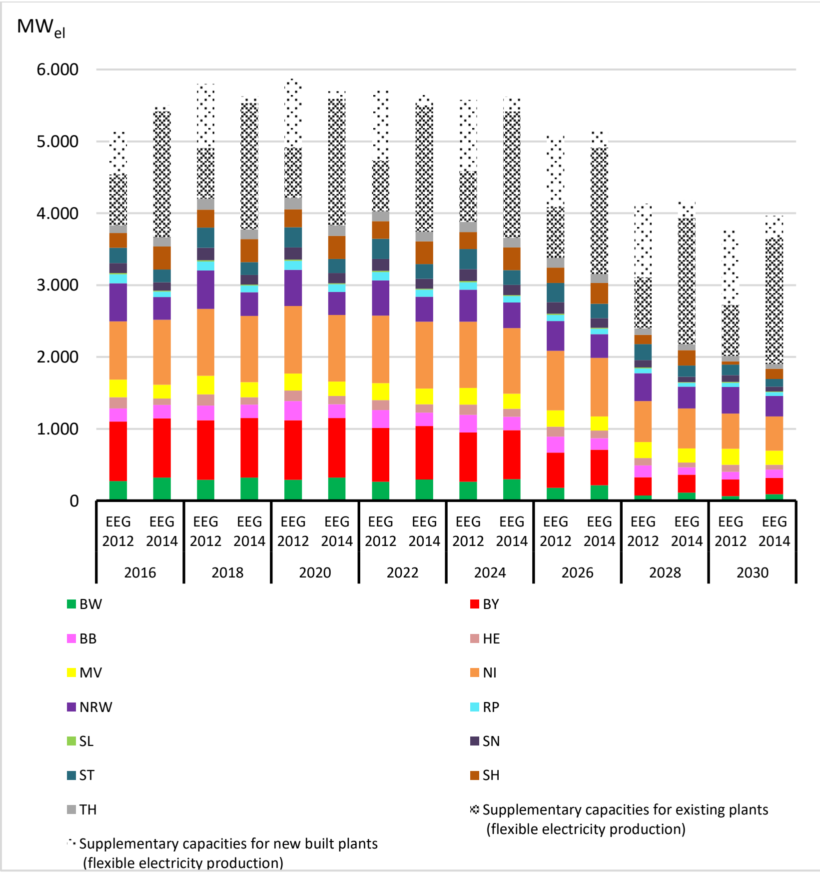

Figure 8.1: Regional total capacity evolution up to 2030 under EEG 2012 and EEG 2014

The evolution of electricity production from biogas in each Federal State is represented in Figure 8-2. By 2030, about 16.55 TWh_{el} should be produced under EEG 2012 and about 18.13 TWh_{el} under EEG 2014.

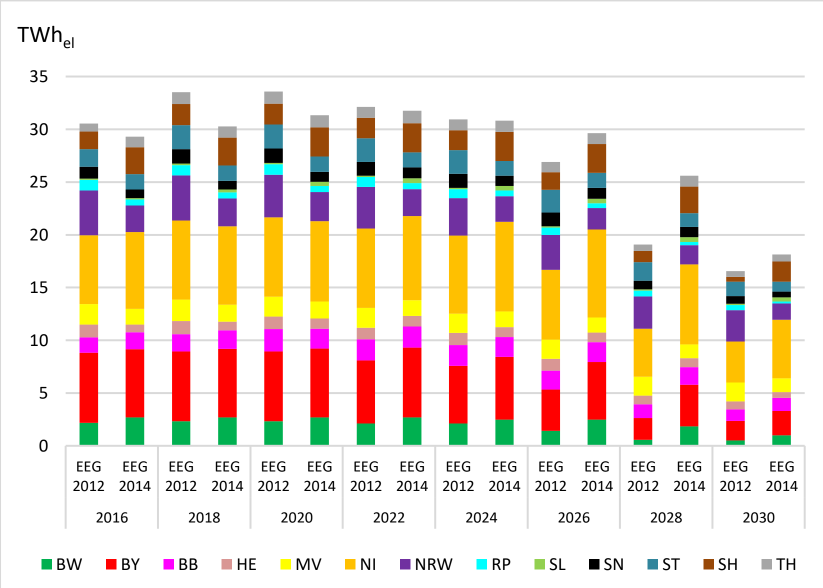

Figure 8.2: Regional total evolution of electricity production from biogas up to 2030 under EEG 2012 and EEG 2014

8.1.2 Results for energy crops and manure plants

Under the EEG 2012 framework, base-load installations with 8,000 full-load hours per year and valorizing energy crops and manure are expected to develop continuously up to the year 2020 (Figure 8-3). The main capacity expansion occurs in North Rhine-Westphalia, Lower-Saxony and Bavaria. A capacity expansion is viable in these Federal States as sufficient biomass potentials remain available and the specific operating profits observed are among the highest. At the end of 2020, the cumulated base-load capacity expansion reaches about 705 MW_{el} (coloured bars). After this time, there is no further capacity expansion because the total biomass potentials of all the Federal States are fully utilised. By 2030 a total new built capacity of about 1,271 MW_{el} including supplementary flexible capacity (black dotted bar) is observed. In addition to regional capacity expansion, Table 8-1 shows the number of the main new built base-load plants by plant unit size.

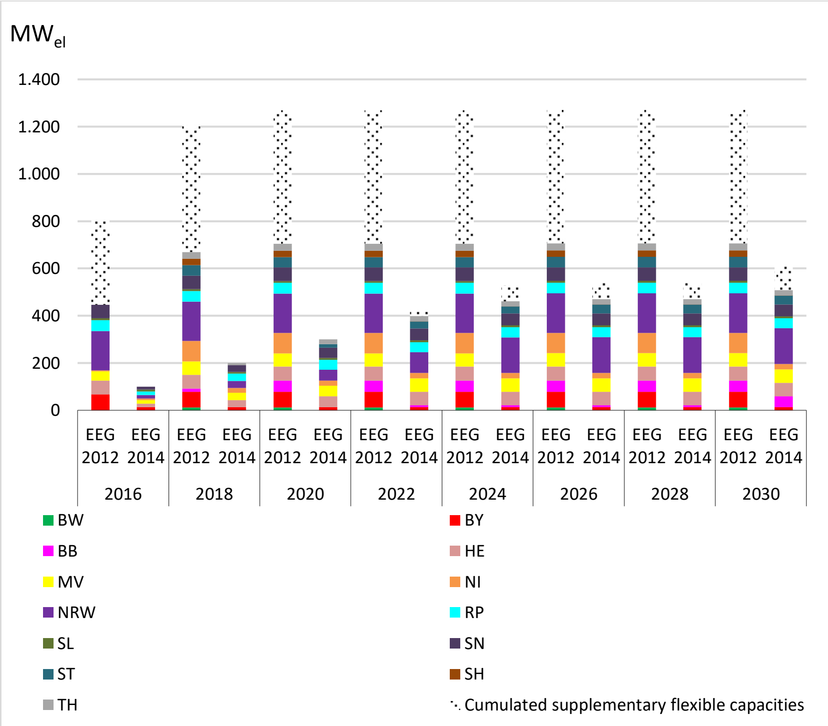

Figure 8.3: Regional cumulated new built capacities for EM plants up to 2030

New built capacity mainly concerns 900 $\mathrm{kW_{el}}$ plants as they show the highest specific operating profit values. As they are larger than 750 $\mathrm{kW_{el}}$ these plants can be operated under the electricity direct marketing model which appears to be economically more attractive to plant operators than the Feed-In-Tariff model relating to plants smaller than 750 $\mathrm{kW_{el}}$.

Table 8.1: Number of new built EM base-load plants according to their unit size under EEG 2012

Plant unit size	Number of new built plants up to 2030
< 75 kW_{el}	13
900 kW_{el}	706
1,000 kW_{el}	69

Under the EEG 2014 legal framework a total cumulated new built capacity for EM plants of about 611 MW_{el}, including new built baseload and new flexible CHPs, is reached by 2030 (Figure 8-3). About 1,271 MW_{el} are reached under the EEG 2012 subsidy scheme. The much lower value observed under EEG 2014 is mainly explained by the cuts in the energy crops subsidies, which came into effect on the 1st of August 2014, and drastically reduced agricultural plant specific operating profits. Another explanation is related to the new built flexible capacity which is clearly higher under the EEG 2012 than under the EEG 2014 framework. Table 8-1 shows that under EEG 2012 most of the new built plants are larger than 750 kW_{el} and can thus benefit from flexibilization according to the operator model defined in section 6.2.2. As mentioned in Table 8-2 most of the new built installations under EEG 2014 are base-load manure plants with a size of 75 kW_{el}. Following the operator model defined under EEG 2014 these base-load capacities do not benefit from flexibilization. This explains then the much lower new built flexible capacity observed under EEG 2014 than under EEG 2012. A further analysis of the observed results shows that the main capacity developments under EEG 2014 should take place in the Federal States of North Rhine-Westphalia, Hesse and Mecklenburg-West-Pomerania which display the highest specific operating profit values for EM plants. A slow-down in capacity development occurs starting from 2024, mainly due to biomass potentials depletion but also due to plant unprofitability in several regions. A clear paradigm shift is also observed in terms of unit sizes for the newly built plants. The cut of the energy crops subsidy, applied in 2014, strongly lowers the number of new built plants using energy crops. In contrast to the EEG 2012 framework, a major increase of the number of new built small manure plants – not affected by the subsidy cut – is foreseen (Table 8-2).

Table 8.2: Number of new built EM base-load plants according to their unit size under EEG 2014

Plant size	Number of new built plants up to 2030
50 kW_{el}	2
70 kW_{el}	2
75 kW_{el}	5,065
2,000 kW_{el}	45
3,800 kW_{el}	10

At the end of the year 2030 electricity production from new built EM plants is estimated at about 5.65 TWh_{el} under the EEG 2012 framework and at about 4.06 TWh_{el} under EEG 2014 (Figure 8-4).

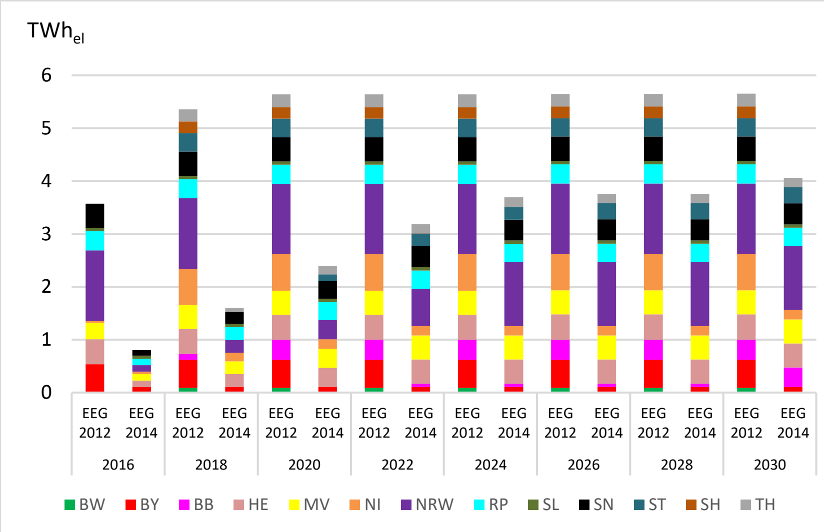

Figure 8.4: Regional electricity production linked to new built EM plants up to 2030

8.1.3 Results for biowaste plants

The results are firstly analysed under the EEG 2012 framework. By the end of 2030, the total cumulated new built capacities for biowaste plants amount to about 389 MW_{el} of which 216 MW_{el} are base-load CHPs (coloured bars) and 173 MWel flexible capacities (black dotted bar). The major capacity expansions occur in Bavaria, North Rhine-Westphalia and Low-Saxony. Only large-scale 3,000 kW_{el} biowaste plants are newly built and the commissioning of 72 new plants is predicted over the whole period.

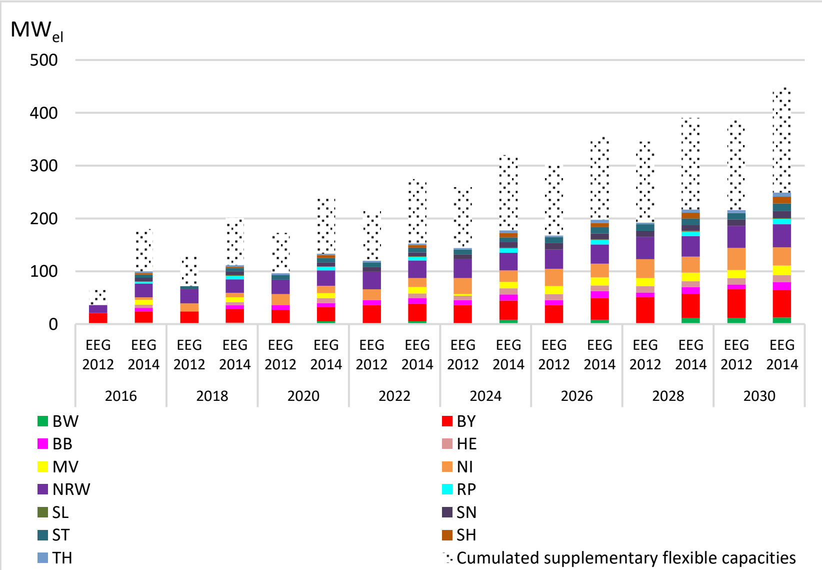

Figure 8.5: Regional cumulated new built capacities for B plants up to 2030

The results of Figure 8-5 reveal a stronger global capacity development under the EEG 2014 framework than under the EEG 2012 version, with cumulated new built capacity of about 448 $\mathrm{MW_{el}}$ being reached by 2030. This stronger evolution is mainly explained by a larger annual capacity expansion limit, increased to 50 $\mathrm{MW_{el}}$ in 2014 from 12 $\mathrm{MW_{el}}$ in the year 2012. Table 8-3 shows the new built B plant numbers observed at the end of 2030 under EEG 2014. New built biowaste capacity should therefore focus on the development of mid to large-scale installations and especially 3,000 $\mathrm{kW_{el}}$ unit sizes.

Finally, the total electricity production related to new built B plants amounts to about 1.54 $\mathrm{TWh_{el}}$ in the case of the EEG 2012 framework and 1.99 $\mathrm{TWh_{el}}$ by 2030 under the EEG 2014 framework (Figure 8-6).

Table 8.3: Number of new built B base-load plants according to their unit size under EEG 2014

Plant unit size	Number of new built plants up to 2030
400 to 700 kW_{el}	19
800 to 1,800 kW_{el}	20
2,000 kW_{el} to 2,800 kW_{el}	29 of which 23 corresponding to the 2,000 kW_{el}-size
3,000 to 3,400 kW_{el}	50 of which 46 corresponding to the 3,000 kW_{el}-size

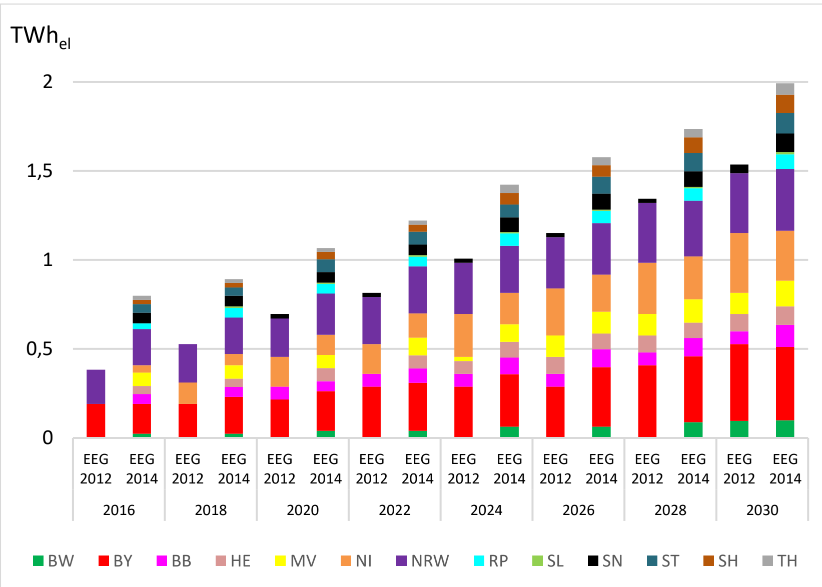

Figure 8.6: Regional electricity production linked to the new built B plants up to 2030

8.1.4 Results for energy crops plants

As mentioned in Figure 8-7, the evolution of new built mono-digestion plants employing energy crops (E plants) under the EEG 2012 framework stops after 2020 as the biomass potential limits are already reached. Cumulated new built capacity of about 696 MW_{el} are reached by 2030 split into about 387 MW_{el} for base-load capacities and 309 MW_{el} for flexible plants.

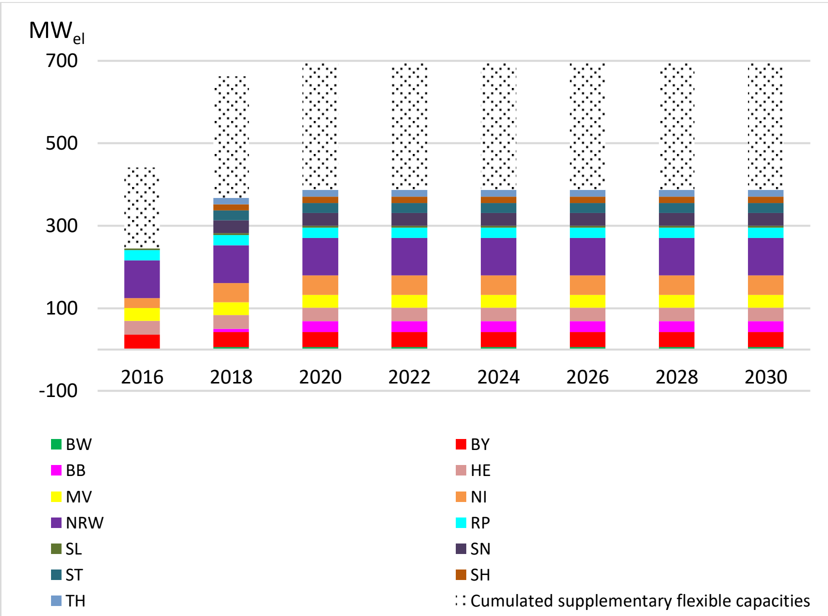

Figure 8.7: Regional cumulated new built capacities for E plants up to 2030 under EEG 2012

The new built base-load capacities result from the commissioning of 424 new plants mainly with 900 kW_{el} unit sizes (Table 8-4).

Table 8.4: Number of new built E base-load plants according to their unit size under EEG 2012

Plant size	Number of new built plants up to 2030
700 kW_{el}	3
900 kW_{el}	366
1,000 kW_{el}	55

Concerning the electricity production, a total cumulated amount of about 3.1 TWh_{el} would be reached by the end of 2030, as shown in Figure 8-8.

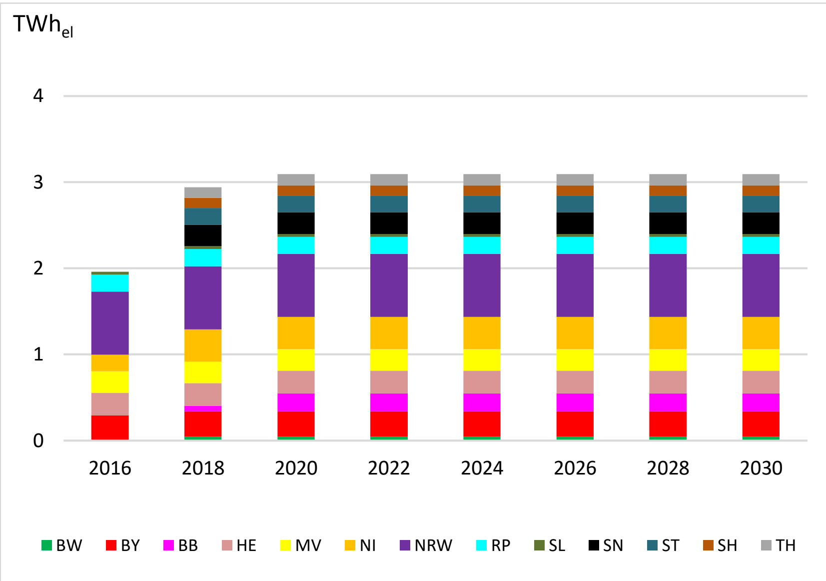

Figure 8.8: Regional electricity production linked to new built E plants under EEG 2012

Finally, no capacity expansion occurs under the EEG 2014 framework for E plants, due to unprofitability. In each Federal State, a negative specific operating profit is observed for all years and all plant sizes, mainly due to the energy crops subsidies cut enacted in August 2014.

8.2 Results under other scenarios

A sensitivity analysis realized in [147] shows that the energy crop costs, the revenues from the sales of electricity and from biowaste valorization are the main drivers of German biogas plant's profitability. The temporal evolution of these three key-drivers is characterized by major uncertainties, in particular due to price volatility[66]. It is therefore the aim of this section to take into account these uncertainty levels in the framework of a scenario analysis. In addition to the base scenario, further scenarios are assessed, firstly considering energy crop costs shocks. The high volatility observed in the biomass commodities markets can strongly impact regional biogas plant developments. A simulation of an energy crop costs increase of +10% per year over the period 2020-2025 and in all Federal States generates a substantial decrease of the cumulated new built base-load EM plant capacity over the same period (Figure 8-9). After the end of the shock, i.e., by the year 2025, the cumulated new built capacity progressively recovers to the values observed in the base scenario.

[66] In the case of the electricity sold volatility applies in particular to the EPEX-Peak spot prices which are set hourly on the European Power Exchange in Paris. In the case of energy crops volatility concerns feedstock prices which are set on the MATIF Commodity Stock Exchange in Paris. Revenues from biowaste valorization can vary strongly from a plant to another between 20 and 100 €/t [229].

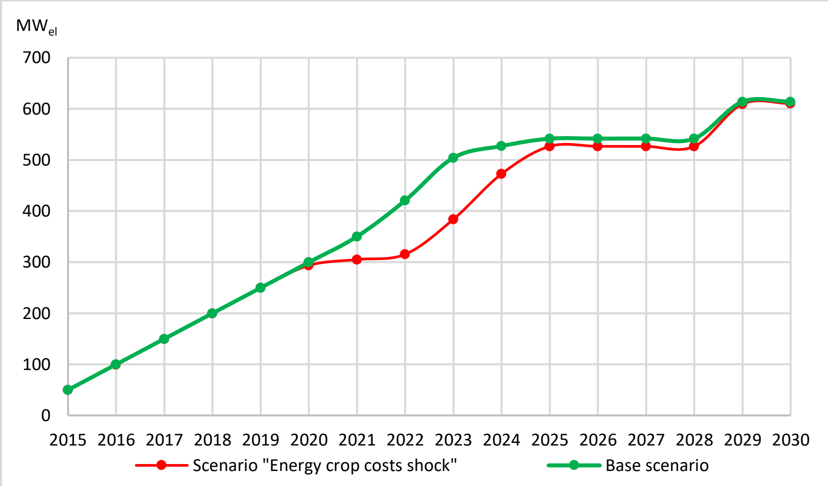

Figure 8.9: Capacity evolution for new built EM plants in the base scenario and under an energy crop costs shock

Under the electricity direct marketing model, German biogas plant operators receive, in addition to the market premium, revenues for electricity sold on the European Power Exchange (EPEX-wholesale price). It is assumed that the operators sell the electricity produced in Peak time characterized by a high electricity demand. In the base scenario represented by the green line in Figure 8-10, the EPEX-Peak wholesale electricity price follows a forecast up to the year 2030 made in 2014 by EWI Prognos and GWS [222]. A wholesale electricity price of 6.7 $\mathrm{ct/kWh_{el}}$ is thus reached by 2030. The red line in Figure 8-10 corresponds then to the price forecast in a "high scenario" with an EPEX-Peak electricity price increase of +30% per year applied during the period 2020-2025. This increase can be justified by future necessary investment in the replacement of existing production plants especially for conventional energy conversion technologies [248].

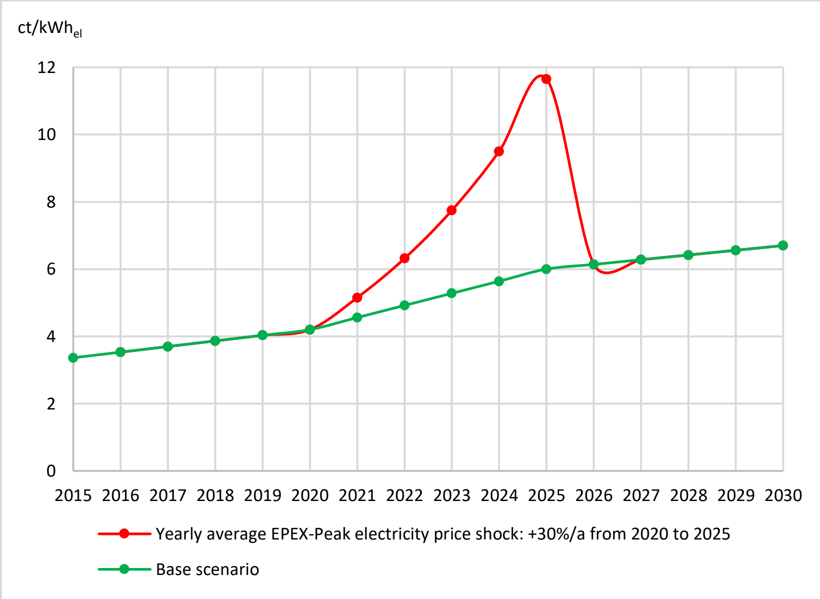

Figure 8.10: Assumed EPEX-Peak electricity price developments according to several scenarios

In reaction to the applied electricity price shock, it appears in the “high scenario” e.g., for EM installations that expansion is globally shifted in the direction of larger capacity unit sizes (blue bars). The electricity direct marketing model also tends to be more favourable to large-scale plants characterized by a high electricity output (size effect). Figure 8-11 compares the results for the main newly built capacities, 75 $\mathrm{kW_{el}}$ and 2,000 $\mathrm{kW_{el}}$, for EM installations under the “high scenario” with the results in the “base scenario” in the context of EEG 2014. A strong electricity price increase thus encourages the development of 2,000 $\mathrm{kW_{el}}$ plants in comparison to the base scenario.

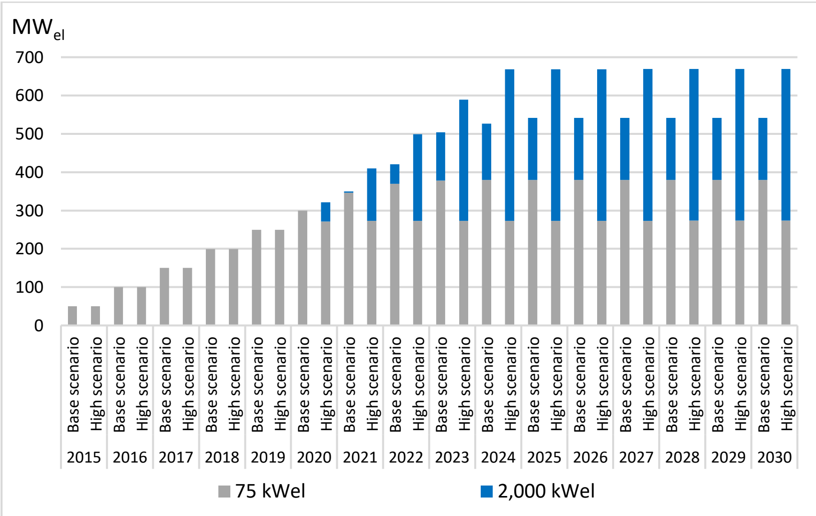

Figure 8.11: Capacity development of the main new built EM plants under EEG 2014 with and without consideration of electricity price shock

The last modelled shock concerns biowaste valorization fee revenues. A biowaste valorization revenue decrease of -20% per year is applied from 2020 to 2025 in comparison with the base scenario. It models a potential market breakdown for biowaste dedicated to biogas production in Germany. In reaction to the applied shock a capacity expansion freeze is observed from 2020 to 2025. After that the new built capacity increases again and reaches the value observed by 2030 in the base scenario (Figure 8-12). Future development of biowaste plants is then highly sensitive to the evolution of biowaste valorization fee revenues.

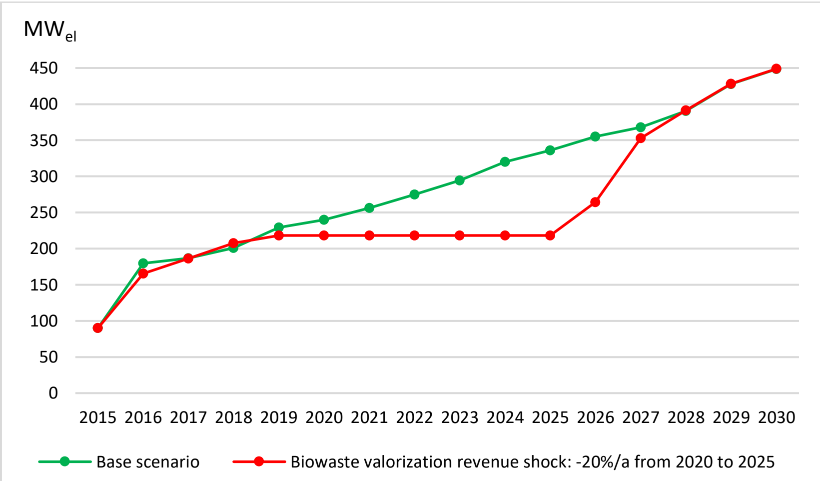

Figure 8.12: Capacity evolution for new built B plants in the base scenario and under a biowaste valorization revenue shock

8.3 Discussion of methodology and results

8.3.1 Methodology

The optimization model developed enables a forecast of future capacity expansion and electricity production from biogas in Germany up to the year 2030. For this an objective function aims at maximizing the total operating profit over all plant sizes, the whole time period and all Federal States combined. The developments are limited by constraints applied to biomass potentials and also concerning the annual capacity expansion caps defined in the EEG legal framework. As with the simulation model pros and cons linked to the employed methodology are highlighted in the following.

Positive aspects firstly concern the type of model approach that has been selected. The objective of biogas companies is to maximize the total operating profit related to the installations that they operate over their whole lifetime i.e., generally 20 years. Therefore, the use of an optimization model appears to be suitable for forecasting the development of future German biogas plants. In the framework of this model the total German biogas plant park is analysed and the objective function aims at maximizing the total operating profit linked to this plant portfolio. Another positive aspect concerns the integration of physical and legal constraints in the developed model. For each plant type EM, E and B, regional biomass potentials limitations have been defined as constraints. This ensures that no further capacity can be built if the corresponding biomass potentials are insufficient. If all biomass potentials are fully employed in a given year and region no further capacity expansion occurs in the following years. Another constraint concerns the capacity expansion caps defined in the EEG legal framework. This capacity expansion limitation ensures that not all the plant sizes are built in the first year of the time period due to a full valorization of biomass potentials. Both of these two constraints aim thus at better representing the physical and legal reality for the future development of German biogas plants. Complementary assessments are carried out in the framework of "shock scenarios". These scenarios provide valuable information for plant operators as they quantify the impact of major profitability drivers on future capacity developments. Potential opportunities and threats for the German market can thus be identified. These mainly concern the development of energy crop and electricity prices as well as the evolution of biowaste valorization revenues.

Disadvantages of the modelling approach should also be pointed out. For a given plant type (E, EM or B), the solver selects every year, and for each region the plant sizes that could be built in order to maximize total operating profit by the end of 2030 over all Federal States. The annual specific operating profit represents the main driver for the selection or non-selection of a plant size to be built in a given region and year and of a given plant type. Plants showing a negative specific operating profit are systematically not built. This approach corresponds to that of a plant operator whose objective is to maximize the total operating profit of their installations. However, it does not take into account the investor perspective. By calculating internal rates of return (IRR), the profitability of the investment in the different biogas plant types could have been estimated. Especially if the IRR remains over a defined Weighted Average Capital Cost (WACC) then the investment is profitable. An example of a WACC value has been published concerning KTG Agrar which is one of the leading biogas production companies in Germany. In [249] a WACC value of 4.5% is given by the end of the year 2015. Further analysis would then estimate the IRR level for each plant type, over all plant sizes and all Federal States combined. Comparing the resultant IRR level with the WACC value of 4.5% previously mentioned would indicate if the investment was profitable or not. However, this requires long-term cash flow forecasts. For example, the decision to commission a plant or not e.g., in 2028 would imply having a cash-flow forecast for the next 20 years. This means that the specific revenues and electricity production costs would have to be estimated up to the year 2048 which leads to data uncertainty. Another disadvantage concerns the modelling approach which focuses solely on the biogas sector and does not integrate other electricity production options (renewable or conventional). The interactions of biogas with other electricity sources impacts the electricity wholesale price and thus the revenues from the plant opera-tor side. In the framework of this thesis a simplified assumption has been made concerning the EPEX-Peak electricity price. This price level has been initially set according to the average of monthly values observed in 2013 for the assessment under the EEG 2012 framework. Under the EEG 2014 framework the average of monthly values for the year 2015 has been assumed. In a further step a forecast of these two prices has been carried out according to the study of [222]. Two reference studies, mentioned in section 3.4.3, deal with the integration of biogas into the electricity system and consider an interaction with other electricity sources [133], [134]. However, they do not highlight regional developments for biogas in Germany and make no differentiation between agricultural, biowaste and manure-based plants. The present resource-oriented model follows a different approach based on the plant operator perspective. It provides insights concerning the evolution of the future whole biogas plant park portfolio according to various plant types and plant sizes. Therefore, the optimization model developed represents an adequate complement to other existing studies based on a (bio)-energy system approach. Figure 8-13 sums up the "Pros" and "Cons" regarding the methodology employed for the analysis of future electricity production from biogas in Germany.

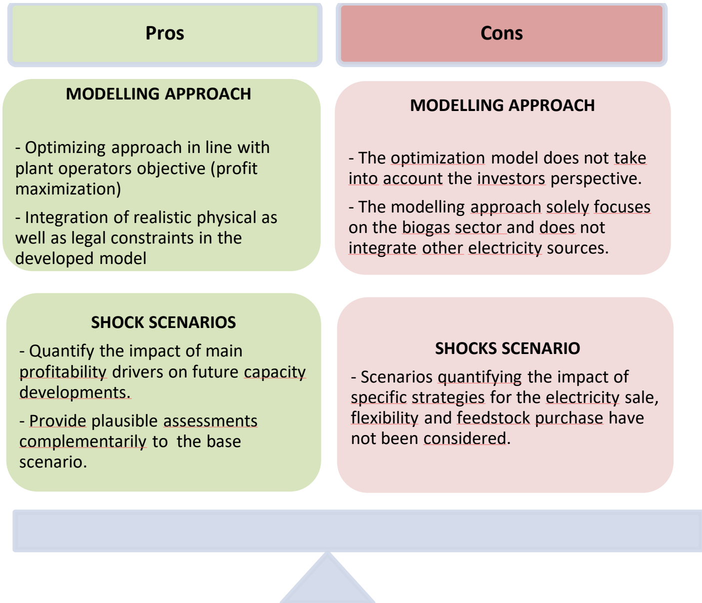

Figure 8.13: Pros and cons regarding the methodology employed for the analysis of future electricity production from biogas in Germany (author's own representation)

8.3.2 Validation and critique of results

A synthesis of the previous results shows that the future development of German biogas plants is dependent on five fundamental drivers. The first is that maximal biomass potentials are reached in some Federal States before 2030 and thus prevent further capacity evolution. In particular, agricultural plants valorizing energy crops in mono-digestion processes are subjected to a capacity expansion freeze starting from 2020 under the EEG 2012 framework.

Biowaste plants are not concerned by this phenomenon as 50% of the existing biowaste potentials are still unused.

The second key driver is plant economics. Revenues derived from the two EEG subsidy schemes and from biowaste valorization as well regionalized energy crop costs play an important role in plant profitability analysis. Furthermore, the price level of the electricity sold directly (EPEX-Peak wholesale electricity price) also has a major influence on capacity development. Plants selling the electricity produced at a very high price tend to be the best positioned for capacity expansion. From the costs side plant capacity expansions most likely occur in Federal States with the lowest energy crop costs.

The third driving force of capacity development is the annual capacity expansion limit defined by the two legal frameworks. As no capacity expansion cap was legally introduced in the framework of EEG 2012 a limit has been set for each of the three plant types derived from historical data. The capacity developments occurring under EEG 2014 are controlled by the legislator through an annual fixed cap of 100 $\mathrm{MW_{el}}$ for all biogas plant types. This discrepancy in the expansion cap values between the two EEG versions can partially explain the observed differences in the capacity evolution for each plant type.

Flexibilization conditions represent another key driver. The flexibilization conditions for new built capacity have been defined according to the two operator models described in section 6.2.2. Most of the new built capacity is larger than 750 $\mathrm{kW_{el}}$ under EEG 2012, which leads to a high level of flexibilization. On the contrary the observed evolution of new built capacity under the EEG 2014 framework is characterized by a low level of flexibilization. Indeed, the major capacity expansion concerns there small-scale manure plants operated in base-load.

The last driver, namely the decommissioning of German biogas plants older than 20 years, has been taken into account starting from 2020. This plant decommissioning dramatically impacts mid-term capacity development as most of the currently existing German biogas plants were built between the years 2000 and 2010. However, the possibility for existing plants to benefit from a subsidy scheme extension will be taken into account in the EEG 2017 legal framework. It would thus be prudent to consider that existing plants older than 20 years might not be systematically decommissioned.

A validation of results is possible by taking into account the four comparison criteria shown in Table 8-5.

Table 8.5: Considered comparison criteria for the model results validation

Comparison criteria	Questions to be answered
Ex-post comparison for the years 2015 and 2016 regarding new build capacity under EEG 2014: model results versus real data	Are the model results plausible when compared with real data and current trends for biogas in Germany?
Comparison of the optimization model results with the simulation model outcomes	Are the most frequent new built plant sizes plausible in regard with the most profitable sizes as determined in the simulation model?
Comparison with other studies analysing the future electricity production from biogas in Germany	Are the optimization model results plausible when compared with existing studies?
Comparison with future capacity developments under the new EEG 2017 framework	What are the changes for future capacity development induced by the new EEG 2017 framework and considering various scenarios?

The first comparison criterion concerns the total new built capacity in the years 2015 and 2016 under the EEG 2014 framework. The model results are compared ex-post with real data derived from annual statistics published by the German Biogas Association [250] (Table 8-6).

The total new-built capacity from the model results has thus been very slightly under-estimated in comparison to real data (-1.4%). Table 8-7 shows the capacity expansion provided by the model results for each plant type and during the first two years under each legal framework.

Table 8.6: Total new built capacity in 2015 and 2016: real data versus model results

	EEG 2014: years 2015 and 2016		
	Real data	Model results	Relative gap (%)
Total new-built capacity (MW_{el})	279 [250]	275	-1,4%

Table 8.7: Model results relative to past capacity expansion under EEG 2012 and EEG 2014

	Capacity expansion in 2013 and in 2014 (EEG 2012 framework)	Capacity expansion in 2015 and 2016 (EEG 2014 framework)
EM plant	403	100
E plant	220	0
B plant	43	175

Under the EEG 2012 framework the capacity expansion delivered by the model results in the years 2013 and 2014 is in line with the observed national policy at that time. The development of agricultural plants is strongly encouraged especially through the manure and energy crops subsidies. Biowaste plants are only subject to a moderate development. The model results observed between 2015 and 2016 under the EEG 2014 framework reveal a paradigm shift which is in accordance with the reality. Under this subsidy scheme the development of bio-waste plants appears to be favored in comparison to the agricultural plants. This is in line with current national trend for biogas in the framework of EEG 2014. As mentioned in [251] the future development of biogas plants should mainly focus on biowaste and manure installations.

A comparison is then made between the results of the simulation and the optimization models. More precisely Table 8-8 compares the most profitable plant sizes determined in the simulation model for the base year 2013 and

2015 with the most frequent new built plants sizes under EEG 2012 and EEG 2014 prospective scenarios in the optimization model.

Table 8.8: Comparison of the most profitable plant sizes from the simulation model with the most frequent new built plant sizes from the optimization model

	EEG 2012		EEG 2014	
	Most profitable plant size	Most frequent new built plant size	Most profitable plant size	Most frequent new built plant size
EM plant	75 kW_{el}	900 kW_{el}	75 kW_{el}	75 kW_{el}
E plant	900 kW_{el}	900 kW_{el}	2,000 kW_{el}	N/A
B plant	3,000 kW_{el}	3,000 kW_{el}	3,000 kW_{el}	3,000 kW_{el}

Under EEG 2012, the most profitable size for EM plants as determined by the simulation model is 75 $\mathrm{kW_{el}}$ (specific profit at about 10.85 $\mathrm{ct/kWh_{el}}$) followed by 900 $\mathrm{kW_{el}}$ (5.63 $\mathrm{ct/kWh_{el}}$ specific operating profit). However, the 75 $\mathrm{kW_{el}}$ plant size is not the most frequent new built capacity in the optimization model. Over the period 2013 to 2030, installations with a capacity of 900 $\mathrm{kW_{el}}$ dominate. This can be explained by the fact that the simulation model only considers one year for the economic evaluation (2013), whereas 18 years are taken into account in the optimization model. Over this 18 years period the evolution of the operating profit is more favorable to 900 $\mathrm{kW_{el}}$ plants than to 75 $\mathrm{kW_{el}}$ installations. As the optimization model aims to maximize the total plant operating profit (in €) over the whole period, the number of new built 900 $\mathrm{kW_{el}}$ plants is consequently higher than the 75 $\mathrm{kW_{el}}$ installations. In the case of E plants, 900 $\mathrm{kW_{el}}$ capacity is the most profitable size and also the most built capacity in both the simulation and optimization models. Finally, 3,000 $\mathrm{kW_{el}}$ B plants are the most profitable and the most frequent new built installations in both models.

Under EEG 2014, 75 kW_{el} represents the most profitable and the most frequent new built size for EM plants. According to the simulation model, a plant capacity of 2,000 kW_{el} shows the highest specific operating profit among all E installations. This specific operating profit however remains negative (-0.97 ct/kWh_{el}) which explains why no E plant capacity is built over the whole period. Similarly to EEG 2012, B plants with a capacity of 3,000 kW_{el} are the most profitable size as determined by the simulation model. They also represent the most frequent new built capacity in the optimization model. The results of the optimization model concerning the size of new built capacity are then in line with the outcomes of the simulation model.

In a further step, the optimization model results are com-pared to other existing studies, which have been presented in section 3.4.3. These studies also assess the development of future electricity production from biogas up to the year 2030 (Figure 8-14). As shown in Figure 8-14 the amount of electricity produced by the end of 2030 is in line with the assessments drawn from [135], [136]. The values mentioned in the “Min scenario” in [134] remain clearly above the forecasts carried in this work[67]. This difference is explained by the fact that this study does not take into account a plant capacity decommissioning starting from 2020. The decom-missioning concerns plants older than 20 years in 2020 and represent a global capacity of 2,319 MW_{el}. Assuming 8,000 h/a operating hours for these plants, a total electricity production of 18.55 TWh_{el} has to be removed from the previous “Min scenario”. Thereby about 11.95 TWh_{el} is determined given the capacity decommissioning occurring by 2020. This value is in line with the forecasts obtained from the present work under the EEG 2012 and EEG 2014 frameworks (Figure 8-14).

[67] This scenario corresponds to an agricultural surface area dedicated to biogas of about 0.78 million ha by 2020 and 0.96 million ha by 2030. In this scenario it is further assumed that 75% of the potentials dedicated to manure and biowaste are valorized into biogas.

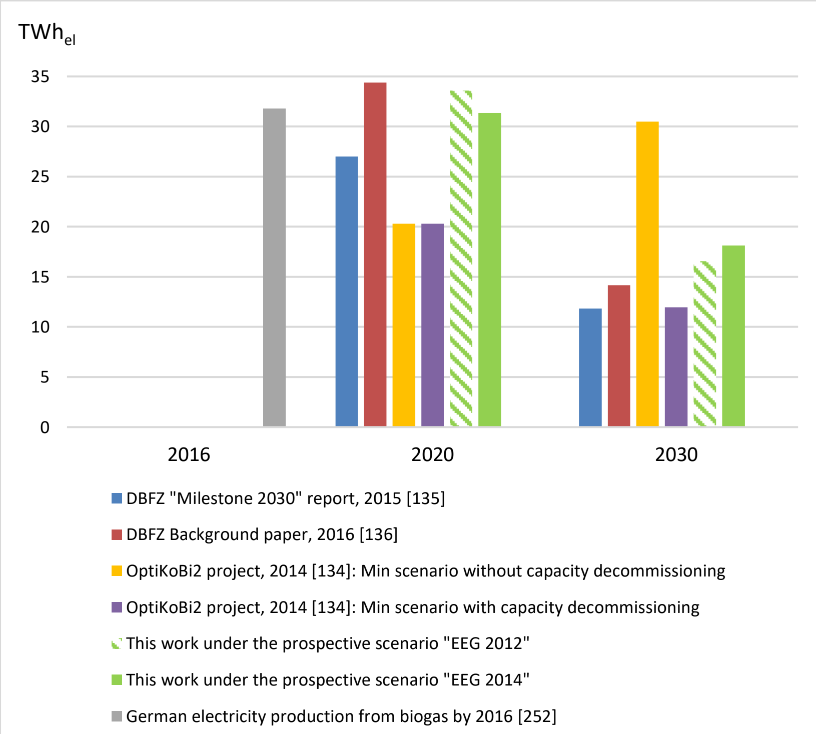

Figure 8.14: Comparison of results from various studies regarding future electricity production from biogas in Germany (author's own representation)

The optimization model results appear as qualitatively and quantitatively plausible both on short-term and long-term horizons. The results observed on a short-term horizon for the years 2013 to 2016 are in accordance with ex-post real data and with the outcomes from the simulation model. The model results concerning electricity production by the end of 2030 are in line with existing forecast studies.

In a last step, the base-load capacity forecasts produced by the optimization model are compared to future developments under the EEG 2017 subsidy scheme. In the framework of EEG 2017 maximal annual capacity expansion caps of 150 MW_{el} over the period 2017-2019 and of 200 MW_{el} from 2020 to 2022 are defined [112]. It is also assumed that the 200 MW_{el} yearly expansion caps are maintained after the year 2022 and up to the year 2030. The capacity expansion caps correspond to the maximal yearly allocable capacity for bioenergy technologies during tendering procedures. Thereby three scenarios are considered for the capacity forecasts under EEG 2017. In the "Low scenario", it is assumed that only 10% of the allocable capacity is won by biogas technologies up to the year 2030. In the "Mid scenario", it is assumed that half of the maximal allocable capacity is attributed to biogas technologies. Finally, in the "High scenario" the maximal allocable capacity is assumed to be attributed to biogas technologies. The forecasts under the EEG 2017 framework are then compared to the model results under the EEG 2012 and EEG 2014 frameworks. The new built plants capacity is evaluated over the period 2017-2030 in each of the three subsidy schemes. The results are shown in Figure 8-15 for the years 2020, 2025 and 2030.

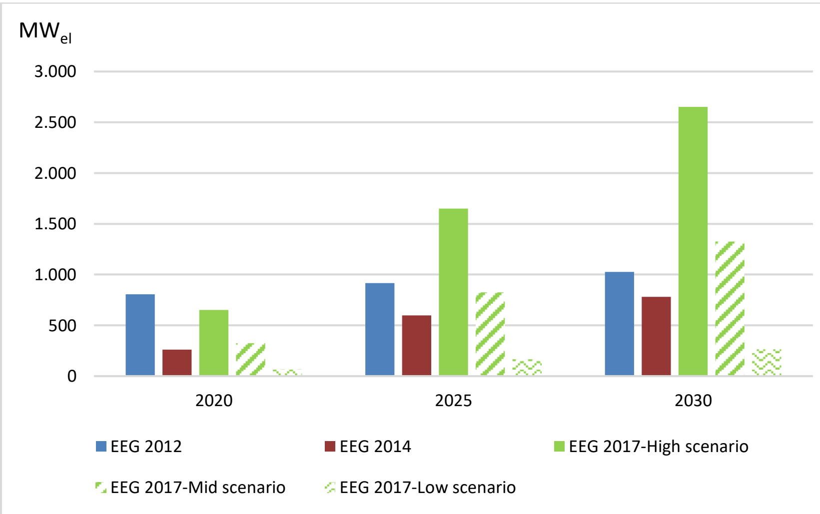

Figure 8.15: Evolution of total new built capacity under EEG 2012, EEG 2014 and EEG 2017 legal frameworks

In the "High" and "Mid" scenarios the capacity expansion forecasts carried out under EEG 2017 appear as more favorable than the optimization model forecasts realized under EEG 2014. A breakeven point is also determined. It represents the critical capacity share which has to be attributed to biogas technologies under EEG 2017 tendering procedures in order to reach a plant capacity at least equal to the capacity forecast under the EEG 2014 framework by 2030. Therefore if 29.4% of the yearly allocable capacity is attributed to biogas technologies, then the forecasted capacity by 2030 would remain at the same level under EEG 2017 as under the EEG 2014 framework.

8.4 Model outcomes evaluation

8.4.1 Policy recommendations

The results of the optimization model emphasize the role and impact of different subsidy schemes, namely EEG 2012 and EEG 2014, on future capacity development. Under the EEG 2014 framework and according to the optimization model results, the future capacity developments up to the year 2030 would mainly concern small-scale manure plants and large-scale biowaste installations, which is in line with the objectives of the Federal Government [251]. For these installations a future capacity expansion contributes to a maximization of the total operating profit for German biogas plant operators. The German biogas sector will thus face a paradigm shift with the increase of biowaste and small-scale manure installations. On the other hand, the results show that agricultural installations should not undergo any major future developments. Contrary to agricultural plants, biowaste and manure installations are not concerned by the "food versus fuel" debate. This should lead to an increase in the public acceptance of biogas in the forthcoming years. Considering all these aspects a first policy recommendation consists in encouraging the valorization of manure and biowaste in biogas plants by maintaining the current corresponding level of subsidies on a mid-term horizon.

Furthermore, the development of flexible biogas plants valorizing biogas into heat and electricity according to demand level has to be strengthened. The possibility of producing flexible electricity provides a new function for the biogas industry which can be seen as a system service in addition to fluctuating photovoltaic and wind energy sources. According to EEG 2014 framework this flexibility is not applicable to small-scale plants with an installed power lower than 100 $\mathrm{kW_{el}}$. The model results under the EEG 2014 framework show however that a major development of manure plant sizes smaller than 75 $\mathrm{kW_{el}}$ would lead to a maximal total profit by the year 2030. A possible way to accelerate the development of flexible biogas plants would be thus to enlarge the flexibilization conditions to all plant sizes including small-scale manure plants.

8.4.2 Strategic outcomes

The future evolution of the German biogas market should be characterized by the development of small-scale manure and biowaste installations. These plants should therefore be given preference at the project planning stage by German biogas companies especially if significant development possibilities for new heat sinks or digestate sales are identified.

The results of the simulated shocks concerning the EPEX electricity price, energy crop costs and biowaste valorization revenues show that the future biogas capacity development is dependent on externalities linked to the electricity, feedstock commodities and biowaste markets. These could be a source of both threats and opportunities. Therefore, mastering the financial risks related to these uncertainties remains a key challenge for biogas plant operators. International agricultural commodity markets generate uncertainties in profitability forecasts, due to high price volatility (see section 6.6.1.1). In the present work regional energy crop costs have been assumed to remain stable up to the year 2030 due to a potential future increase of agricultural residues use in German biogas plants. A future challenge for plant operators will be the valorization of these residues which would stabilize energy crop costs and further reduce electricity production costs.

Another aspect concerns the biomass potentials mobilization and valorization. Biomass potentials represent an important driver for future biogas plants, whose locations are usually determined by resource availability and access. According to [172] the total potential dedicated to energy crops is estimated at about 69 TWh (primary energy). About 90% of this potential is currently used by the existing biogas plants which shows that further development is possible but limited. An intensification of the cultivation of the German agricultural surface area as well as the improvement of regional hectare yields could slightly increase biomass potentials for energy crops. In [172] an increase of 500,000 ha in the cultivable surface area could lead to supplementary potentials of about 17 TWh (primary energy). In the case of biowaste plants a potential of about 6 TWh is estimated of which 3 TWh are currently used [172]. About half of existing potentials for biowaste are currently not valorized. An increase of biowaste production in households combined with an improvement in biowaste sorting habits and a redirection of most of the sorted mass flows to anaerobic digestion would improve the potentials mobilization and valorization. The existing potential for manure is estimated at about 22 TWh of which 11 are currently used [172]. Thus about 50% of the existing potentials related to manure are currently not valorized in biogas plants and are simply spread on the farmers land. According to the European Biogas Association an improved integration of biogas plants in agricultural farms could make them more sustainable and economically competitive especially in the framework of local circular economies [72]. A new type of farm management should emerge and be generalized in which farmers fully integrate biogas solutions as an opportunity to valorize manure and agricultural residues into an environmentally friendly digestate with a high N-, P- and K-content. The systematization of agricultural residues and manure valorization into biogas would thereby improve the humus balance of the soil and create local digestate markets as well as cooperative networks between neighbouring farms.

Finally, alternatives for German biogas plant operators should be developed in case plants turn out to be unprofitable. These alternatives could consist in a shift towards more economically attractive markets than heat and electricity. For example, the biomethane market for gaseous biofuel applications could represent a possible post-EEG option especially if stronger financial incentives for (bio)-CNG car stations and vehicles are developed by the German Federal Government. A last option for German biogas plant operators would be to export their expertise and technologies to other European countries where biogas and biomethane are growing continuously (e.g., Sweden, France and Italy).

8.5 Summary

This chapter analyses possible future developments for German biogas plant capacities as well as for the electricity production from biogas up to 2030. For this purpose, a regional optimization model is employed and future developments are assessed under the EEG 2012 and EEG 2014 legal frameworks. The base scenario characterized by an energy crop costs stability shows that the EEG 2012 framework - if maintained - would have fostered the development of agricultural plants, especially co-digestion plants valorizing energy crops and manure (see section 8.1). The EEG 2014 framework stops the expansion of energy crops mono-digestion plants, which will no longer be built as they are unprofitable. The German biogas market will thus face a paradigm shift and move towards the increase of biowaste and small-scale manure plants. Plant flexibilization options have further a major impact on future capacity developments. Additional scenarios analyse the impact of shocks concerning energy crop costs, the EPEX-Peak electricity price and the biowaste revenues on future capacity development (see section 8.2). A strong variation of these fundamental drivers impacts future developments. A discussion in section 8.3 emphasizes pros and cons regarding the methodology employed and confirms the plausibility of the results gained. The observed evolutions for the new built capacities between the years 2013 and 2016 are in line with past and current national biogas policy. Based on the model results policy recommendations and strategic outcomes linked to future electricity production from biogas are derived (see section 8.4). The development of biowaste and residues-based plants as well as small manure installations should be politically fostered as they lead to a maximization of the total profit up to the year 2030 and over all Federal States. The volatility characterizing energy crop costs, EPEX-Peak electricity price and biowaste valorization revenues is a source of opportunities but also of risks for the future development of German biogas plants. Biogas plant operators then will face new challenges and must be able to master the risks and opportunities linked to the volatile evolution of these main profitability drivers.

9 Transferability of the developed methodology

The objective of this chapter is to analyse the transferability of the developed methodology to different contexts beyond Germany. This is done by analysing four case studies in several countries. The considered countries involve other pathways than the electricity production from biogas. The main available bioenergy conversion routes, like e.g., bioethanol in the transport sector or woody biomass combustion for renewable heat production, are then covered (Figure 9-1). The first case study deals with biomethane injection in France, the second with district heating from biomass combustion in Finland, the third with bioethanol production in Brazil and the last one with biodiesel production from jatropha in Indonesia. In each case study the current situation as well as the lessons learned are assessed. In a further step the transferability of the developed methodology for biogas in Germany to these countries is discussed in order to identify future drivers and challenges.

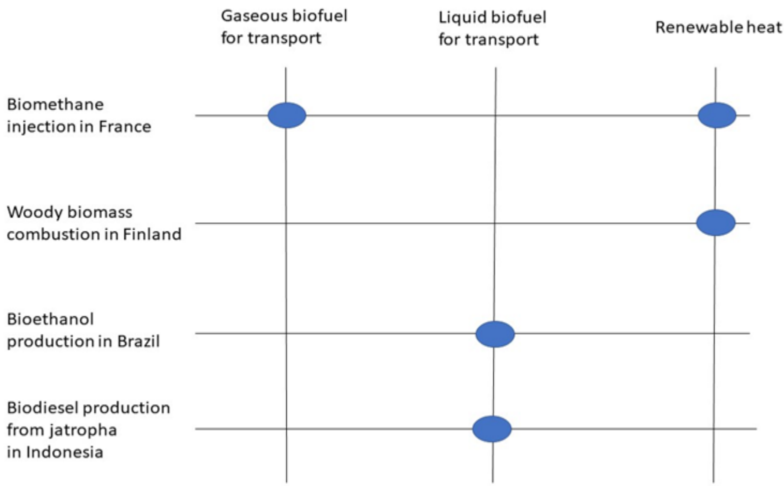

Figure 9.1: Considered case studies and bioenergy conversion pathways

9.1 Biomethane injection in France

9.1.1 Current situation and lessons learned

The first injection of biomethane into French natural gas grids occurred in August 2013. Since this time the French biomethane market has continuously grown and by the end of the year 2016 about 26 biomethane plants were running [253]. The French energy transition law enacted on August 17th 2015 has defined a national target for biomethane which must cover 10% of total gas consumption by 2030 [254]. A decree adopted on April 26th 2016 sets mid-term objectives for biomethane injected into the gas grids of 1.7 TWh/a by 2018 and 6 to 8 TWh/a by 2023 [255]. Specific targets are also defined for biomethane as a transport fuel for vehicles with 20% of Natural Gas Vehicles consumption to be reached by 2030 [255].

In France biomethane projects can be divided into five categories. The first corresponds to autonomous agricultural projects with biomethane plants valorizing agricultural materials from a group of farmers. Territorial agricultural projects are generally linked to co-digestion plants using more than 50% of input feedstock from agricultural farms and the rest from territorial waste (e.g., biowaste or sewage sludge from wastewater treatment plants). The third category valorizes household waste and biowaste. Fourthly sewage sludge fermentation projects involve urban and industrial wastewater treatment plants in which sludge is transformed into biomethane through anaerobic digestion. The last category, i.e., the territorial industrial projects, gathers partners from various sectors like agriculture, industry and waste treatment. Figure 9-2 highlights the share of the different project categories in total biomethane installed capacity (in TWh/a). By the end of 2016 about 0.41 TWh/a capacity was installed on the French territory [254]. Household waste and biowaste installations as well as autonomous and territorial agricultural plants represent the major share in the total installed capacity (about 25% each).

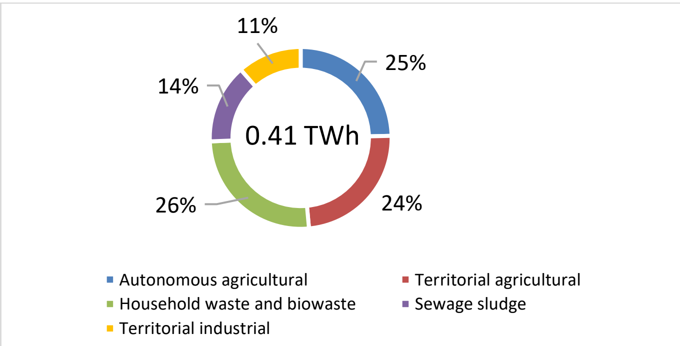

Figure 9.2: Biomethane project typology in France

The potentials for the different biomass feedstock valorization into biomethane are far from being depleted. According to [256], a biomass potential of about 56 TWh dedicated to biogas production could be reached by 2030 and would be mainly dominated by crop residues and by livestock effluents like slurry and manure. This corresponds to a total raw biomass feedstock amount of about 130 million t. From this potential the French Environment and Energy Management Agency (ADEME) has estimated in its “Biomethane 2030 roadmap” that about 30 TWh could be dedicated to biomethane injection at about 1,400 sites [257].

Past development of biomethane injection projects have been supported mainly by Feed-In-Tariffs which the French Government implemented in 2011 [258]. Biomethane producers benefit from a guaranteed Feed-In-Tariff for 15 years. The Feed-In-Tariffs level remains between 46 and 139 €/MWh depending on maximum biomethane feed-in capacity (in $\mathrm{Nm^3/h}$) and on the valorized biomass feedstock type. A base tariff is complemented by a feedstock premium for the valorization of sewage sludge, agri-food and agricultural waste, municipal and household biowaste or landfill gas. Complementarily to Feed-In-Tariffs, calls for tenders have been set in 2016 in order to further support the development of biomethane injection projects [259]. Other revenue sources are heat and digestate sale as well as subsidies from the ADEME. For this last revenue category, a subsidy rate, expressed in percentage of the total capital investment, is attributed to plant operators. An analysis of the profitability for past biomethane injection projects was published in 2015 [260]. For the sample of projects considered the subsidy rates varied between 10 and 15% of the total capital investment, which is much lower than for biogas projects for electricity production. The average Internal Rate of Return of past biomethane injection projects was located between 6 and 13%, which represents a satisfactory profitability level.

Beside the biomethane produced by anaerobic digestion, the production of renewable gas using thermochemical processes has benefited from significant research efforts in the past years. With the help of combined pyrolysis and gasification processes a synthetic natural gas (syngas) is obtained from the valorization of lignocellulosic biomass and/or solid recovered fuels. The syngas can be further upgraded to natural gas quality and then injected into the gas grids. The injected gas, also called 2nd generation biomethane, is seen as a promising driver for the achievement of the 2030 target which specifies that 10% of total demand should be met by renewable gas by 2030 [254]. A first demonstration project named GAYA is currently operating [261]. It aims to quantify production yields as well as to evaluate the economic and environmental relevance of 2nd generation biomethane production in France. Based on this analysis an industrialization phase involving new pyro-gasification projects is expected by 2020. Adequate financial support schemes appear crucial, however, in order to ensure the profitable development of future projects.

9.1.2 Methodology transferability: drivers and challenges for a future model implementation

The French biomethane market has been growing strongly in the past five years. These developments have been driven by specific Feed-In-Tariffs dependent on project size and on the valorized biomass feedstock. Research questions concerning the identification of the most profitable biomethane plant sizes and types as well as forecasts of future French biomethane injection appear as important but have currently not been answered. The methodology used for the analysis of current and future electricity production from biogas in Germany appears to be transferable to the case of biomethane injection and electricity production from biogas in France. The model input data regarding existing biomethane plants as well as biomass potentials for biomethane production is available in [256]. Economic analyses from existing projects are already published in [260]. Revenues from the biomethane Feed-In-Tariffs can be estimated with the help of a calculation tool developed by the French Club Biogas [262]. In addition, specific revenues from digestate sale and/or biowaste valorization remain similar to those considered in Germany for biogas. The results gained from the simulation model could deliver strategic information for plant operators and policymakers regarding the most economically attractive biomethane installations given current legal framework conditions. The optimization model outcomes could provide valuable indications regarding mid-term developments, e.g., up to the year 2030, for injected biomethane quantities. Future developments could then be compared to the legally defined mid-terms objectives for French biomethane injection. This could lead to strategic recommendations and facilitate the national energy transition.

The transferability of the model results to other renewable gas valorization routes than 1st generation biomethane is more difficult. Biomass gasification and pyrolysis aiming to produce 2nd generation biomethane are still at the research stage. The demonstration platform project GAYA will provide the first techno-economic data concerning the production and valorization of thermo-chemical biomethane. However technological and economic optimizations still remain to be made. In particular a next objective consists in minimizing the costs of biomethane production through the identification of the most efficient gasification and syngas upgrading technologies. Optimization of biomass logistics and supply is also needed especially for large plants sizes. In this case an important amount of biomass (superior to 100,000 t/a) is required and has to be transported which significantly increases biomethane production costs. Other challenges concern the biomass feedstock quality. Biomass quality characterized by the low heating value as well as by moisture content have an important impact on plant's profitability [263]. The valorization and sale of by-products such as charcoal, oil or black carbon would further improve plant profitability [264]. Finally, the future definition and implementation of adequate support schemes, e.g., Feed-In-Tariffs or call for tenders, appears as a fundamental driver for the development of the 2$^{\text{nd}}$ generation biomethane pathway.

9.2 Biomass combustion for district heating in Finland

9.2.1 Current situation and lessons learned

Following the objective of the European Commission, a target of 38% in the energy demand has been set for renewable energy sources in Finland by the year 2020 [265]. This represents about 127 TWh (35 TWh for heating, 52 TWh the industry sector, 35 TWh for electricity and 5 TWh in the transport sector). Finland has already reached the objective set by the European Commission as the national renewable energy production was estimated at more than 130 TWh by 2016 [266].

District heating represents the main driver of the total Finnish heating market with a share of almost 50% [267]. More than half of house buildings and offices are connected to district heating systems which meet 90% of building heat demand [267]. More than 400 medium and large-scale plants – mainly CHP – are valorizing biomass in combustion or co-combustion processes using peat or coal [267].

Among all existing national initiatives for the promotion of biomass district heating, the project of North Karelia[68] provides best practices for future project implementations in Finland or in other Baltic states [268]. The project objective is to plan, build and operate a wood chip district heating plant in order to create local jobs and to lower the dependence on external (fossil) energy sources.

The total annual energy consumption in North Karelia is about 10 TWh including electricity, heating and transport [268]. With a consumption share

[68] The North Karelia region is located in the east of Finland at about 300 km from Russian boarder. Forestry and forest-based bioenergy represent an important economic driver there. Woody biomass represents about 50% of the local primary energy consumption and the local renewable energy sector employs about 1,300 persons each year.

of 49.2% wood energy represents by far the main renewable energy source in the region, followed by fossil fuels (24.1%), hydropower (9.3%) electricity import (8.9%), peat (6.9%), heat pumps (1.3%) and other bioenergy feedstock (0.4%) [268]. Renewable energy represents about two-thirds of the primary energy consumption of North Karelia and is mainly drawn from woody biomass (81%) [268].

The North Karelia region has been a forerunner in renewable energy in recent years. In 2013 a new biorefinery simultaneously producing bio-oil, heat and electricity was opened in Joensuu [268]. About 50,000 t of bio-oil is produced yearly meeting the heating requirements of 10,000 households and this new plant has led to the creation of 65 new local jobs [268].

A Climate and Energy Program has been developed for North Karelia with defined targets to be reached by 2020 [268]. This program focuses on the sectors of energy (supply and consumption), transport, infrastructure, land use planning, construction, waste management, agriculture and forestry. As North Karelia is the most advanced region in Finland for the use and production of renewable heat, it has been selected as a demonstration region in order to establish best practices and to benefit from lessons learned.

For this, two surveys of plant operators have been carried out. Workshops have been organized in Joenssu, Koli and Valtimo. The results and experience gained have been transferred and applied to the municipality of Masku and to the counties of Pirkanmaa and Pohjois-Savo [268]. The main barriers for the profitable development of district heating projects have been identified and are the poor viability and low availability of funding as well as a lack of knowledge of subsidies, legal framework conditions, accounting and taxes [268]. The storage of wood and cooperation between manufacturers were not considered as problematic. From the plant operator side, challenges remain in the use of best available technologies needed to improve wood chip quality [268]. Clarification of the legal processes related to heat and electricity sale for small-scale CHP-plants is also needed. High level of investment required at the beginning of the operation and the low price of energy in

Finland could represent additional barriers for future project development [268].

9.2.2 Methodology transferability: drivers and challenges for a future model implementation

The recent developments for biomass district heating plants in Finland are very encouraging and will have to be fostered. In particular the identification of the most profitable biomass heating plant sizes would facilitate the implementation of new installations. A possible approach would be to assess the profitability of CHP district heating plants according to variable biomass feedstock mass flow and type (e.g., wood chips and fuel wood). The simulation model developed for biogas in Germany could be then applied to Finnish biomass district heating plants. Best practices transfer from existing projects or local implementation approaches, such as those in the region of North Karelia, is necessary in order to gather input data concerning the costs of heat and/or electricity production. On the revenues side a main barrier to future model implementation concerns the subsidy level for the heat and electricity produced. The subsidy level has decreased over the last few years so that the visibility and profitability of future projects remains uncertain. CHP district heating plants currently benefit from Feed-In-Tariffs but only for a period of 12 years which is shorter than is the case of Germany (20-years period). Plant operators receive a fixed subsidy at 50 €/MWh for the heat produced which has a major influence on plant profitability. Data uncertainties for the biomass input feedstock also remain especially concerning resource price and quality. The implementation of a regional optimization model for the analysis of future district heat production from biomass in Finland is currently not feasible. A regionalization of the required techno-economic data does not exist which limits future model developments at a regional scale. This also applies to currently available and future regional biomass potentials which have not been evaluated. The land use competition between bioenergy and wood industry should be taken into account for future regional biomass mass flows and potentials estimation.

Future challenges consist in the valorization of small-scale wood in young forests in order to reach the target of 25 TWh by 2020 for forest chip use. This remains a difficult task because working in young forests is less profitable than in clear cuttings. The main barriers to a profitable biomass harvesting in young forests are the small tree sizes, logistic aspects and difficult forest hauling. Furthermore, future development and policies for Finnish biomass heating plants must not lead to a competition of use with the wood processing industry. Priority has then to be given to the valorization of residues like woodchip, barks or sawdust.

In conclusion the transferability of the model-based approach used for biogas in Germany to district heating in Finland appears as difficult as regional data are missing. An aggregated evaluation at the national level remains however possible, especially by relying on past projects such as in the North Karelia region and assuming future legal framework stability. Mid-term forecasts for the development of future district heating plants based on woody biomass combustion would assist plant operators and policy makers with further project implementation. This would contribute to attaining national energy and environmental targets and to the creation of local added value.

9.3 Bioethanol for transportation in Brazil

9.3.1 Current situation and lessons learned

With about 28 billion liters of ethanol produced in 2016 Brazil is the second largest producing country behind the United States and also the largest sugarcane ethanol producer worldwide [269]. Past governmental initiatives such as PROALCOOL, the National Plan for Agroenergy and the Plan for Supporting Innovation in the Sugar-Energy and Sugar-Chemistry sectors have led to continuous development of the Brazilian bioethanol sector [270]. Research work has provided major impetuses for improvements in bioethanol production both at the agricultural and industrial scales. Sugarcane productivity has doubled since the 1960s due to research efforts in genetic breeding [270]. Technological innovations, e.g., in vinasse treatment or in the field of process energy efficiency, have accelerated industrial developments and were always supported by governmental incentives. Another main driver for bioethanol growth in Brazil was the introduction of flex-fuel engines in the early 2000s [271]. Due to different energy content, bioethanol and gasoline cannot be perfectly substituted from each other and the price of bioethanol has to remain under 70% that of gasoline in order to be competitive for consumers [271].

In order to meet the strongly increasing demand for bioethanol at both national and international levels in the forthcoming years, Brazil has to expand the sugarcane area harvested for both bioethanol and sugar production[69]. Bioethanol production should increase in a sustainable way in order to minimize competition regarding land use. According to [272] land-use change, and environmental problems could occur as a result of future sugarcane production especially in Cerrado areas (e.g., Goias and Mato Grosso). The increase of sugarcane production applies to area subject to environmental restrictions like the Pantanal and Amazon regions of the Paraguay River basin. Consequently, the Brazilian Government decided in 2009 to set up and to monitor a sugarcane agroecological zoning system so as to regulate land adaptation for sugarcane in these regions [272].

The bioethanol production in Brazil raises a “food versus fuel” debate. The conversion of sugar cane into bioethanol potentially impacts land-use and food security as it valorizes an edible crop into fuel. These impacts - and their significance - have been assessed in [273] based on a regional simulation model. A multi-period computable general equilibrium model (CGE) of Brazil has been developed. It follows a bottom-up regional representation of 15 aggregated Brazilian regions and involves 38 sectors, 10 household types and labor grades. It is further combined to a land use change (LUC) model which

[69] This area expansion would be caused by a stagnation of the sugarcane yields, as no new feedstock variety are currently developed [272].

tracks land use evolution in each region. In particular land-use change results from various parameters such as an increase of non-land inputs, a greater use of dedicated crop land and a conversion of pasture and unused lands to crop land. Model results show that the sugarcane production will be concentrated in regions characterized by a productivity increase. In order to reach the 2022 bioethanol target only 0.07 million ha new land and only 0.02% additional deforestation rates are necessary. An increase of bioethanol production would further have a very limited impact on food security [273].

If the past development of bioethanol in Brazil can be considered as a success, important technological bottlenecks still remain [272]. The innovation and technology transfer from research institutes to companies is relatively low and in particular the 2^{nd} generation of bioethanol biofuels[70] is still at an early stage of development [272]. The future development of Brazilian bioethanol as a global commodity is dependent on the implementation of dedicated policies and regulations. This would encourage companies to invest in innovation and research and development programs. Only then will innovative biofuels have a chance to emerge.

9.3.2 Methodology transferability: drivers and challenges for a future model implementation

In order to analyse the conditions for a future emergence of 2nd generation bioethanol, robust evaluation and forecast of production costs are necessary. In [275] an outlook for bioethanol production costs in Brazil up to 2030 is given. It includes first and second generation of bioethanol, that last one being produced from elephant grass or eucalyptus. In 2016 the production costs for bioethanol from elephant grass and eucalyptus were estimated at about 870 and 810 $\$/m^3$ respectively [275]. A production costs decrease of up to 750 $\$/m^3$ for elephant grass and 710 $\$/m^3$ for eucalyptus is foreseen

[70] The 2nd generation bioethanol results from the conversion of lignocellulosic and starchy materials in fermentable sugars that are able to be further processed into a sustainable biofuel [274]

by 2030 [275]. This major cost reduction would be achieved essentially by improving the biomass yields and process efficiencies [275]. The current situation for bioethanol in Brazil can be assessed with the help of a process simulation model. The model would lead to the identification of the most cost-effective bioethanol plant sizes and types assuming variable and differentiated biomass input.

Optimized second-generation bioethanol from eucalyptus could lead to competitive production costs compared with first generation biofuels. To this aim cost minimization coupled with process simulation represent promising and applicable modelling approaches. The profit maximization model employed in Germany for biogas remains however not transferable to Brazilian bioethanol. No subsidies directly linked to plant sizes and types are employed for bioethanol in Brazil, which limits the optimization model to a cost minimizing approach. A forecast of regional bioethanol production costs[71] and regional biomass potentials combined with the estimation of existing bioethanol plants would provide the main input data for an optimization model. The model objective would consist in minimizing the total bioethanol production costs for all Brazilian regions and plant sizes up to 2030. The model outcomes would provide valuable information for research institutions, policy and decision-makers concerning the most promising regions[72] and strategies for the development of 2^{nd} generation bioethanol. In [275] future challenges to be overcome by the Brazilian bioethanol industry are highlighted. Crop improvement, supply chain optimization as well as the integration of socio-economic impacts - including the "food versus fuel" debate - are pointed out. The future development of bioethanol supply chains in Brazil has to integrate sustainability criteria and thus requires integrated approaches.

[71] A possible way to obtain regional bioethanol production costs in Brazil would be to evaluate and to integrate regional biomass feedstock costs in the optimization model.
[72] In [275] the adjoining regions of Sao Paulo are identified as economically attractive for a future bioethanol production.

9.4 Biodiesel production from jatropha in Indonesia

9.4.1 Current situation and lessons learned

By 2016, total Indonesian fuel consumption in the transport sector was estimated at about 70 billion liters [276]. It was mainly dominated by gasoline and diesel representing 47% and 46% of total national consumption respectively [276]. Since 2005 continuous development of biodiesel[73] in Indonesian fuel consumption has been observed. The biodiesel blend rate increased from 0.2% in 2009 to 10.2% in 2016 [276]. First generation biofuels produced from starch, sugar, animal fats or vegetable oil as well as crude palm oil were initially developed in Indonesia in order to reduce oil imports and carbon emissions. The National Medium-Term Development Plan RPJMN[74] has the objective of producing between 4.3 and 10 million liters of biodiesel and 0.34 and 0.93 million liters of bioethanol by 2019 [279]. A target share of 25% biodiesel in the global diesel fuels by 2019 has been set and a mandatory biodiesel rate of 20% was imposed in 2016 [279]. The Indonesian biofuels industry is principally dominated by palm oil. This development has been supported in the past by the imposition of export levies of at about 50$ a ton for palm oil and 30$ for processed products [279]. The funds raised by these levies were reused to subsidize biodiesel production and to launch new research and development programs.

[73] Biodiesel is a chemically modified alternative fuel which can be used in diesel engines. It can be derived from vegetable oils and animal fats, soybean, cottonseed, groundnut, sunflower, rapeseed, sesame, palm oil, coconut, linseed, castor, camelina, hemp, olive, jatropha, corn, tallow, lard, poultry and rendered fats, used frying oil [277].

[74] The RPJMN objective is to encourage "sustainable growth, increasing value added of natural resources with the sustainable approach, increasing quality of the environment, disaster mitigation and tackling climate change". It concerns in particular the reduction of greenhouse gas emission in the forestry and peat lands, agriculture, energy and transportation, industrial and waste sectors. A specific target 26 % is set by 2019, in line with the National Action Plan for Greenhouse Gas Emission Reduction (RAN – GRK) [278].

The growth of the Indonesian palm oil industry, however, incurred high environmental and social costs [279]. Increasing local palm oil production caused a massive land clearing of most of the carbon-dense forests and rising greenhouse gas emissions. Further environmental problems were biodiversity losses in forest areas as well as pollution due to combustion in palm oil plantations [279]. Social conflicts over land use frequently arise between local population and industrial palm oil corporations. An alternative to palm oil valorization consists in producing biodiesel from jatropha curcas. The use of jatropha curcas as a biodiesel source was first promoted in 2005 by the Indonesian government. The objective was to lower the effects of increasing world crude oil prices by developing jatropha-based biodiesel.

The advantages and disadvantages of jatropha curcas are summed up in Table 9-1. In spite of its non-edible character and its low labour and nutrient requirements, jatropha curcas also has disadvantages which jeopardize profitable valorization into biodiesel.

Table 9.1: Advantages and disadvantages of jatropha curcas [280], [281], [282], [283]

Advantages	Disadvantages
Non-edible plant which does not compete with the food supply chain when used for biodiesel production. Can be used as a hedge against soil erosion and desertification. Can be grown on degraded poor soils in semi-arid conditions. Has low nutrient requirements and requires limited labour input (perennial crop). Seed cakes contain nitrogen and can thus be used as organic fertilizer. Jatropha has medicinal properties.	Jatropha generally takes four to five years to reach maturity The seed cakes cannot be used as animal feed. There is a risk of land use competition with food crops if the plantations are cultivated on arable soils Only limited agronomic data concerning the plant are available (yield and production costs uncertainty, unknown environmental impacts).

	The toxicity of jatropha extracts from fruit, seed, oil, roots, latex, bark, and leaf is well-established.

In [284] an economic assessment of jatropha biodiesel projects has been carried out and further highlights poor profitability levels. This is mainly explained by low hectare yields, high production costs, limited seed availability and decreasing fossil fuels price. According to [285], jatropha yields vary from 0.1 to 1 t/ha which is very low in comparison to other biomass feedstocks. High maintenance, labor and transport costs also generate high production costs. According to [285] a possible way to reach profitability could consist in using Clean Development Mechanisms (CDM) in order to finance the projects. Taking into account these revenue sources a profitable situation can only be reached from a jatropha yield of about 2.5 t/ha [285]. This critical yield can currently not be achieved in Indonesia so that farmers would tend to cultivate more productive crops. In addition, Indonesian jatropha oil and seed sectors suffered from a lack of a consistent national market strategy. Jatropha was mainly supported by governmental incentives without stimulating biodiesel demand. Farmers were then unable to sell their harvests and production [286].

Due to its non-competition with the food value chain the cultivation of jatropha curcas on degraded soils at first sight represents a potentially interesting option for biodiesel production especially in remote areas. However, numerous research and development projects have been launched in recent years and have produced, unfortunately, disappointing and negative results. A lack of theoretical and scientific knowledge regarding the crop cultivation, low commercial availability, poor profitability and insufficient yields have induced major failures but also led to the identification of new challenges described in the next section.

9.4.2 Methodology transferability: drivers and challenges for a future model implementation

A lack of reliable techno-economic data combined with the unprofitability of past jatropha projects in Indonesia renders the transfer of the methodology applied to biogas in Germany very difficult. Nevertheless, a possible modelling approach would consist, if data were available, in coupling agroeconomic models with integrated economic evaluation tools. Such models have already been developed for biogas in Germany [287]. A first step would be to determine the conditions leading to maximal biodiesel production yields from jatropha. An improvement of the oil extraction methods as well as the implementation of suitable enzymes could improve productivity. Transesterification and thermal cracking processes, mostly used for the conversion of jatropha crude oil into biodiesel, have still to be optimized by using environmentally friendly catalysts with high conversion efficiencies. The crop properties could further be modified with the help of biotechnological applications (plant breeding). The work on the jatropha genome is still at the early stage and remains far behind that of other agricultural crops. An optimized valorization of by-products such as seed cake and glycerin would have positive impacts on the process economic balance and its sustainability. The increase of the recovery rate for the glycerin derived from the transesterification process as well as the detoxification of seed cake are in particular key issues. All these optimization measures would contribute to minimize the production costs of jatropha-based biodiesel. Given these production costs an economic evaluation tool could be developed. This would lead to the determination of the critical revenue level needed for project profitability. The Clean Development Mechanism as well as incomes from seed cake sale as an organic fertilizer represent possible revenues sources. Recommendations for government and policy makers could then be formulated highlighting in particular the local benefits created by jatropha biodiesel.

9.5 Summary

The model transferability towards other valorization pathways than biogas in Germany has been assessed in several case studies and leads to heterogeneous conclusions. The biomethane injection in France is strongly developing and is mainly driven by a stable legal framework corresponding to Feed-In-Tariffs. First techno-economic assessments and data are already published and current as well as future biomass potentials have been clearly identified. This creates suited conditions for a model transfer from the German biogas experience to French biomethane injection. A simulation model would help plant operators to identify most profitable biomethane plant capacity under a variable biomass feed-stock input. The optimization model would lead to a forecast of future biomethane injection capacity. Future developments could be then compared to the defined national objective for biomethane under various scenarios.

Biomass district heating plays a major role in the Finnish renewable energy system. Best practice exchanges already exist, e.g., in the North Karelia region. However, an instability related to the employed Feed-In-Tariffs as well as the lack of regional data for biomass feedstock prices and potentials render the model transferability at the regional scale difficult. Future challenges consist in developing new projects in young and small-scale forests. This would contribute to reach defined national targets for wood chip energetic valorization.

Bioethanol production in Brazil can be considered as a “success story” since 1960 so that currently biofuels represent about 20% of the national transportation fuel demand. These developments have been supported by governmental initiatives (e.g., the PROALCOOL program) and by continuous research and development efforts. Future challenges for the Brazilian bioethanol industry remain in the expansion of the sugarcane area harvested for bioethanol. This expansion should respect sustainability criteria and minimize the competition regarding land-use change. A further challenge concerns the future industrial development of 2nd generation bioethanol. Brazilian lignocellulosic bioethanol still remains at the research stage. In order to expand it up to an industrial scale a cost minimization approach is necessary. To this aim optimization models minimizing the total bioethanol production costs over all Brazilian regions could be employed. They would provide insights about future bioethanol plant developments under optimal economic conditions.

The conversion of jatropha curcas into biodiesel in Indonesia at first sight represents a promising technological solution for the production of biodiesel as a sustainable biofuel. Jatropha is a non-edible plant which can be cultivated on degraded lands so that no competition with the food value chain occurs. Nevertheless, low yield and profitability levels as well as a lack of scientific and agroeconomic data render the model transferability from biogas in Germany to jatropha in Indonesia very difficult.

In conclusion the transferability of the developed methodological framework from Germany to other countries and bioenergy pathways is depending on several key-factors. A stable subsidy framework, e.g., Feed-In-Tariffs, as well as a robust production costs forecast are systematically required. The evaluation of biomass potentials at the regional scale is further necessary for the implementation of regional optimization models. This would contribute to estimate mid-term development for each considered bioenergy pathway under various scenarios. Furthermore, the implementation of the models and methodology used in Germany to other countries has to take into account sustainability criteria. This includes in particular the assessment of socio-economic impacts as well as a reduced competition between food and fuel and/or between energy and material use.

10 Summary, conclusions and outlook

10.1 Summary

In this thesis, a model-based framework is developed for the assessment of current and future electricity production from biogas in Germany. It provides answers to two main research questions. The first one concerns the identification of the most profitable biogas plant sizes and types under different legal frameworks of the Renewable Energy Sources Act (EEG 2012 and EEG 2014). Which installation types and sizes should be built under these framework conditions in order to lead to the highest profitability for German biogas plant operators? The second research question concerns future developments regarding new built biogas plant capacity on a mid-term time horizon, i.e., up to the year 2030. Which future capacity developments can be foreseen up to the year 2030 at the Federal State level in order to ensure maximal operating profits for German biogas plant operators?

The modelling concept corresponds to the perspective of biogas plant operators with the objective of a profit maximization. The objective is to provide an economic foresight for operators both on short and mid-terms. Model input data concern biomass feedstock characteristics, plant operation mode, existing biogas capacity, current and future biomass potentials as well as all costs and revenues positions. The data is derived from literature sources, from questionnaires sent to plant operators and also results from own methodology. In particular, the total capital investment is estimated for each plant size and type by using the Multiplier Values Method. A methodology is also developed for the evaluation of energy crop costs at the Federal State level based on regional hectare yields. A simulation model leads to the identification of the most profitable plant sizes for the three major installation types in Germany employing energy crops and manure in co-digestion (EM plant) and biowaste and energy crops in mono-digestion processes (B and E plants). The model developed is based on a process simulation tool which enables the economic assessment of the three plant types under a variable biomass input mass flow. The results are analysed under the EEG 2012 and EEG 2014 legal frameworks dedicated to electricity production from biogas in Germany. For small-scale plant sizes below to 75 $\mathrm{kW_{el}}$ the results show that manure plant types appear as the most profitable installation type due to high electricity sale revenues (e.g., 23.53 $\mathrm{ct/kWh_{el}}$ in 2014). Starting from 550 $\mathrm{kW_{el}}$, biowaste plants represent the most economically attractive option under EEG 2014. Furthermore, all agricultural plant sizes turn out to be unprofitable under the EEG 2014 framework. This is essentially due to the subsidies cut applied to energy crops. In addition to the economic assessment, sensitivity analyses are realized for the most profitable plant sizes. They quantify the impact of the main drivers on plants profitability. Energy crop and investment-related costs, electricity sale price as well as revenues from the biowaste valorization represent the main factors influencing plant profitability. Their evolution can generate risks but also opportunities for plant operators. A technical assessment leads to the estimation of energetic efficiencies for the most profitable plant sizes over the whole supply chain. The most profitable plant sizes identified in the simulation model appear as plausible with regard to the legal framework conditions of EEG 2014 which is favourable to small manure plants and large-scale biowaste installations. For plants smaller than 150 $\mathrm{kW_{el}}$ an economic comparison with the new EEG 2017 is realized. This new legal framework only has a very slight negative impact on the profitability in comparison with the results observed under EEG 2014.

In a further step, future capacity expansion and electricity production from biogas are estimated up to the year 2030 with the help of a regional optimization model. The model’s objective is to maximize the total operating profit over all plant sizes, the whole time period and all Federal States combined. This aims to provide information regarding future mid-term developments for biogas in Germany from a plant operator perspective.

Several constraints apply concerning biomass potential limitations as well as annual capacity expansion caps. A “base scenario” is defined on the basis of the costs and revenues data employed in the previous simulation model. A methodology for determining energy crop costs at the Federal State level is developed and leads to a regionalization of the optimization model. These data sets are completed by the evaluation of the existing biogas plant park in each Federal State according to the three reference plant types. Current and future regional biomass potentials for electricity production are further estimated based on literature data.

The results show that the EEG 2012 framework – if maintained – would have strengthened the development of agricultural plants and especially co-digestion plants valorizing energy crops and manure. The EEG 2014 framework stops the initially expected development of energy crops mono-digestion plants which will not be built anymore as they are unprofitable (negative specific operating profit for all plant sizes in all regions and over the whole time period). At the end of 2030 and under the EEG 2014 framework, an installed electric power of about 4 GW_{el} should be reached over all Federal States. This total capacity is split into 1.94 GW_{el} linked to base-load capacities and 2.06 GW_{el} related to existing and new built flexible capacities. Further scenarios quantify the robustness of the optimization model in reaction to shocks applied to revenues from the annual average EPEX-Peak electricity sale, to the energy crop costs and to biowaste valorization revenues between the years 2020 and 2025. A strong EPEX-Peak electricity price increase favours the development of large-scale plants and limits the expansion of small-scale manure installations. A strong energy crop costs increase generates unprofitability in several Federal States which limits future capacity developments. An important decrease of biowaste valorization revenues freezes future capacity expansion. The results linked to these “shock scenarios” represent precious information for policymakers and plant operators as they contribute to quantify the potential threats and opportunities for the future German biogas market on a mid-term horizon. A forecast comparison with existing studies as well as with the recently enacted EEG 2017 legal framework is further realized.

The transferability of the developed methodological framework towards other countries and other bioenergy conversion pathways is then evaluated. Both the simulation and optimization models could be implemented in France where the biomethane injection into the natural gas grid is strongly developing. A robust legal framework combined with available regional data offer adequate conditions for a future model integration. The combustion of woody biomass for district heating in Finland is a subsidized and mature bioenergy conversion technology. It plays a major role in the national heat demand and already benefits from best practices exchange issued from projects in the eastern region. The simulation model developed for the analysis of current electricity production from biogas in Germany is applicable to Finnish biomass district heating plants. It would lead to the identification of most profitable plant sizes and types under current legal framework conditions. Unavailable regional data especially regarding biomass potentials, prices and quality renders the optimization model transfer at the regional scale difficult. An implementation at the national Finnish level remains however possible. The transferability of the methodology to the liquid biofuel sector has been further examined through the cases of bioethanol in Brazil and biodiesel production from jatropha in Indonesia. On the basis of existing economic studies and projects, a simulative approach as well as an optimization model minimizing the total Brazilian bioethanol production costs up to the year 2030 are implementable. Future developments for bioethanol in Brazil should however take into account environmental and social aspects in particular concerning greenhouse gas balance, impacts on biodiversity, water and air, as well as regarding the “food versus fuel” debate. The valorization of jatropha into biodiesel in Indonesia represents at the first sight a promising pathway for biofuels production, as jatropha does not compete with food value chain. However, the low production yields currently observed in Indonesia and a lack of reliable data do not provide suitable conditions for a future model transfer. Technical process improvements are required in order to reach profitable yields and the implementation of Clean Development Mechanisms (CDM) would represent possible financing options for future projects. In all case studies a robust forecast of productions costs and revenues as well as stable legal frameworks and regional data are prerequisites for a further model implementation.

10.2 Conclusions

Several conclusions and recommendations can be formulated in relation to the analysis of current and future electricity production from biogas in Germany. Currently only discrete economic analyses of individual German biogas plants exist. The added-value of the simulation model developed is thus to enable a continuous profitability assessment under variable biomass input and taking into consideration different legal frameworks (versions 2012 and 2014 of the Renewable Energy Sources Act). The simulative approach further provides indications regarding the most profitable biogas plant sizes to be built under various legal frameworks. The identification of the most profitable plant sizes combined with the quantification of the main profitability drivers through a sensitivity analysis provides a useful assistance to plant operators. It enables more strategic installation design taking into account existing legal frameworks for biogas in Germany. The simulation model thus gives valuable insights for plant operators wishing to operate their installation in the most profitable way.

The optimization model developed delivers strategic outcomes concerning the evolution of future regional developments for biogas plants in Germany. The modelling approach is considered from the plant operator perspective and represents an added value in comparison with other existing studies. These assessments are based on a systemic approach and do not quantify the regional evolution of various biogas plant types and sizes. The model results show that the German biogas market will thus face a paradigm shift and move to strong development of small-scale manure plants and large-scale biowaste plants. The development of these plant types and sizes should lead to the highest profitability from the plant operator perspective. This forthcoming shift into the development of waste and residues-based plants should clear the main acceptance problems which have raised in the past years for biogas in Germany [15]. Acceptance problems in Germany concern notably the “food versus fuel” debate and in particular the increasing use of maize silage for biogas production. In addition, citizens are potentially concerned by the commissioning of new biogas plants close to their housings. They fear negative impacts due to biogas like increasing road traffic or odour emissions [15]. The model results further show that a generalized decommissioning will occur starting from 2020 for plants older than 20 years. This aspect must be balanced by a continuously improved integration of biogas into the German electricity market. According to the model results, about 50% of the electricity from biogas will be produced in 2030 by flexible plants based on the direct electricity marketing model. The simulation and optimization models deliver insights for plant operators regarding the current and future electricity production from biogas in Germany. Based on these outcomes, recommendations are addressed.

A first recommendation consists in improving the economic balance for small to mid-scale biowaste plants which are not profitable under the EEG 2014 framework. A future development of this installations type would establish local circular bio-economies and decentralized markets both for biowaste and for the produced digestate. A better involvement of local actors in biowaste plant projects should be encouraged and could lead to an increase of the municipal fee revenues dedicated to biowaste valorization in biogas plants.

A second recommendation concerns the need for developing biogas plants based on agricultural residues. Residues are generally available for free and do not compete with the food value chain. This development would provide new perspectives especially for agricultural biogas plants whose profitability was strongly impacted by the energy crops and manure subsidy cut under the EEG 2014 framework.

A third recommendation is related to the development of small-scale manure biogas plants. The subsidy level linked to this plant type has to be maintained in order to ensure a continuous valorization of manure potentials of which only 50% are used by 2013 [172]. A new generation of local farming systems could thus emerge and contribute to the integration of biogas plants into small farming systems. This would contribute to a revitalization of the rural economy and facilitate the German energy transition by new job creation.

Another recommendation concerns the flexibilization degree of existing and new built plants which has to be improved by enlarging the flexibilization possibility to all plant sizes including small-scale manure plants. The flexibilization of future biogas plant should thus be fostered, especially regarding the set objective of 80% renewable energy sources in the national gross electricity consumption by 2050 [93]. This ambitious target implies a strong increase of fluctuating electricity sources like wind power or photovoltaics and thereby the need of flexible biogas plants in order to stabilize the electricity grid [288].

The methodological framework applied to the case of biogas in Germany is further transferable to other countries and to other conversion pathways under certain conditions. Robust and stable framework conditions involving e.g., Feed-In-Tariffs as well as consistent regional data for biomass potentials and prices are required. Lessons learned and best practices from past projects would further lead to substantial profitability improvements. For example, the developed methodology and models could be used for the analysis of the biomethane injection in France and the biomass district heating in Finland. This would contribute to reach specific targets for bioenergy and to facilitate the national energy transition in these countries.

10.3 Outlook

Future challenges and research needs for biogas in Germany are remaining and should be pointed out. In the context of volatile biomass feedstock and electricity prices, biogas plant operators must be able to understand and master the financial risks impacting the profitability of their installations. The models results show that the current economic balance as well as the future development of German biogas plants are highly sensitive to this volatility. The acquisition of new competencies and deep knowledge in the field of energy economics, commodities and electricity markets could thus help plant operators to strategically manage their installations.

The identification of model regions for biogas in Germany represents a strategic aspect for the European biogas sector. As Germany is by far the European biogas leader, best practices can be gathered and transferred to other European countries. The results of the optimization model show in particular that Lower-Saxony and North Rhine-Westphalia will be leading the future German biogas market and represent respectively about 25% and 15% of the total base-load biogas plant capacities at the end of 2030. These two “flagship regions” could be the seat of research and innovation projects. Innovative business models, applied to both agricultural and biowaste plants, could thereby be developed. In particular a first challenge remains in a better approach to flexibility from the feedstock side as well as from the gas storage side. Further research needs to be carried out on the optimization and strategic planning of biomass input loading and/or gas storage. Complementarily to gas storage, another possibility would be to operate flexible biogas plants by loading the biomass feedstock input and producing biogas only during high electricity price hours. For this a digitalization of existing and future biogas plants is necessary. This can be achieved by information and communication technologies (ICT) with an access to online data monitoring e.g., regarding process parameters or EPEX electricity prices [289]. In [290] the operation of flexible biogas plants following the electricity demand and price is described. The biomass loading step and the gas storage are strategically combined in order to maximize plant flexibility. A case study highlights cooperative approaches and strategies that have been experimented for a pool of flexible biogas plants in Switzerland. All flexible biogas plants in the pool are connected to a centralized control and regulation system. This control system synchronizes the operation of all connected biogas plants. This enables economically optimal and demand-driven electricity production occurring in peak times and linked to a high price level. In addition, modelling approaches such as an agent-based simulation of single decentralized biogas plants represent further research needs. These models would enable the simulation of interactions between individual installations belonging to a pool of flexible biogas plants. Flexibility options could be simulated according to biomass feedstock price and availability or depending on EPEX electricity price level. This would deliver insights regarding the optimal integration of flexible biogas plants into the German electricity system.

Another challenge is to increase the collection, mobilization and valorization rates of biowaste potentials for biogas plants. A separate collection of biowaste in households is compulsory according to the Waste Management Act 2012. However, continuous optimization measures must be applied at the household level in order to improve the biowaste collection rates. According to [291] these optimization measures can be divided into three major steps. The first step concerns the evaluation of the connection rate of a given municipality or a district to biowaste bins. Streets, districts or areas showing low connection rates should thereby be identified. In a second step a biowaste sorting analysis has to be performed in the settlement areas characterized by low connection rates. The content of biowaste bins must be qualitatively and quantitatively assessed. Further research work in this area would consist in deploying questionnaires in various German municipalities in order to better characterize biowaste management habits. This would lead to the formulation of concrete optimization measures for a more sustainable biowaste use.

A further aspect concerns synergies and mutualization effects to be found between biowaste fermentation and composting pathways. Household biowaste can be divided into green waste and kitchen biowaste which can generate biogas by fermentation but also a humus rich fertilizer through an aerobic composting process. According to [292] and [293] about 300 composting plants and 113 biowaste fermentation plants were operated in Germany at the end of 2014. Composting plants essentially valorize woody green waste with a high lignin-content. Fermentation processes employ easily degradable feedstock with a low lignin-content. The competition of use between these two valorization routes therefore remains limited. In [294] an economic and environmental comparison of biowaste composting and biowaste fermentation processes is carried out. Fermentation processes tend to show a better greenhouse gas and energy balance than composting technologies but are generally characterized by higher investment and operating costs. Current trends consist in finding complementary solutions between composting and fermentation processes, which should be combined and not opposed. As mentioned in [292], about 80 combined plants exist in Germany and employ both composting and fermentation processes on the same installation site. This hybrid plant model creates synergy effects especially if high fee revenues for biowaste valorization or high heat sale revenues are reached. In the future continuous development of this combined installations type must be politically encouraged. An optimal allocation of the household biowaste mass flows between composting and fermentation plants represents another important issue for the German biogas industry. For this, optimal logistic channels should be defined and the collection process of the biowaste should be coordinated and managed from centralized control platforms. To this aim further research work have to focus on the model-based assessment of logistic supply chains dedicated to biowaste valorization. This would contribute to identify optimal logistical pathways and to minimize transport costs as well as environmental impacts.

Biogas plants are more and more involved in local approaches dedicated to autonomous energy supply. In Germany the “Bioenergiedorf” concept has been developed in several villages like in Jühnde [295]. In this village a decentralized energy supply is deployed and includes citizen participation. A biogas plant valorizing energy crops and manure in co-digestion, as well as a wood chip heating plant connected to a local heating network fully satisfy the local energy demand. A research project dealing with the profitability analysis of a flexible biogas plant has been launched there and highlights the importance of local heat valorization in the plant profitability. The European Institute for Energy Research (EIFER) also analysed the “Bioenergiedorf” concept in six villages located in Germany and in France [296]. In each village a case study has been developed. In a first step, biomass potentials and the energy consumption have been spatialized. Sociological, environmental as well as economic studies have been further carried out. This led to the elaboration of scenarios for local authorities, based on local data and dedicated to a local valorization of biomass resources. Most of the developed concepts had a positive impact on the heat production costs in comparison with a “Business as usual” scenario. Local pollutant emissions could be significantly reduced (especially CO_2, SO_2 and fine particles), e.g., by replacing the fuel oil energetic use by woody biomass or by implementing more efficient energy conversion systems (e.g., micro-cogeneration). Further research work is required in order to enlarge the “Bioenergiedorf” approach to new villages and to identify the main barriers and drivers for a future implementation.

A last challenge concerns the increase of the biogas contribution to the German heat transition[75]. At the end of the year 2015 the German heat mix was dominated by fossil energy sources with a share of 86.8% and 12% were related to bioenergy sources (the remaining 1.2% correspond to geo-thermal and solar thermal energy sources) [297]. The realization of the German heat transition is thereby deeply linked to the development of bioenergy sources. Solid biomass, mainly used in combustion or gasification process, shows the highest share in the renewable heat mix with approximatively 74.6% followed by biogas, sewer gas and landfill gas with about 12% [298]. An optimized valorization of the heat produced by biogas plants would therefore significantly contribute to reaching the objective of the German heat

[75] In the context of the German heat transition a share of 14% of renewable energy sources of the heat demand has to be reached by 2020 [87].

transition. However, planning uncertainty for a future increase of heat valorization remains [299]. This is especially the case for a plant operation after the 20 years EEG subsidy period. The development of renewable district heating networks connected to existing and future biogas plants would increase the valorization rate of the heat produced. A diversification of heat sinks (e.g., valorization in hospitals, schools, buildings for wood and cereals drying) and optimized heating contracting could further improve plants profitability [299]. Seasonal heat storage could there-by easily store the heat produced and feed it into district heating networks during high thermal demand time [300]. Further research work has to focus on the spatialization of heat sinks close to biogas plants, e.g., by using Geographical Information Systems (GIS). This would then facilitate the acquisition of supplementary heat sinks and also increase the contribution of biogas to the German renewable heat transition.

Appendix

Tables

Table A. 1: Current support schemes for the electricity production from biogas in each European country [70]

	FIT	Premium Tariff	Tenders	Quota System	Net Metering	Investment grants	Subsidy	Loan	Tax regulation	R & D	Grid connection	Other	N/A
Austria	■	■				■				■			
Belgium				■		■	■			■			
Bulgaria	■											■	
Republic of Cyprus											■		
Czech Republic							■						
Germany	■	■	■				■	■	■				
Denmark		■										■	
Estonia		■				■							
Greece	■												
Spain							■						
Finland		■				■	■						
France	■		■										
Croatia		■					■	■					
Hungary	■						■	■					
Ireland	■												
Italy	■	■	■		■								
Latvia	■		■				■	■			■		
Luxembourg	■						■						
Lithuania													■
Malta													■
Netherlands		■							■	■			
Poland				■			■	■					
Portugal	■												
Romania				■									
Sweden				■					■				
Slovenia	■		■				■	■					
Slovakia	■								■				
United Kingdom	■	■		■					■				

Table A. 2: Numerical values of the methane formation rate for each plant type

	Specified values for methane formation rate k (d^{-1})
Agricultural plant EM	0.00044
Agricultural plant E	0.00052
Biowaste plants B	0.00113

Table A. 3: Technical input data for the estimation of the flexibility premium

	Unit	Value
Existing base-load biogas plant		
Initial installed electric power (input data)	[kW_{el}]	1,000
Electric efficiency of the initially installed CHP (input data)	[%]	42.62 (see Figure A.15)
Full-load hours of the initially installed CHP (input data)	[h]	8,000 (own author's assumption)
Electricity amount fed into the grid and linked to the initially installed CHP (calculated)	[kWh_{el}]	8,000,000
Methane concentration in biogas (input data)	%	52 [162]
Biogas volume flow for the initially installed CHP (calculated)	[m^3/h]	453
Daily gas production in baseload (calculated)	[m^3]	10,862
Existing effective gas storage volume (input data)	[m^3]	4,000 (own author's assumption)
Plant upgrading: flexibilization		
Installed electric power for the supplementary flexible CHP (input data)	[kW_{el}]	800
Electric efficiency for the supplementary flexible CHP (input data)	[%]	39.7 (see Figure A.15)
Biogas volume flow for supplementary CHP in part-load (calculated)	[m^3/h]	391
Global plant		
Total installed electric power (calculated)	[kW_{el}]	1,800
Installed electric power linked to part-load for flexible CHP (input data)	[kW_{el}]	800
Full-load hours of the global flexible plant (calculated)	[h]	4,713

Table A. 4: Estimation of the flexibilization costs and flexibility premium

	Unit	Value
Supplementary flexible electric CHP power (input data)	[kW_{el}]	800
Investment for supplementary flexible CHP (calculated according to [150])	[€]	347,931
Specific investment-related costs for supplementary flexible CHP (calculated)	[ct/kWh_{el}]	0.71
Gas storage expansion: supplementary required volume (calculated)	[m^3]	32
Investment for gas storage (calculated as a function of storage volume based on [188])	[€]	15,572
Specific costs for gas storage (in ct/kWh_{el}) linked to the initially installed CHP running 8000 h per year (calculated).	[ct/kWh_{el}]	0.02
Flexibility premium under the EEG 2012 framework (calculated according to Eq. 3.2)	[ct/kWh_{el}]	1.13

Table A. 5: Regional hectare yields for maize silage [191]

	Hectare yields maize silage (t/ha)
Baden-Württemberg	46.22
Bavaria	50.04
Brandenburg	31.24
Hesse	49.41
Mecklenburg-Western Pomerania	34.50
Lower Saxony	44.86
North Rhine-Westphalia	46.64
Rhineland-Palatinate	45.97
Saarland	44.23
Saxony	40.07
Saxony-Anhalt	36.29
Schleswig-Holstein	36.65
Thuringia	41.43

Table A. 6: Regional hectare yields for rapeseed [191]

	Hectare yields rapeseed (t/ha)
Baden-Württemberg	39
Bavaria	34
Brandenburg	37
Hesse	40
Mecklenburg-Western Pomerania	33
Lower Saxony	40
North Rhine-Westphalia	40
Rhineland-Palatinate	39
Saarland	37
Saxony	39
Saxony-Anhalt	41
Schleswig-Holstein	43
Thuringia	38

Table A. 7: Regional hectare yields for grass silage [192]

	Hectare yields grass silage (t/ha)
Baden-Württemberg	16.57
Bavaria	21.14
Brandenburg	14.14
Hesse	14.86
Mecklenburg-Western Pomerania	12.57
Lower Saxony	23
North Rhine-Westphalia	17.86
Rhineland-Palatinate	15.14
Saarland	16.43
Saxony	19.86

Saxony-Anhalt	13.71
Schleswig-Holstein	21.71
Thuringia	18.71

Table A. 8: Regional hectare yields for cereal grain [191]

	Hectare yields cereal grain (t/ha)
Baden-Württemberg	6.55
Bavaria	6.01
Brandenburg	4.86
Hesse	6.66
Mecklenburg-Western Pomerania	5.74
Lower Saxony	6.56
North Rhine-Westphalia	6.78
Rhineland-Palatinate	6.33
Saarland	6.03
Saxony	5.64
Saxony-Anhalt	5.86
Schleswig-Holstein	7.07
Thuringia	6.38

Table A. 9: Regional hectare yields for cereal silage [191], [193]

	Hectare yields cereal silage (t/ha)
Baden-Württemberg	37.11
Bavaria	34.07
Brandenburg	27.56
Hesse	37.75
Mecklenburg-Western Pomerania	32.50

Lower Saxony	37.20
North Rhine-Westphalia	38.42
Rhineland-Palatinate	35.85
Saarland	34.19
Saxony	31.96
Saxony-Anhalt	33.21
Schleswig-Holstein	40.07
Thuringia	36.16

Table A. 10: Regional surface area for each energy crops type

	Maize silage (ha)	Grass silage (ha)	Cereal silage (ha)	Cereal grain (ha)
Baden-Württemberg	98,523	30,822	7,760	14,979
Bavaria	283,284	62,987	25,352	48,935
Brandenburg	64,540	19,806	6,196	11,961
Hesse	22,356	6,854	1,714	3,309
Mecklenburg-Western Pomerania	71,638	16,480	6,665	12,866
Lower Saxony	324,419	79,957	28,329	54,681
North Rhine-Westphalia	81,314	29,537	7,638	14,744
Rhineland-Palatinate	17,855	6,768	1,734	3,347
Saarland	1,404	418	126	244
Saxony	35,621	10,744	2,888	5,575
Saxony-Anhalt	55,437	10,664	3,762	7,261
Schleswig-Holstein	99,511	31,634	9,195	17,749
Thuringia	43,136	10,886	3,668	7,079

Table A. 11: Number of existing milk cows and remaining cattle at the end of the year 2012 [197], [198]

	Number of milk cows	Number of remaining cattle
Baden-Württemberg	353,715	661,271
Bavaria	1,244,456	2,111,455
Brandenburg	160,303	394,189
Hesse	149,180	314,472
Mecklenburg-Western Pomerania	171,573	372,585
Lower Saxony	769,283	1,715,346
North Rhine-Westphalia	392,466	988,357
Rhineland-Palatinate	118,501	250,379
Saarland	14,255	36,116
Saxony	187,011	302,033
Saxony-Anhalt	123,562	213,294
Schleswig-Holstein	364,240	772,932
Thuringia	111,478	224,895

Table A. 12: Regional manure mass flows

	Manure mass flows (t)
Baden-Württemberg	12,624,361
Bavaria	42,587,596
Brandenburg	6,524,606
Hesse	5,626,776
Mecklenburg-Western Pomerania	6,564,118
Lower Saxony	29,812,244
North Rhine-Westphalia	16,171,861
Rhineland-Palatinate	4,474,541

Saarland	589,235
Saxony	6,270,098
Saxony-Anhalt	4,259,527
Schleswig-Holstein	13,781,874
Thuringia	4,118,872

Table A. 13: Regional energy crop costs for the base year 2013

	Maize silage costs year 2013 (€/t)	Grass silage costs year 2013 (€/t)	Cereal silage costs year 2013 (€/t)	Cereal grain costs year 2013 (€/t)
Baden-Württemberg	31.70	27.69	33.22	182.87
Bavaria	25.23	24.23	33.32	187.59
Brandenburg	44.94	29.77	33.27	187.48
Hesse	30.35	28.73	33.51	186.94
Mecklenburg-Western Pomerania	36.03	27.14	31.40	186.55
Lower Saxony	34.02	29.56	37.28	204.74
North Rhine-Westphalia	32.47	31.63	33.90	186.75
Rhineland-Palatinate	31.61	30.11	33.33	185.69
Saarland	31.65	30.11	32.90	184.85
Saxony	36.27	25.64	33.10	187.50
Saxony-Anhalt	42.16	27.64	33.90	189.20
Schleswig-Holstein	44.77	29.81	34.75	190.83
Thuringia	34.62	32.93	33.54	189

Table A. 14: Feedstock specific electric yields

	Specific electric yield in kWh_{el}/t
Maize silage	401.45
Grass silage	333.96
Cereal silage	343.45
Cereal grains	1,068.02

Figures

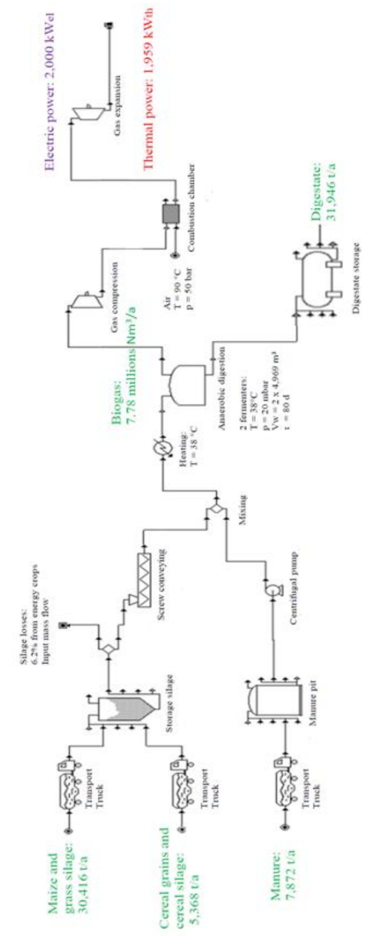

Figure A. 1: Example of a technical flowsheet for a 2,000 kWel EM plant

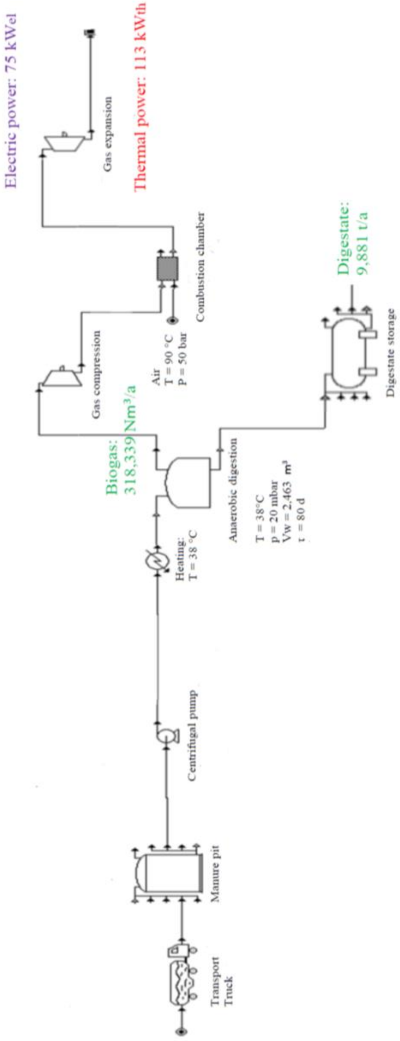

Figure A. 2: Example of a technical flowsheet for a 75 kWel small manure EM plant

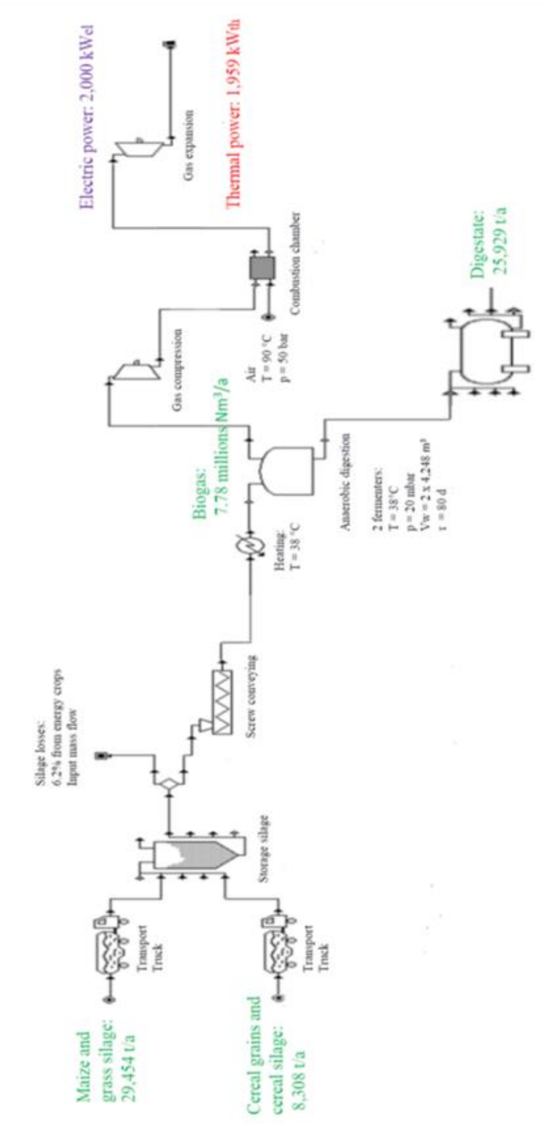

Figure A. 3: Example of a technical flowsheet for a 2,000 kWel E plant

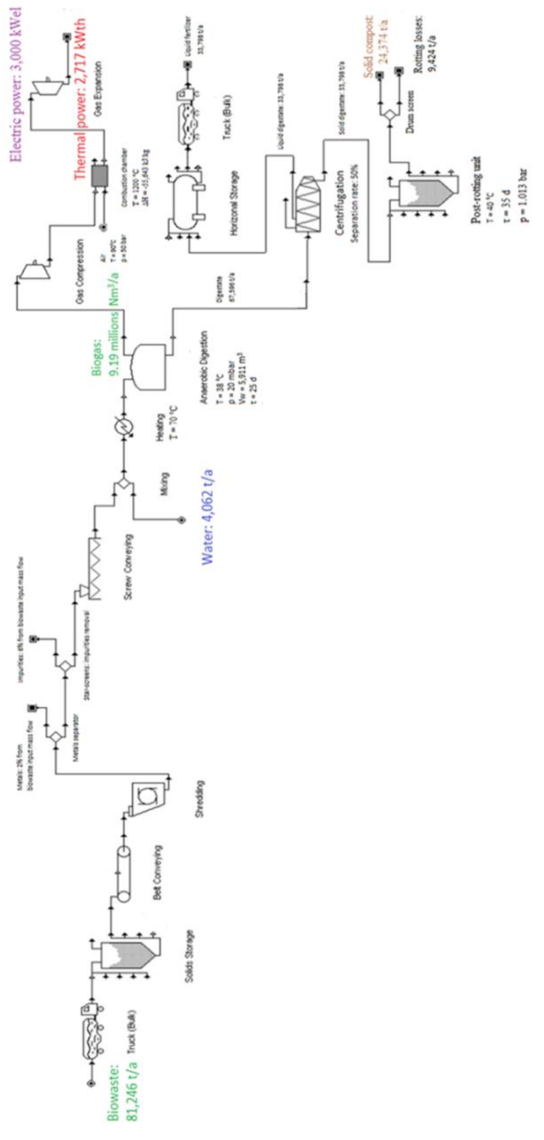

Figure A. 4: Example of a technical flowsheet for a 3,000 kWel B plant

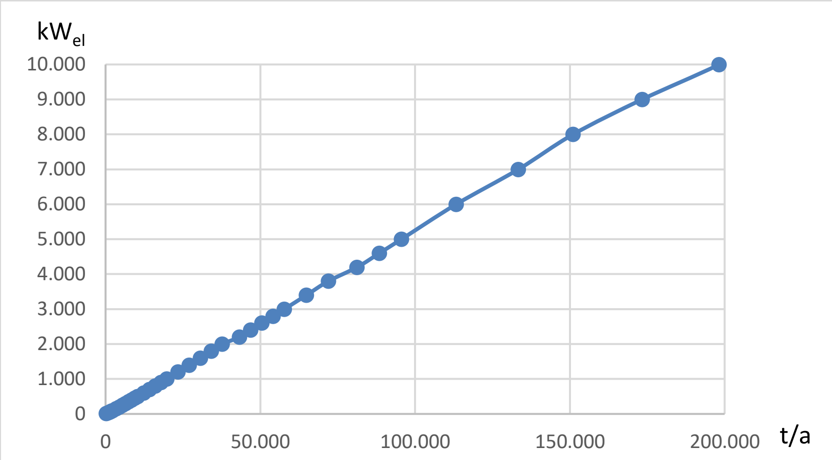

Figure A. 5: Electric power as a function of the biomass input mass flow (E plant)

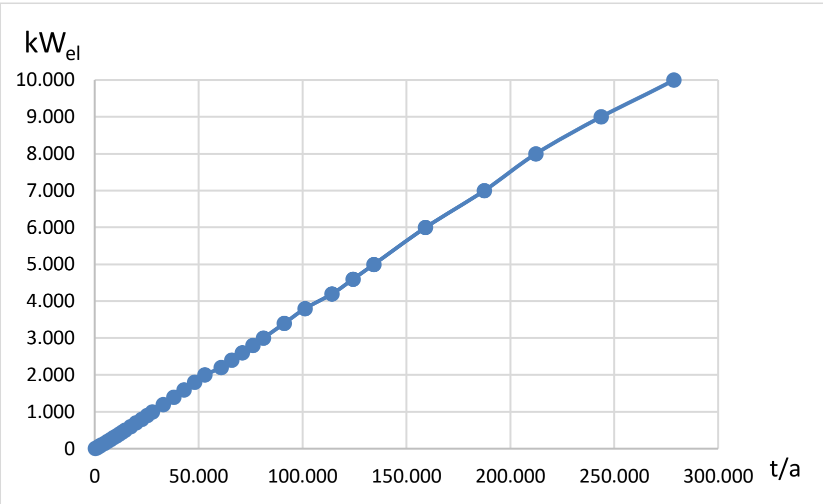

Figure A. 6: Electric power as a function of the biomass input mass flow (B plant)

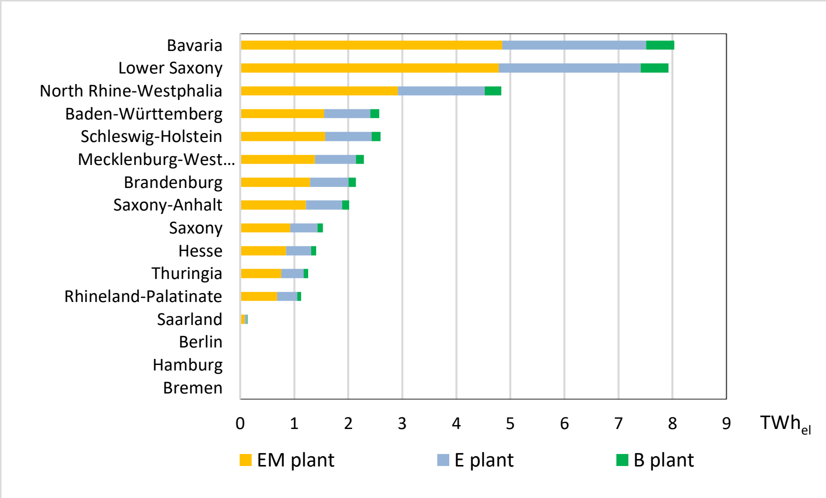

Figure A. 7: Allocated biomass potentials for electricity production at the end of the year 2012 in each Federal State

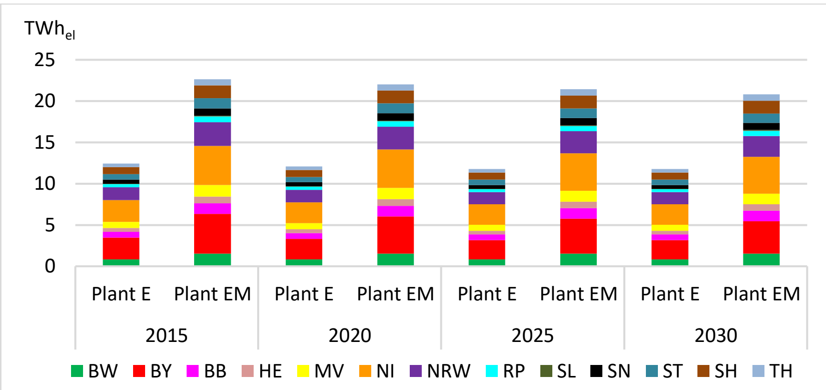

Figure A. 8: Evolution of biomass potentials for E and EM plants up to the year 2030 at the Federal State

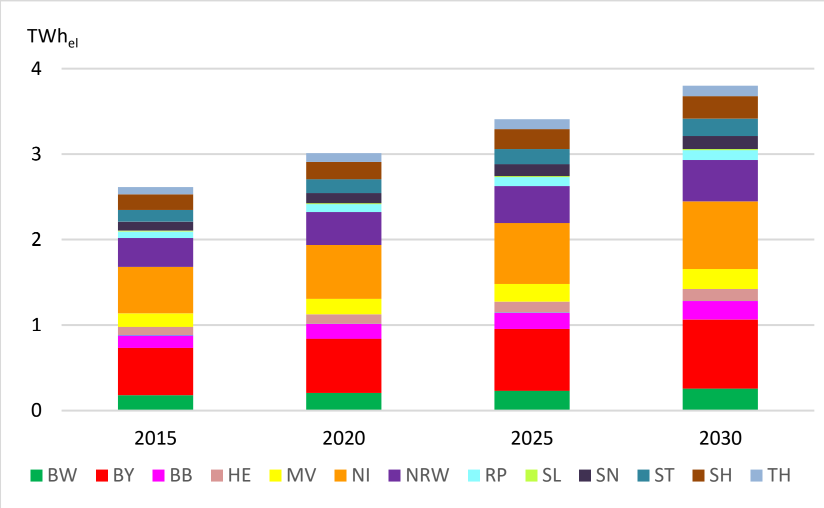

Figure A. 9: Evolution of biomass potentials for B plants up to the year 2030 at the Federal State level

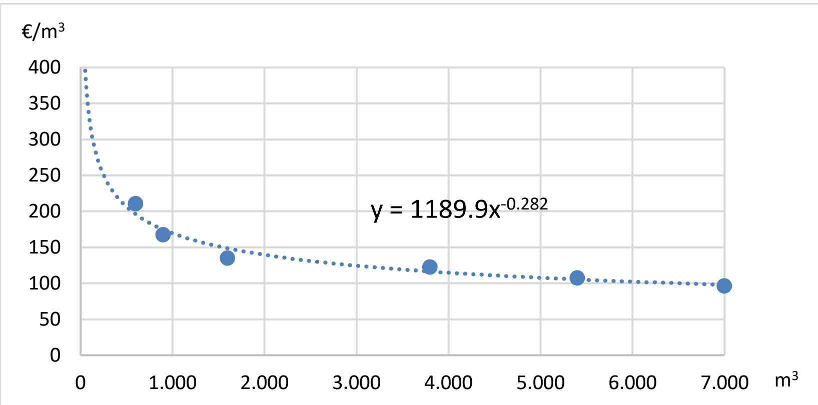

Figure A. 10: Specific acquisition costs for fermenter as a function of the fermenter working volume (EM plants)

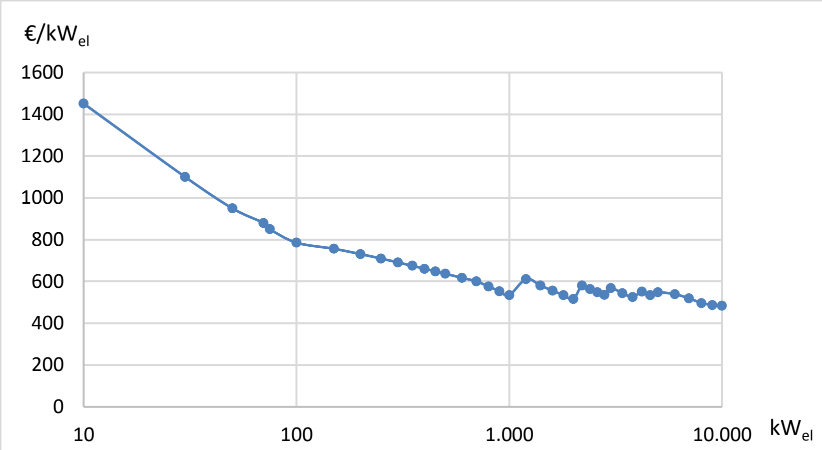

Figure A. 11: Specific acquisition costs for fermenter as a function of the installed electric power (EM plants)

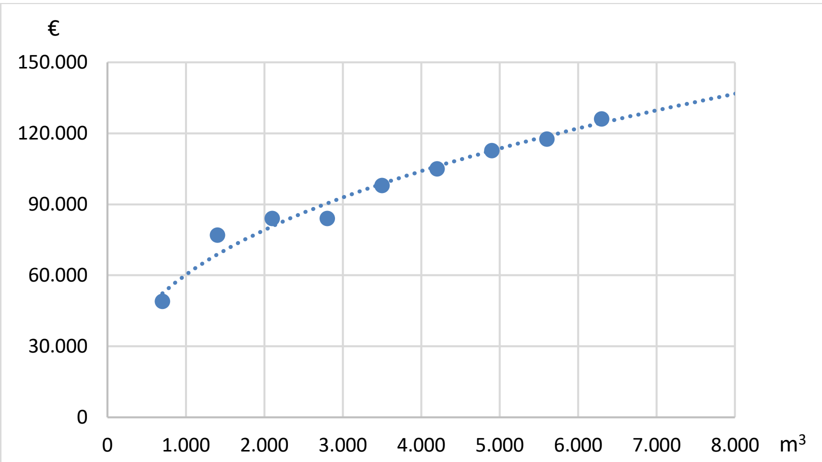

Figure A. 12: Capital investment for gas storage as a function of the storage volume [188]

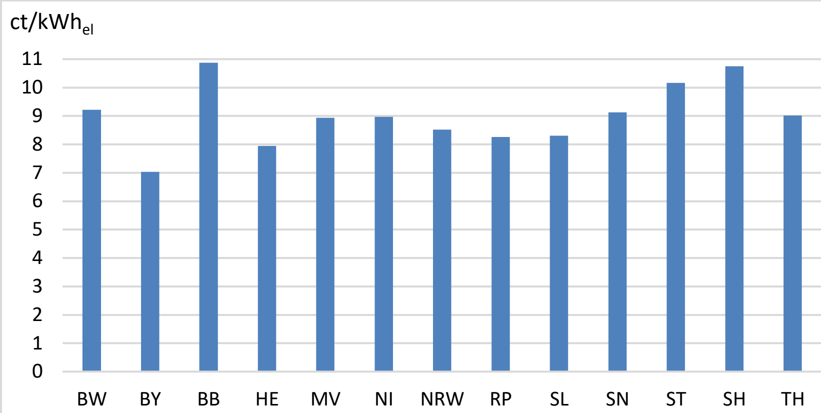

Figure A. 13: Energy crop cost contribution in the total electricity production costs for E plants and in each Federal State (year 2013)

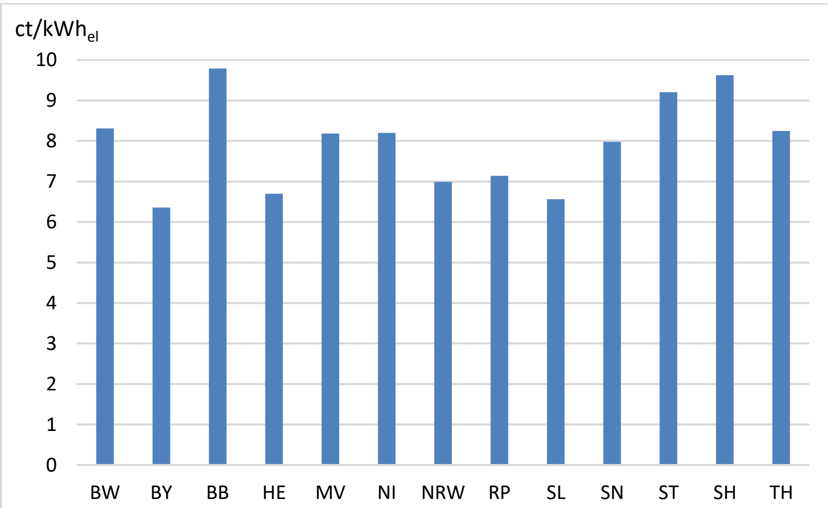

Figure A. 14: Energy crop cost contribution in the total electricity production costs for EM plants and in each Federal State (year 2013)

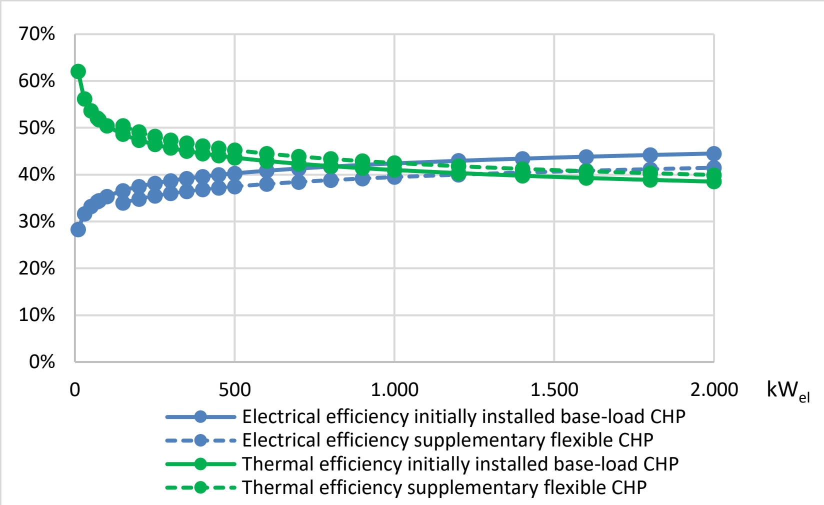

Figure A. 15: Thermal and electric CHPs efficiency for base-load CHPs and supplementary flexible CHPs as a function of the installed electric power [150]

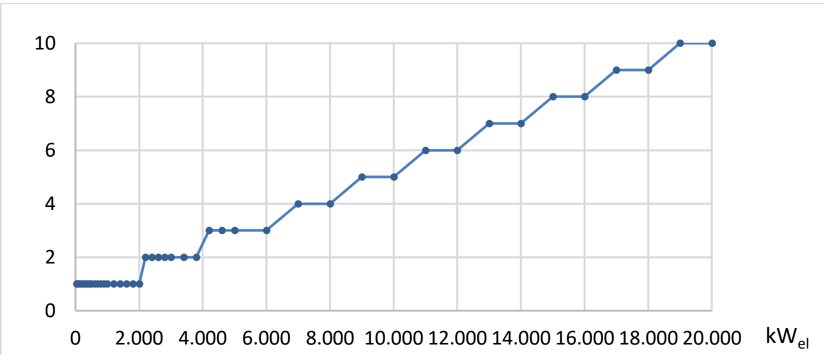

Figure A. 16: Number of CHP gas engines as a function of the installed electric power

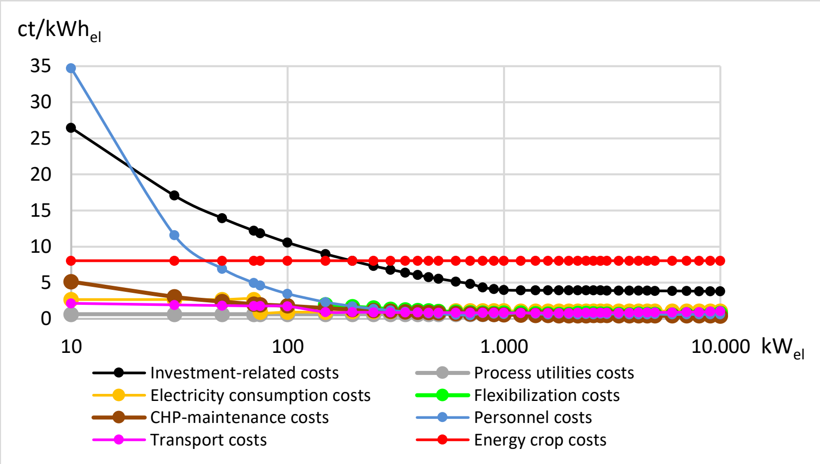

Figure A. 17: Specific annual costs for E plants as a function of the electric power for the base year 2015

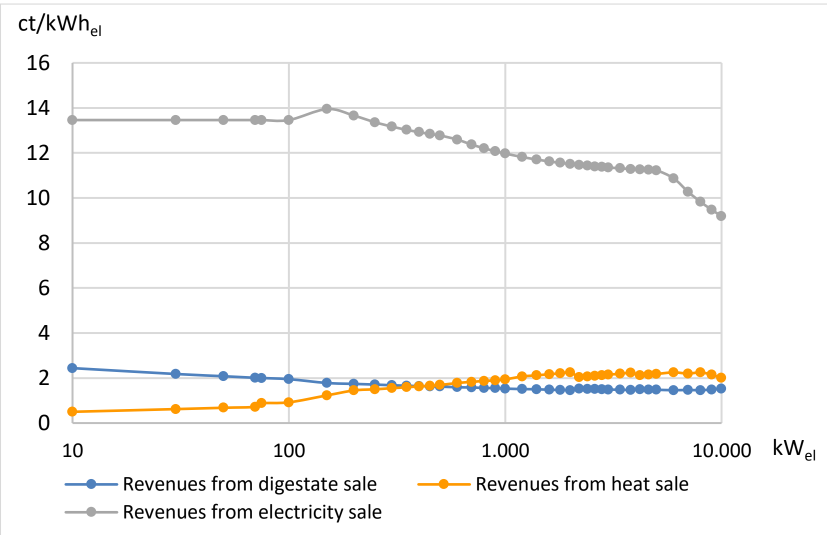

Figure A. 18: Specific annual revenues for E plants as a function of the electric power for the base year 2015 and under the EEG 2014 framework

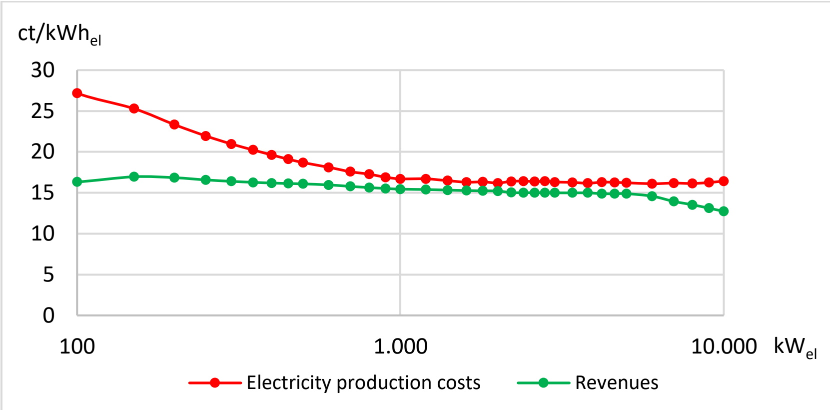

Figure A. 19: Specific electricity production costs and revenues for E plants as a function of the electric power for the base year 2015 and under the EEG 2014 framework.

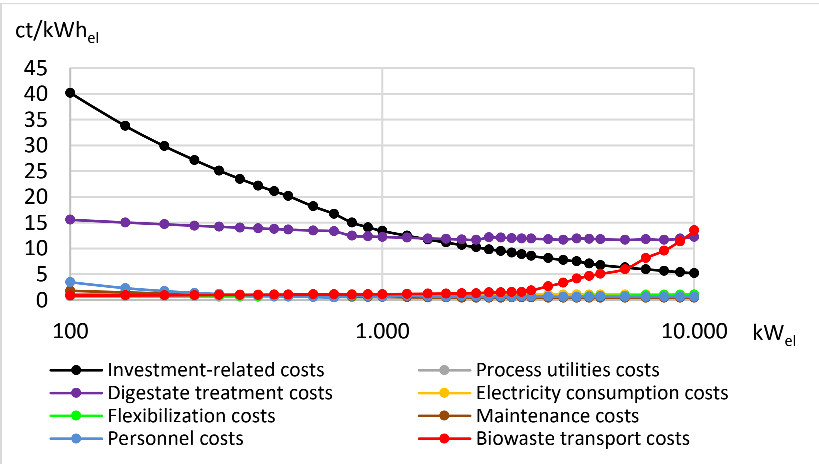

Figure A. 20: Specific annual costs for B plants as a function of the electric power for the base year 2015

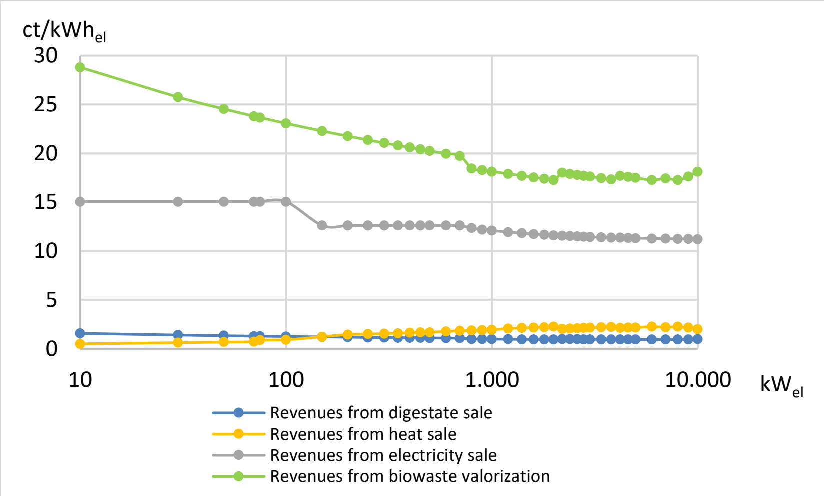

Figure A. 21: Specific annual revenues for B plants as a function of the electric power for the base year 2015 and under the EEG 2014 framework

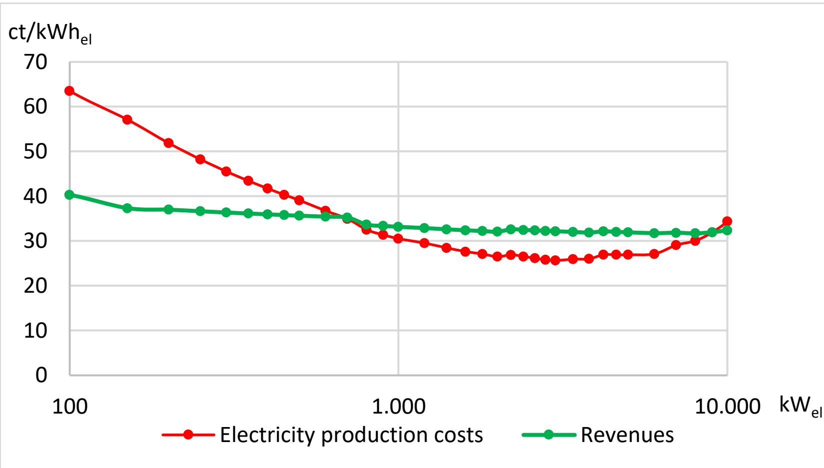

Figure A. 22: Specific electricity production costs and revenues for B plants as a function of the electric power for the base year 2015 and under the EEG 2014 framework

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DEUTSCH-FRANZÖSISCHES INSTITUT FÜR UMWELTFORSCHUNG

In this work a process simulation model coupled with an economic evaluation tool identifies the most profitable German biogas plant types and sizes. The results show that small manure and large-scale biowaste plants are currently the most economically attractive installations whereas the valorization of energy crops turns out to be unprofitable. The future development of German biogas plants is assessed with an optimization model. The objective function aims to maximize under constraints the total operating profit for each of the main plant types using energy crops, biowaste and manure up to the year 2030 at the Federal State level. Capacity expansion concerns small-scale manure and biowaste installations rather than plants based on energy crops. The transferability of the methodology to other countries and bioenergy pathways is examined. Stable framework conditions, the exchange of best practices and lessons learned between actors are pre-requisites for successful implementation.

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