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# Master Thesis

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# The Future of Gas Markets: Conventional vs. Second Generation Gas – A Comparative LCA



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Nürnberg, 29. Mai 2018

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# CONTENT

# LIST OF FIGURES

# List of Tables

# NOMENCLATURE

### *Abbreviations*

| | |
|---|---|
| bio | biologic |
| bio$CH_4$ | biomethane |
| bioSNG | synthetic natural gas from gasification of biomass |
| cat | catalytic |
| el | electric |
| GHG | greenhouse gas |
| GWP | global warming potential |
| IP | imported pellets |
| LCA | life cycle assessment |
| LCI | life cycle inventory analysis |
| LCIA | life cycle impact assessment |
| LHV | lower heating value |
| MC | Monte Carlo |
| ODT | oven dry ton |
| PEM | proton exchange membrane |
| PtH | Power to Hydrogen |
| PtM | Power to Methane |
| PtX | Power to X |
| reg$H_2$ | regenerative hydrogen |
| reg$CH_4$ | regenerative methane |
| RFW | residual forest wood |
| th | thermal |
| SNG | synthetic natural gas |
| SOEC | solid oxide electrolysis cell |
| SR | steam reforming |
| SRF | short rotation forestry |

### *Units*

| | |
|---|---|
| a | year |
| bar | bar |
| °C | degree Celsius |
| d | day |
| g | gram |
| h | hour |
| ha | hectare |
| J | joule |
| K | Kelvin |
| l | liter |
| m | meter |
| mol | mole |
| $Nm^3$ | standard cubic meters |
| t | ton |
| tkm | ton kilometers |
| vol% | percentage by volume |
| W | watt |
| Wh | watt hours |

### *Symbols*

| | |
|---|---|
| C | carbon |
| $CH_4$ | methane |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $CO_{2,\,eq}$ | carbon dioxide equivalents |
| $H_2$ | hydrogen |
| $H_2O$ | water |
| $N_2O$ | dinitrogen monoxide |

# ABSTRACT

This thesis investigates emissions from alternative gas production technologies with the life cycle assessment methodology according to DIN EN ISO 14040:2006 and 14044:2006. The least greenhouse gas emission intensive gas production processes are identified. This thesis compares three different technologies. First, production of biomethane from anaerobic digestion of manure, maize silage and biowaste; second, production of synthetic natural gas from the gasification of residual forest wood, short rotation forestry wood, straw and imported pellets; third, the production of hydrogen and methane via Power to X technologies from excess renewable electricity. In contrast to data from literature discussing this topic which is often incomplete and incomparable due to methodological inequalities, this study provides comparable and consistent results.

The results reveal the production of synthetic natural gas via gasification of biomass being the least greenhouse gas emission intensive technology. Best results for this technology are achieved by using residual forest wood and imported pellets as substrates. Anaerobic digestion of biowaste and steam reforming of methane to produce hydrogen leads to the highest emissions. The conversion processes anaerobic digestion and gasification, and the respective upgrading processes contribute most to the emissions of gas production from biomass. The environmental impact of gas production from excess renewable energy mainly depends on the electricity supply.

The findings of this study are available for further application in the project *SustainableGas* investigating strategies for the substitution of natural gas in the electricity and heat sector. Further investigations are recommended on the substrate provision processes.

# 1 Introduction

In 2015, the Sustainable Development Goals of the United Nations were defined. They aim at end poverty, to fight inequalities and to protect the planet and its natural resources. Seventeen Goals were stated to achieve these objectives [1, pp. 3, 14]. One of the goals is providing affordable, reliable and sustainable energy worldwide. Measures are to increase the share of renewable energy in the global energy mix, to improve the energy efficiency of energy production, and to promote investment in clean energy technology [1, p. 19]. Another goal is fighting climate change and its impacts. Supporting this goal, the Paris Agreement was adopted in 2012. Based on this agreement, the participating nations work to limit global temperature rise to below 2 °C by defining and implementing respective climate actions [2].

Compared to 1990, German climate protection objectives schedule a 55 to 56% reduction of greenhouse gas emissions until 2030, and a reduction of 80 to 95% until 2050 [3, p. 7 f.]. Subsequently, a transformation of the energy sector is required. This transformation is driven by further development of renewable energies, by the increase of energy efficiency and by the decline of fossil energy production [3, pp. 23, 34]. This also applies for the gas market.

The transformation of the energy sector is accompanied by challenges. Wind and solar power lead to weather-related fluctuations in the electricity supply which need to be balanced. Alternative energy sources are required to provide climate friendly heat [4, p. 3]. The coupling of the electricity and gas sector can meet these challenges by using energy storage capacities in the German natural gas grid. When the demand for electricity is low, energy surpluses from intermittent renewable electricity production can be converted into gas to be used in other sectors. It can be reconverted into electricity at times of increasing demand. Additional renewable gases can further bridge timespans with low electricity supply from solar or wind power and reduce the dependence of the German gas sector on foreign imports by substituting natural gas [4, p. 4], [5, p. 9].

## 1.1 Motivation and Goal

The project *SustainableGas* investigates strategies for the substitution of natural gas in the electricity and heat sector. The project is supported by the Federal Ministry of Economics and Technology (Bundesministerium für Wirtschaft und Energie) which examines the long-term transformation of the German energy supply system and its social acceptance. *SustainableGas* assesses especially the interaction of the developed strategies with alternative and conventional heat supply. To make recommendations based on the investigated strategies and their economic aspects, process chains are evaluated with regard to their potential, availability and costs, to possible ecological consequences and their interconnection with the regional or global ecosystem, and to their social acceptance [6].

This thesis aims at investigating greenhouse gas emissions from alternative gas production technologies. These emissions occurring during the production of biogas are a crucial contributor to the ecological consequences and to the social acceptance.

Compared to other studies investigating the emissions from biogas, this thesis provides a sustainable added value. Most of the reviewed studies are not comparable as they only assess a limited number of technologies with inconsistent conditions. This thesis compares renewable gas production technologies in a consistent way and therefore enables an informative comparison of their environmental performance.

To determine the respective emissions, a life cycle assessment (LCA) according to the guidelines DIN EN ISO 14040:2006 [7] and 14044:2006 [8] is conducted. The LCA is an internationally accepted methodology for determining the environmental aspects and impacts of product systems. The results of the executed LCA can be used to identify contributors on environmental impacts and to inform for discussions and decision-making [7, p. 4].

The assessed technologies in this thesis are

- biomethane from anaerobic digestion of manure, maize silage and biowaste,
- synthetic natural gas from the gasification of residual forest wood, short rotation forestry wood, straw and imported pellets, and
- hydrogen and methane produced via Power to X technologies from excess renewable electricity.

As mutual conventional reference, the production, distribution and combustion of natural gas is investigated.

Once the implementation of the LCA for each technology is executed, the results are further evaluated in a Monte Carlo simulation and are compared to data from literature. By comparison of the different technologies, the less greenhouse gas emission intensive one is identified.

The execution of this thesis is supported by the international research network ABBY-Net. ABBY-Net is a research alliance between Bavarian and Albertan universities investigating solutions for future energy systems. This thesis contributes to the project “Challenges and opportunities of alternative gas technologies in Germany and Alberta” assessing current gas production technology pathways for both Bavaria and Alberta.

## 1.2 LCA of Alternative Gas Production in the Literature

There is an enormous amount of literature discussing the environmental impacts of alternative gas production. This section provides a representative selection of studies implementing LCAs or comparable investigations on alternative gas production technologies.

Concerning the production of biogas from biomass, more studies on anaerobic digestion than on gasification can be found. The commonly assessed substrates are maize silage, manure, short rotation forestry wood, wood chips and wood pellets. Concerning Power to X technologies, there are less studies in general. Most of them focus on largely established technologies like alkaline electrolysis and catalytic methanation.

Most studies provide only relative final values as they compare alternative technologies with each other or with conventional options like the production of energy from natural gas. Absolute values are only given for certain intermittent steps. Furthermore, they often only provide greenhouse gas reduction potentials but no absolute emission values. Some studies are not implemented according to equal standards or do not specify the scale of the assessed facilities. Additionally, nearly every study is based on its individual system boundaries and fundamental assumptions. This literature review shows the considerable added value of this thesis as it provides LCAs of different technological pathways in a comparable and consistent way.

The following sections summarize the reviewed literature dealing with the production of biogas from biomass and with Power to X technologies producing hydrogen and methane from excess renewable energy.

***Biogas from biomass***

Fusi et al. [9] investigate the environmental impacts incurred by the anaerobic digestion of agricultural products and waste and the subsequent cogeneration of electricity and heat from biogas. They evaluate five biogas plants in Italy with different mixes of feedstock in accordance with the internationally accepted guidelines from the ISO 14040 series [7], [8]. According to this study, the main contributors to the environmental impacts are the operation of the anaerobic digestion process itself and the open digestate storage. Furthermore, most impacts arise from the digestion of maize silage. Animal slurry has the lowest greenhouse gas emissions considering the emissions avoided from digestate substituting slurry as a fertilizer.

Giuntoli et al. [10] provide input values and greenhouse gas emissions for different bioenergy pathways. The simplified LCA methodology is based on mainly secondary data. According to their calculations, more than 100% of greenhouse gases can be saved by production of biomethane from manure. This reduction is achieved due to the avoided emissions from manure storage being considered as credits. If a mixture of maize silage and manure is used as substrate, the savings still account for more than 80% of total emissions. The study identifies the conversion processes as main contributor to the emissions.

Zhang et al. [11] evaluate the biogas generation from anaerobic digestion of dairy manure in British Columbia, Canada. The implementation of this system on the farm leads to a reduction of the non-renewable energy consumption. Therefore, the impacts on climate change and acidification are reduced. The researchers state that the treatment of the digestate influences the environmental impacts significantly with digestate substituting chemical fertilizers being the best option. The biggest contributors on environmental impacts from the farm operation are the anaerobic digestion and upgrading process and the use of diesel and electricity for further farming activities.

Liebetrau et al. [12] determine the methane emissions occurring from biogas production in the agricultural sector. They compare the emissions of ten biogas facilities in Germany and work with primary data. The processes with installed capacities of 350 kW to 1500 kW are assessed from the delivery of the raw material to the application of digestate as fertilizer. Main raw materials are energy crops and manure. This study pays special attention to biogas-carrying equipment and identifies design-related factors like open digestate storage, and cogeneration units, and operational factors like improper handling of equipment as main contributors to environmental impacts.

Dunkelberg et al. [13] assess ecological and economic aspects of the upgrading and application of biomethane in the German energy system. They consider a mixture of substrates from maize silage and cattle manure. The results reveal the high greenhouse gas reduction potential of biomethane contradicting its huge impact on acidification and eutrophication compared to fossil alternatives. Furthermore, they identify amine scrubbing as preferred upgrading technology due to its low methane slip.

Claus et al. [14] develop a greenhouse gas balance of biomethane and subsequent energy production from maize in Germany. They study the whole process chain from crop production to the conversion to biogas and the production of energy from it. Their results show a carbon dioxide reduction potential of 55 to 61% when energy is produced from biogas compared to fossil alternatives. The biggest contributors to the emissions are the crop production and the biogas storage in case of open storage.

Müller-Langer et al. [5] study renewable raw materials substituting natural gas in an ecologic and economic way. In accordance with the ISO guidelines [7], [8], the LCA assesses cultivation of the biomass, its conversion and upgrading to biomethane and the distribution. The different pathways are compared to each other and to fossil energy sources. Substituting natural gas by biomethane turns out to be a spatial and temporal flexible possibility to avoid 62% of greenhouse gases. For anaerobic digestion, conversion of the biomass and the provision of the raw material contribute most to the emissions. The conversion is also the crucial factor for biogas produced by gasification. In general, the transport processes show a small influence on the total emissions.

Alamia et al. [15] compare emissions from the use of biomethane in heavy duty engines with fossil alternatives. The bioSNG pathway is based on the GoBiGas gas plant in Gothenburg, Sweden, and assesses all processes from pellet production, pellet conversion to biomethane, the compression and the final injection into the local gas network. The outstanding result of this study is the identification of the electricity mix as most important contributor to the greenhouse gas emissions. For the conversion of biogas into biofuels, a bigger amount of energy provided by electricity is required than for the conversion of natural gas. This results in higher emissions when biogas is used to produce biofuels.

Holmgren et al. [16] investigate the impact of the raw material supply chain on the greenhouse gas emissions in Sweden. Assessed substrates are 430 MW locally produced wood chips and wood pellets from Latvia and Canada. Furthermore, they study the impact of using excess heat and $CO_2$ storage on the final emissions. Findings from the study state that imported biomass increases the total emissions. Using excess heat for drying and storing the emitted $CO_2$ decreases emissions significantly.

Summarizing the literature research and review on biogas production from biomass, it can be observed that more studies are implemented on the production of biomethane from anaerobic digestion than on the production of bioSNG from gasification of biomass. Often values given in the results do not indicate the total emissions of the investigated pathway but only its potential to reduce emissions in comparison with a defined reference pathway. Different assumptions on including or excluding certain processes or byproducts further complicate the comparison of different technological variations.

***Power to X***

Sternberg and Bardow [17] assess the environmental impacts of energy storage systems in the US, Brazil, Germany and Japan. Relevant for this thesis are the assessed Power to Fuel systems. Concerning the feed-in of hydrogen into the natural gas grid, the results show that the global warming potential is caused solely by the construction of the plant. Additional contributors are the supply of heat and grid power and credits for avoiding $CO_2$ emissions for the conversion of hydrogen to hydrocarbons.

Parra et al. [18] implement a LCA according to the ISO guidelines [7], [8] of Power to X systems in Switzerland and study their economic and technological aspects. The LCA includes the production of renewable electricity, electrolysis (1 MW), provision of $CO_2$, methanation (6 MW), product gas processing and application, and construction of the required facility. The study reveals that Power to X processes are only beneficial compared to conventional processes if they use clean electricity free from emissions.

Collet et al. [19] conduct a LCA and a techno-economic analysis of Power to Gas processes compared to the methane production via biogas upgrading in France. From an economic point of view, with increasing electricity costs either the electricity consumption of the electrolysis needs to decrease or the operation time of the methanation needs to increase to provide competitiveness in the future. $CO_2$ for the methanation is assumed to be provided by amine scrubbing of raw biogas. According to this study, the Power to Gas process leads to higher greenhouse gas emissions than the conventional biogas upgrading, but to lower emissions than natural gas being combusted. Electricity consumption is an important contributor to ecological and economic aspects.

Zhang et al. [20] implement a LCA of Power to Hydrogen and Power to Methane processes according to the ISO guidelines [7], [8]. Their scope is to study different electricity sources, different process variations and different approaches for the consideration of carbon capture and storage. Their findings are compared to several conventional hydrogen and methane production processes. The study reveals that PtX can reduce greenhouse gas emissions depending on the electricity supply and on the $CO_2$ source. Wind power in combination with $CO_2$ from the combustion of wood is the least emission intensive option. The production of hydrogen has a higher emission reduction potential than the production of methane. Furthermore, Power to Hydrogen processes show lower emissions than the conventional production of hydrogen, while the opposite occurs for methane.

Acar and Dincer [21] compare hydrogen production methods from renewable and non-renewable sources in Turkey. Inter alia, natural gas steam reforming, water electrolysis with different electricity sources, gasification of biomass and coal, and nuclear high temperature electrolysis are compared. Steam reforming is seen to be the least expensive and most common option. The lowest emissions occur from electrolysis with electricity supply from wind power and nuclear high temperature electrolysis. They identify costs, efficiencies, and impurities as challenges to increase the application of renewable energies.

Summarizing the literature research and review on regenerative gases produced by Power to X processes, it can be generally stated that there are less studies than for biogas from biomass. This is caused by most of the assessed Power to X technologies still being at the research and development stage. Especially for the ecological aspects of biological methanation hardly any literature can be found. Many of the reviewed studies focus strongly on economic factors as they are an immense challenge for the increased use of Power to X technologies.

# 2 THEORETICAL BASIS

This chapter provides a basic knowledge on the investigated alternative gas production technologies and the applied methodology. The investigated gas production technologies are gas being produced by biomass via anaerobic digestion and gasification, and gas being produced from surpluses of renewable electricity via Power to X technologies. The technologies are described in the required level of detail. The life cycle assessment is implemented on this basis. The correspondingly applied methodology of LCA according to universally accepted guidelines is explained step by step.

## 2.1 Gas from Biomass

All substances of organic origin can be defined as biomass. This definition includes plants as primary products that are formed by direct photosynthetic use of solar energy, and animals and their residues as secondary products that are formed by degradation and conversion of organic substances in higher level organisms [22, p. 3].

Natural gas substitutes can be produced from biomass on numerous pathways. The pathways start with the provision of the raw material biomass including production, acquisition and processing. The transport of biomass is followed by conversion to raw biogas and waste products. The main distinction can be made between bio-chemical, physical-chemical and thermo-chemical conversion. This thesis assesses bio-chemical and thermo-chemical conversion. Bio-chemical conversion technologies are based on anaerobic digestion of biomass. Thermo-chemical technologies use gasification, pyrolysis or combustion to produce biogas. The raw biogas is then upgraded before its injection into the natural gas grid [22, p. 3 ff.].

***Biomass potential***

The deployment of renewable gas production technologies is limited by the available biomass potential. Due to insufficient data availability and numerous biomass sources, only rough estimations of the biomass potential are possible. Of various definitions of potential, the technical potential is relevant for this thesis. The technical potential is the technically accessible part of the total physical energy supply available in certain spatial and temporal boundaries. Structural and ecological limitations are also taken into account [22, p. 10 f.].

For the year 2020, Kaltschmitt et al. [22] forecast a decreasing technical potential of 366 PJ/a from forestry products, a constant technical potential 452 PJ/a from waste products and an increasing technical potential of 486 PJ/a to 1274 PJ/a from energy crops due to increasing use of agricultural land for energy crop production [22, p. 23 f.].

***Biogas in the market***

The role of biogas in the market depends on the development of the natural gas market. Worldwide, Germany is one of the biggest natural gas importing nations and the demand for imported gas is predicted to increase. Preventing supply problems and reducing the dependence on the suppliers, led to the self-commitment of German gas suppliers to substitute 20% of natural gas in the fuel sector with biogas until 2020 [5, pp. 2, 6, 9]. Considering these factors, biogas will gain in importance in the German gas market.

Biogas produced by anaerobic digestion is wide-spread and state of the art. The development from small-scale units at farms to industrial plants comes along with increasing conversion to electricity and feed-in into the natural gas grid [5, p. 18].

The technology of producing biogas by gasification is still developing and mostly at the stage of demonstration plants. Nevertheless, projects like the biogas plants in Güssing and Gothenburg promote meeting the challenges of up and downscaling and increasing the process efficiency [5, p. 27].

### 2.1.1 Biomethane from Anaerobic Digestion of Biomass

This thesis assesses the production of biomethane from manure, maize silage and municipal organic waste, called biowaste.

***Provision and transport of biomass***

Manure originates mainly from agriculture. Conventionally, manure is used as organic fertilizer and spread on agricultural land. During storage and spreading a significant amount of emissions are released [22, p. 159]. These emissions can be reduced by converting manure into biogas. Maize silage is produced by chopping and ensiling maize whole plants [22, p. 129]. Biowaste originates from biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants and agroindustrial processing [10, p. 61]. Municipal organic biowaste is brought into focus in this thesis.

After collecting and processing the raw material, it is transported to the biogas facility by truck where the anaerobic digestion of the substrate takes place.

***Bio-chemical conversion***

In an anaerobic environment, bacteria degrade biomass and release raw biogas during methane fermentation. The raw biogas consists mainly of methane and carbon dioxide. The fermentation takes place in three steps happening simultaneously: During hydrolysis (step 1), organic polymer compounds in the biomass are converted into low-molecular compounds. During acidogenesis (step 2), the low-molecular compounds are converted into acetic acid, carbon dioxide and hydrogen. In the last step of methane formation (step 3), acetic acid is broken down to carbon dioxide and methane, and hydrogen and carbon dioxide form methane and water. During anaerobic digestion, scarcely any waste heat is released [22, p. 853 ff.].

Main influencing parameters on the raw biogas production are the composition of the substrate, the fermentation temperature and the substrate's retention time in the fermenter [22, p. 874]. In general, the degradation of the biomass occurs faster at higher fermentation temperatures. The optimum is between 35 °C and 57 °C [22, p. 864]. On the other hand, the carbon dioxide content in the raw biogas increases with higher temperatures [22, p. 868]. Very long retention times are necessary for maximum degradation of biomass. For economic reasons, retention time usually is around 30 days [22, pp. 858, 871].

The methane yield of the raw gas mainly depends on the substrate composition, on its water content (the more liquid the substrate, the higher the amount of methane in the raw biogas), on the fermentation temperature, on the fermentation pressure (the higher the pressure, the higher the amount of methane) and on the retention time (the longer the retention time, the higher the amount of methane) [22, p. 868 f.].

As an example, Table 1 shows the composition of raw biogas from a mixture of 80% maize and 20% manure.

Table 1: Exemplary composition of raw biogas, based on [13, p. 44]

| *Component* | *Share [%]* |
|---|---:|
| Methane | 52 - 57 |
| Carbon dioxide | 42 - 48 |
| Hydrogen sulfide | 0.01 - 0.3 |
| Ammonia | 0.0001 - 0.05 |
| Hydrogen | 0.005 - 0.5 |
| Nitrogen | 0.1 - 0.5 |
| Oxygen | 0 - 0.3 |

The digestate as waste product of the fermentation process returns to the agroindustry as organic fertilizer [22, p. 918].

***Upgrading of raw biogas***

The raw biogas is purified from hydrogen sulfide, water and carbon dioxide [22, p. 895]. Apart from desulphurization and drying, the carbon dioxide is to be separated to meet the requirements for injection into the natural gas grid. Pressure swing adsorption, pressure water scrubbing and amine scrubbing are the most relevant methods of biogas upgrading [22, p. 897 ff.].

Pressure swing adsorption occurs at low temperatures and high pressures up to 10 bar. Adsorbing carbon dioxide on carbon molecular sieves results in methane yields up to 99% and in methane slipping of 1 vol% to 3 vol% [13, pp. 20, 26]. Pressure water scrubbing occurs at pressures between 5 bar and 10 bar and is based on absorption of carbon dioxide in water [13, p. 22]. It results in methane yields higher than 96% [22, p. 898] and methane slipping between 0.8 vol% and 1.8 vol% [13, p. 26]. Amine scrubbing uses organic solvents to absorb carbon dioxide at low temperatures and high pressures [13, p. 21]. It leads to methane slipping lower than 0.1 vol% [13, p. 26]. Upgraded raw biogas is called biomethane. Further information on upgrading technologies can be found in Kaltschmitt et al. [22] and Dunkelberg et al. [13].

Before the biomethane is injected into the natural gas grid, heating values, density and Wobbe index are adjusted, the biomethane is odorized and the pressure is adjusted to the grid's pressure [22, p. 900].

### 2.1.2 BioSNG from Gasification of Biomass

Synthetic natural gas produced from biomass is called bioSNG. Substrates are residual forest wood, short rotation forestry, straw and imported pellets from demolition wood.

***Provision and transport of biomass***

All waste products from forestry remaining unused in the forest are defined as residual forest wood [22, p. 82]. Residual forest wood and wood from short rotation forestry is processed to wood chips [22, p. 188]. Straw is an agricultural waste product from the cultivation of crops, oilseeds or grain maize. In Germany, the majority of straw originates from crop production [22, p. 150]. Conventional pellets are residual products from sawing industry or forestry [22, p. 199]. This thesis assumes demolition wood as source for the pellet production.

After collecting and processing the raw material, it is transported by truck to the gasification facility where it is transformed to bioSNG.

***Thermo-chemical conversion***

Complete thermo-chemical conversion consists of four steps: During heating and drying, water is released at temperatures up to 200 °C. The evaporation enthalpy of water limits the increase in temperature in this endothermic process [22, p. 381]. Pyrolysis starts at temperatures between 150 °C and 220 °C and ends at temperatures between 500 °C and 700 °C. In an anaerobic environment, macromolecules are destroyed. At the end of this step, 80% to 85% of the organic substrate is converted into gaseous products [22, p. 382 f.]. After the step of gasification, oxidation is the last process. Gasification products and oxygen are completely converted into heat at temperatures between 600 °C and 1300 °C [22, p. 397]. As the required result from the production of bioSNG is gas, oxidation is not relevant for this thesis.

Gasification is an endothermic, temperature and pressure dependent process taking place at temperatures higher than 600 °C. Oxygenic gasification agents together with heat are added to the pyrolysis' products and converted into a combustible gas. Gasification agents are, for example, oxygen, air, water vapor, carbon dioxide or hydrogen [22, p. 389 f.]. Depending on the agent, gasification is an autothermic or allothermic process.

The product gas consists mainly of carbon monoxide, carbon dioxide, hydrogen, methane, vaporous water and – if air was chosen as gasification agent – nitrogen. Apart from this, it contains undesired substances like tar, ashes or dust. The composition of the product gas depends on the substrate, the gasification agent, the gasification temperature and pressure and on the retention time [22, p. 395].

For producing bioSNG, gasification in an allothermic double fluidized bed gasifier with water vapor as gasification agent is recommended as it results in the highest methane yields. The typical product gas consists of 35 vol% to 40 vol% hydrogen, 22 vol% to 25 vol% carbon monoxide, 20 vol% to 25 vol% carbon dioxide, 9 vol% to 11 vol% methane and less than 1 vol% nitrogen. The lower heating value lies between 12 $MJ/m^3$ and 14 $MJ/m^3$ [22, p. 621].

***Upgrading of the product gas***

The product gas is purified from pollutants like particles, tar, nitrogen, sulfidic substances and halogens, and conditioned to fulfill the requirements as a synthetic gas that can be used in further upgrading processes [22, p. 628]. Methanation transforms the synthetic gas to raw bioSNG.

Methanation is further described in chapter 2.2.2.

After methanation the same upgrading processes as for biomethane take place. The final product of the process chain is bioSNG that can be injected into the natural gas grid.

## 2.2 Power to X: Gas from Renewable Electricity

In addition to the preceding pathways, natural gas substitutes can be produced by Power to X (PtX) technologies like electrolysis and methanation. These technologies convert excess from renewable electricity into gaseous fuels like hydrogen or methane. Furthermore, they facilitate the interconnection of the energy and the gas sector and the distribution of energy among them [23, p. 4570].

***Excess renewable energy***

Increasing shares of renewable energy increase the potential of the Power to X technologies. Renewable energy growing in the electricity sector increases fluctuations in electricity supply. This problem calls for energy storage systems to balance supply and demand of electricity in large electrical grids. Furthermore, energy storage systems are required in smaller and remote grids with huge differences in demand and supply [23, p. 4569]. Excess electricity resulting from fluctuating renewable electricity generation is the input into PtX processes.

***Power to X in the market***

Studies confirm the promising potential of PtX processes in the market. PtX as a future excess energy storage option has the potential to increase grid stability and promote decarbonization of energy systems. From 2009 onwards, the international attention on PtX increased and caused the start of the majority of research and development projects. Today, Germany is the leading nation in developing PtX technologies focusing on the catalytic methanation of $CO_2$ [24, pp. 292, 295].

Current PtX projects and plants come with all variations. They investigate the application of different electrolysis and methanation technologies with larger scale projects focusing on catalytic methanation. The electrolyzer scales range from a few $kW_{el}$ up to several $MW_{el}$. Some of the plants are already in operation and connected to the natural gas grid, many projects are at the pilot, research and demonstration stage [24], [25].

Challenges to be met in the future are the high costs of the electrolysis processes, heat management and efficiency to be increased. Furthermore, $CO_2$ sources from renewable origins have to be researched further [24, p. 305], [26, p. 1385 f.].

### 2.2.1 Power to Hydrogen

Conventionally and in large-scale applications, hydrogen is produced by steam reforming. Alternatively, it can be produced by different types of electrolysis [27, p. 334]. The conversion efficiency varies between 54 and 84%, depending on the level of compression for further application [27, p. 464].

Hydrogen produced in a Power to Hydrogen (PtH) process can be stored as gas or liquid or can be embedded, for example, in metal hydrides. In industrial applications it can be used to produce fertilizers or refrigerants, to refine metals or to produce hydrocarbons. Pure hydrogen can be used in electric mobility as fuel for fuel cell vehicles or in electricity and heat applications [25], [27, p. 452 f.]. Hydrogen can also be used as an input to methanation in Power to Gas processes.

***Steam reforming***

Usually, raw material for steam reforming is natural gas or crude oil fractions with low boiling point. Biogas can be used as an alternative. The natural gas is purified before entering the steam reformer to avoid deactivation of the nickel catalyst. Water vapor and methane from natural gas form carbon monoxide and hydrogen in an allothermic process. Reaction takes place between 800 °C and

900 °C and at 20 bar to 40 bar. In the consecutive water gas shift reaction, carbon monoxide and water vapor are converted into hydrogen and carbon dioxide [27, p. 337 f.].

### *Electrolysis*

Water electrolysis produces hydrogen from excess electricity. Water gets broken down into hydrogen and oxygen by applying an electrical potential to two electrodes in an electrolyte. The hydrogen formed at the cathode and the oxygen formed at the anode are separated by a diaphragm. The most common types of electrolyzers are alkaline electrolyzers, proton exchange membrane electrolyzers and high-temperature electrolyzers [28, p. 4286].

Alkaline electrolyzers represent the contemporary state of the art and are commercially available. They operate at temperatures around 80 °C and pressures up to 30 bar. The electrolyte is aqueous potassium hydroxide, catalysts based on nickel, cobalt and iron are added to the electrodes. The maximum stack efficiency is 67%. A drawback of the alkaline electrolyzer is its inflexible and efficiency decreasing part-load behavior [28, p. 4287].

Proton exchange membrane (PEM) electrolyzers are only available on a small scale. That is the reason for their low stack efficiency compared to alkaline electrolysis. PEM electrolyzers use the reverse principle of a fuel cell with a proton-conducting polymeric membrane as electrolyte and diaphragm. Operating temperatures are limited to 80 °C, operating pressure accounts for up to 100 bar. The advantage of the PEM electrolyzer is its good part-load behavior and behavior under pressure, a disadvantage of the PEM electrolyzer is the high investment costs [27, p. 357 f.], [28, p. 4287].

High-temperature water electrolyzers are also called solid oxide electrolysis cells (SOEC). They are at the development stage. As the operation temperature accounts for 700 to 1000 °C, water vapor is used instead of liquid vapor. Operation pressure is approx. 30 bar. As the vaporization takes place in an external process, no energy is needed for the phase change from liquid to vapor. Therefore, the demand for electricity is lower than for alkaline and PEM electrolysis and the electric efficiency can exceed 100%. The solid oxide electrolyte usually consists of $O^{2-}$ conducting yttria-stabilized zirconium oxide [27, p. 359 f., f.363], [28, p. 4287 f.].

## 2.2.2 Power to Gas

Methanation produces methane from hydrogen and carbon dioxide. Via the Sabatier reaction, carbon dioxide and hydrogen are converted into methane and water [24, p. 293]. To distinguish biomethane from anaerobic digestion and bioSNG from gasification, the product of Power to Gas processes is called regenerative methane. Methanation distinguishes between two pathways: catalytic methanation and biological methanation [27, p. 371]. Methanation processes reach efficiencies between 49% to 79%, depending on the level of compression for further application [27, p. 464].

Like biomethane or bioSNG, regenerative methane can be injected into the natural gas grid, used in gas turbine for electricity and heat production or in mobility [27, p. 456].

### *$CO_2$ sources*

The required carbon dioxide can be green carbon or black carbon. Green carbon is atmospheric carbon dioxide precipitated from air, biogenic carbon dioxide from biogas upgrading or recycled carbon dioxide from carbon capture processes. Black carbon is fossil carbon dioxide from carbon capture processes in power plants burning fossil fuels [27, p. 372].

### *Catalytic methanation*

Catalytic methanation is based on the reverse reactions of steam reforming: The water gas shift reactions form carbon monoxide and water from hydrogen and carbon dioxide. The Sabatier reaction is the main reaction forming methane and water from hydrogen and carbon monoxide. The in total exothermic reaction is supported by nickel catalysts. To avoid deactivation of the catalysts, the purity requirements of the input gases are very high. Operation temperatures are between 200 °C and 600 °C, operation pressure accounts for 20 bar to 80 bar. Catalytic methanation is still in pilot stage and demonstration plants are being tested [27, p. 376 f.].

***Biological methanation***

Biological methanation is called methanogenesis. Like the catalytic methanation, methanogenesis is based on the conversion of hydrogen and carbon dioxide into methane. The driving force for the reaction is unicellular organisms called Archaea which use enzymes as catalysts. Methanogenesis works only in an anaerobic environment. Compared to catalytic methanation, some advantages are the lower process temperatures of 40 °C to 60 °C and the lower pressure of 1 bar to 3 bar. Moreover, the purity requirements of the input gases are very low and methane shares of 98% can be reached without any upgrading of the raw product gas. The drawbacks are the constant feeding of the Archaea and the necessary wastewater recycling. Compared to catalytic methanation, upscaling is more complicated [27, p. 382 ff.].

## 2.3 Use of Regenerative Gases

For the use of regeneratively produced gases, the same applications are possible as for natural gas. This section describes the applications relevant for the LCA to be implemented in this thesis.

### 2.3.1 Injection into the Natural Gas Grid

Biomethane, bioSNG and regenerative methane can be injected into the natural gas grid if they meet the relevant requirements. Distributed by an existing infrastructure, they enable the substitution of conventional energy carriers in mobility and electricity and heat production. For technical reasons, hydrogen can only be injected into the natural gas grid up to 1.5 vol% [27, pp. 449, 452].

The requirements for the injection of biogas into the natural gas grid are determined in the Gas Network Access Regulations (Gasnetzzugangsverordnung) [29]. Paragraph 36 (1) states that injected biogas needs to fulfill the quality requirements of working sheet G 260 and G 262 from the German Technical and Scientific Association for Gas and Water (Deutscher Verein des Gas- und Wasserfachs e.V.). The working sheets define the requirements for combustion characteristics like Wobbe-Index, heating value and relative density and the requirements for the gas composition [30].

### 2.3.2 Electricity and Heat Production

This thesis assesses the combined production of heat and power from biogas. Combined heat and power can be produced in combined cycle power plants or in cogeneration units.

Combined heat and power plants use the technology of gas turbine processes as well as steam turbine processes. In gas turbine processes, air is compressed and heated up by combustion with the biogas. The resulting gas stream with temperatures of approx. 1500 °C expands in the gas turbine releasing its enthalpy. The gas turbine drives a generator which converts mechanical energy into electricity. The heat of the flue gas of the gas turbine process evaporates and overheats the water in the steam power cycle. The steam with temperatures between 550 °C and 560 °C expands in a steam turbine driving another generator and condensates to restart the steam power cycle. The combination of the gas turbine process and the steam turbine process with efficiencies of 38% and 35%, respectively, result in a combined efficiency of 62% [27, p. 437 f.].

Cogeneration units are used near the location of heat demand or in connection with a heat grid. Small-scale gas turbines or gas engines produce electricity via generators. Heat is received from the engines' and turbines' waste heat and from the hot flue gas and distributed to heat customers [27, p. 439].

## 2.4 Life Cycle Assessment

The method of life cycle assessment (LCA) is standardized in the ISO 14040 series and this study is based on the internationally accepted DIN EN ISO 14040:2006 [7] and 14044:2006 [8]. These standards define the method of LCA as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [7, p. 7]. The LCA examines the whole life cycle of a product, shown in Figure 1. Boxes indicate physical processes, arrows indicate product flows, broken arrows indicate elementary flows. The life cycle starts with extracting raw materials. Following this "cradle", the whole production including waste management is assessed up to the "gate" where the product leaves the industrial system. After assessing the use of the product, the life cycle ends with the disposal, the "grave". Environmental impacts like greenhouse gas emissions occur during the product's life cycle. The LCA investigates all these environmental impacts of the product [31, p. 19].

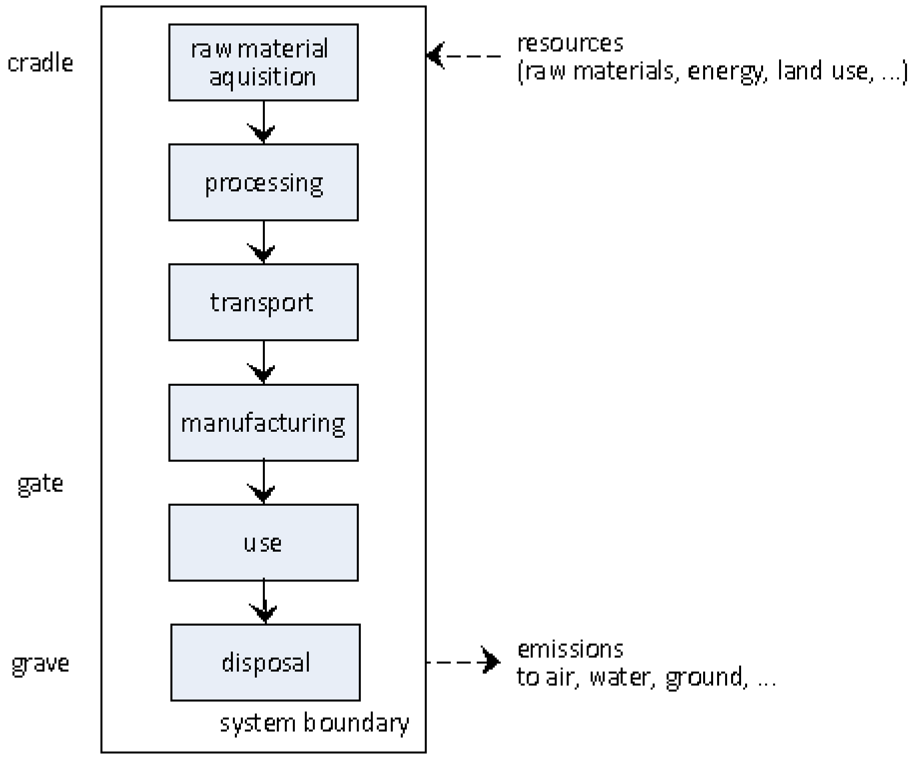


Figure 1: General life cycle of a product, based on [31, p. 20]

Studying the whole product system is the strength of the LCA. Being an interdisciplinary tool, it assesses a technical system and examines its environmental impacts. The LCA relates results to the function of a product. This enables the comparison of alternative life cycles resulting in different products with the same function. The LCA is limited by excluding economic and social aspects as well as risks. Largely, the results are not site specific as the whole life cycle does not take place in a single location [31, p. 21].

The results of the LCA can be used in personal and policy decision making, in adapting and improving industrial processes, in market communication and to inform stakeholders about environmental properties [31, p. 40].

According to ISO 14040 the LCA consists of four iterative phases, which are explained within the next chapters [7, p. 4]:

1. goal and scope definition
2. inventory analysis

3. impact assessment
4. interpretation

As conducting a LCA is an iterative process, the consistency with the intended application, with the defined goal and scope and with assumptions made must be revised during the whole process and resulting modifications must be documented. This thesis documents the final version of the conducted LCA.

### 2.4.1 Goal and Scope Definition

Within the goal and scope definition phase, the product to be studied and the purpose of the study and thereby the requirements on the modelling are to be examined [31, p. 24]. The goal of a LCA defines the intended application of the LCA, the reasons for carrying out the study and the intended audience. Furthermore, it states whether the results are to be used in comparative assertions intended to be disclosed to the public [7, p. 22 f.].

The scope determines the fundamental framework of the study. The modelling requirements and methodological choices depend on the type of LCA to be conducted. An accounting LCA examines environmental impacts connected to one specific product. A change-oriented LCA models effects of changes and thus compares consequences of alternative actions [31, p. 78]. Further specifications resulting from the type of LCA will be mentioned in the relevant sections. The scope includes the following information [7, p. 23]:

***Definition of the product system, its functions and the functional unit***

Central element of the LCA is the product system to be modelled. According to ISO 14040, a product system is the "collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product" [7, p. 11]. Unit processes are defined by their functions. Therefore it has to be indicated where the process begins, which operations occur during the process and where the process ends [8, p. 18]. Unit processes are connected to the environment by elementary flows and inter-connected by product and waste flows [8, p. 19]. It is recommended to describe the product system including all unit processes and their inter-relationships in a process flow diagram [8, p. 18].

The functional unit provides the reference function which all inputs and outputs are related to. As a reference flow it ensures the comparison of different unit processes and product systems [7, p. 23 f.].

***System boundary***

The system boundary defines the unit processes to be included in the system [7, p. 24]. All flows crossing the system boundaries should be elementary flows. System boundaries of an accounting LCA include the complete life cycle, while in a change-oriented LCA only parts of the system are affected [31, p. 79].

***Allocation procedures***

ISO 14040 defines the allocation process as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" [7, p. 10]. Processes with multiple outputs flows need to be assigned to specific products. ISO 14044 recommends three steps for allocation. First, allocation should be avoided by dividing the relevant unit process into sub-processes (partitioning) or by expanding the product system to include additional functions related to co-products (system enlargement). If allocation cannot be avoided, flows are separated between products in a way that reflects the underlying physical relationship between them in the next step. Finally, if allocation by physical relationship is not significant, flows are separated between products in a way that reflects other relationships between them [8, p. 29].

Allocation in an accounting LCA reflects causes of the system and favors partitioning. In a change-oriented LCA effects of change are reflected by system enlargement [31, p. 79].

#### *Impact categories, methodology of impact assessment, interpretation to be used*

Impact categories are for example global warming potential, eutrophication or acidification potential. They are derived by specific impact assessment methods. The interpretation of the corresponding results is made to be consistent with the goal.

#### *Data requirements and initial data quality requirements*

Data requirements specify the origin of the data to be used. Primary data derives directly from measurements, e.g. at production sites. Secondary data derives from other sources, e.g. studies. Often it must be converted in accordance to the functional unit. It is common to use a mixture of primary and secondary data [8, p. 20 f.].

Data quality requirements specify further characteristics of the data like time-related coverage, geographical coverage, technology coverage, precision, completeness, consistency, reproducibility, sources, and uncertainty [8, p. 21].

In an accounting LCA, mainly average data is chosen, while a change-oriented LCA works in part with marginal data [31, p. 79].

#### *Assumptions and Limitations*

General assumptions and limitations are stated and are valid for the whole LCA procedure. Assumptions made at this point are major assumptions like technological definitions, but not assumptions on single datasets or unit processes. Limitations can result from decisions made during the goal and scope definition or iteratively from problems during the conduction of the study [31, p. 92].

#### *Type of critical review*

If a critical review is requested the type of the review and the requested level of expertise are defined [8, p. 21].

#### *Type and format of the report required for the study*

The type and format of the report as a mandatory step of the LCA are stated.

### 2.4.2 Life Cycle Inventory Analysis (LCI)

ISO 14040 defines the life cycle inventory analysis as the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" [7, p. 7]. According to the process flow diagram, data is collected and calculated.

#### *Data collection*

In the phase of data collection, all data concerning energy, raw material and other inputs, products and waste, outputs, emissions and other environmental aspects within the system boundary are collected [7, p. 26].

#### *Data calculation*

Data calculation consists of the following iterative steps: validation of the collected data, relating the data to unit processes, relating the data to the functional unit [7, p. 26]. As a fourth step refining the system boundary can be necessary [8, p. 28].

For multi-output processes, data need to be allocated according to the defined allocation procedures.

### 2.4.3 Life Cycle Impact Assessment (LCIA)

The impact assessment is “aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” [7, p. 7]. In this phase, data from the LCI gets connected with defined impact categories and the corresponding category indicators. The category indicator results quantify the environmental impact and provide information for the final interpretation of the LCA [7, p. 27]. The mandatory steps of the impact assessment are the following [7, p. 30]:

***Selection of impact categories, category indicators and characterization models***

The impact category represents “environmental issues of concern to which life cycle inventory analysis results may be assigned” and is represented in a quantitative way by the impact category indicator [7, p. 13]. The interrelation of category and indicator is described in the characterization model.

The selected categories, indicators and models are required, amongst others, to be internationally accepted, scientifically and technically valid and environmentally relevant [8, p. 37 f.].

***Classification: Assignment of LCI results***

To classify the LCI results, every result is sorted into a selected impact category. Results that relate to more than one category or results that cannot be assigned to any category are identified [8, p. 39].

***Characterization: Calculation of category indicator results***

The LCI results are characterized by calculation and aggregation of the category indicator results within one impact category. The category indicator results are the final outcome of the LCIA [8, p. 39].

### 2.4.4 Interpretation

In the last phase of the LCA, all results are summarized and discussed. They are the basis for conclusions and recommendations in accordance with the goal and scope definition [7, p. 31].

First, significant issues are identified. In the following step, completeness, sensitivity and consistency are evaluated. The last step consists of drawing conclusions, identifying limitations and making recommendations [8, p. 45].

***Reporting***

Results and conclusions are reported in the type and format defined in the goal and scope definition to provide the use of the results and interpretation in a consistent way. The report includes all results, data, methods, assumptions and limitations in a transparent presentation and in sufficient detail [8, p. 54].

***Critical Review***

A critical review is conducted to verify whether the LCA meets all requirements for methodology, data, interpretations, reporting and to verify its consistence with the principles of the ISO standard. It ensures that classification, characterization, normalization, grouping and weighting elements are sufficient and documented appropriately [7, p. 33].

***Further evaluation***

Baumann and Tillman [31] give further recommendations on interpretation and evaluation of the results. To analyze the robustness of the results and to examine the effect of changes in most critical input parameters, a sensitivity analysis is recommended [31, p. 177].

To conduct a sensitivity analysis, input parameters are changed systematically. Changes in input parameters leading to an immense change in the overall results are identified as the most critical ones.

For these parameters, particular attention is to be put to the choice of appropriate data. For making a sensitivity analysis or to further evaluate results, a Monte Carlo simulation can be used [31, p. 199 f.].

OpenLCA provides a tool to conduct a Monte Carlo simulation. It is based on the uncertainty distribution of all critical parameters. Depending on the available information, the uncertainty can be represented by a logarithmic normal distribution, a normal distribution, a triangle distribution or a uniform distribution. According to the uncertainty distribution, the input parameters are varied randomly in several thousand simulation steps. The Monte Carlo simulation tool provides the distribution of the overall result as well as the resulting mean value, standard deviation, 5% percentile and 95% percentile, median, minimum and maximum value [32, pp. 60, 63]. These values provide insight into the robustness and precision of the LCA results.

# 3 Implementation of LCAs

As preparation for implementing LCAs, studies and literature data are to be reviewed and evaluated thoroughly. The resulting findings are considered for the subsequent definition of goal and scope. Divergent from the guidelines, this thesis separates the steps of inventory analysis, impact assessment, and interpretation into three distinct steps which are executed for each of the technology pathways: biomethane, bioSNG, and Power to X. Finally, the results of the LCAs are summarized and evaluated in comparison to each other.

## 3.1 Evaluation of Studies

As mentioned in 1.2, numerous studies and literature sources were assessed in preparation for the implementation of the LCAs. This section summarizes the main findings and fundamental assumptions from the investigated studies in the categories of methodology, technology, assumptions and main contributors. They form the basis for parameters determined in the goal and scope definition like important aspects to be considered, important influences not be assessed, criteria for data collection, and limitations to deal with.

### *Methodology*

Most of the assessed studies implement environmental analyses according to the ISO guidelines 14040 [7] and 14044 [8] and investigate especially the processes influences on the global warming potential, the eutrophication potential, and the acidification potential. The global warming potential is expressed as kg $CO_{2,\,eq}$ according to the IPCC 2007 [33].

The functional unit of nearly every study is defined in a different way. For example, Zhang et al. [11, p. 19] relate the emissions to the disposal of 1,100 tonnes of dairy manure, while Fusi et al. [9, p. 5] express their results related to the generation of 1 MWh of electricity to be fed into the grid.

*Considered studies: Müller-Langer et al.* [5]*, Fusi et al.* [9]*, Giuntoli et al.* [10]*, Zhang et al.* [11]*, Parra et al.* [18]*, Collet et al.* [19]*, Zhang et al.* [20]*, Lansche and Müller* [34]*.*

### *Technology*

The studies dealing with the anaerobic digestion of biomass, investigate mainly maize silage, and in smaller part manure from different animals and waste from varying origins like municipal solid waste or household biowaste. Wood pellets, wood chips, short rotation forestry and straw are considered for gasification processes. Concerning Power to X technologies, mainly alkaline electrolysis, PEM electrolysis, and catalytic methanation are assessed.

*Considered studies: Müller-Langer et al.* [5]*, Fusi et al.* [9]*, Giuntoli et al.* [10]*, Zhang et al.* [11]*, Liebetrau et al.* [12]*, Dunkelberg et al.* [13]*, Claus et al.* [14]*, Holmgren et al.* [16]*, Sternberg and Bardow* [17]*, Parra et al.* [18]*, Collet et al.* [19]*, Zhang et al.* [20]*, Acar and Dincer* [21]*, Lansche and Müller* [34]*.*

### *Assumptions*

One of the most important assumptions for the biomethane pathways is the consideration of avoided emissions from manure storage as credits to the process and the subsequent use of the digestate as fertilizer. Furthermore, many studies agree on treating the substrate waste as free from emissions and other burdens.

If emissions from land use change are mentioned in the investigated studies, they are excluded from the assessment due to insufficient data and disproportionately complex calculations.

Construction and decommissioning of plants are considered in some of the studies. In these cases, the studies conclude that their influence on the global warming potential is negligibly low. Other studies exclude construction and decommissioning by default.

*Considered studies: Müller-Langer et al.* [5]*, Fusi et al.* [9]*, Giuntoli et al.* [10]*, Zhang et al.* [11]*, Dunkelberg et al.* [13]*, Alamia et al.* [15]*, Sternberg and Bardow* [17]*, Parra et al.* [18]*, Lansche and Müller* [34].

***Main contributors***

For the biomethane and bioSNG pathways, most important contributors to the greenhouse gas emissions are the raw material provision, the conversion processes themselves and the open storage of substrates and digestate.

Heat and power supply are the most important parameters for the Power to X pathways. Especially for methanation processes, the origin of the required carbon dioxide plays an important role.

*Considered studies: Holmgren et al.* [16]*, Parra et al.* [18]*, Fusi et al.* [9]*, Giuntoli et al.* [10]*, Liebetrau et al.* [12]*, Claus et al.* [14]*, Müller-Langer et al.* [5]*, Sternberg and Bardow* [17]*, Collet et al.* [19]*, Zhang et al.* [20].

## 3.2 Goal and Scope

### 3.2.1 Goal of this Study

The goal of this LCA is to identify the alternative gas production pathway which is the least greenhouse gas (GHG) emissions intensive. Therefore, the amount of GHG emissions that occur during the whole life cycle is assessed.

#### *Intended application*

The results are intended to be used as basis knowledge to inform discussions about alternative gas resources. The results enable the comparison between different alternative gas sources and the comparison with conventional gas sources.

#### *Reasons for carrying out the study*

Many studies conduct LCAs for alternative gas production pathways. However, every study only assesses a limited number of substrates or technologies, each on its individual conditions. Therefore, the various studies are not comparable and studies that deal with alternative gas sources in a consistent way are scarce. Being part of the research project *SustainableGas*, this work assesses alternative gas production technologies in a consistent and therefore comparable way.

#### *Intended audience*

This LCA is relevant for the project participants as well as for scientists investigating alternative gas sources. It forms the basis of a comprehensive approach to finding benefits and drawbacks of alternative gas generation options and for further or more specific research on other pathways. This study contributes to a solid knowledge base for engineers and policy makers. As an academic publication it is accessible for the interested public and facilitates communication between stakeholders and political decision-makers. The results can inform regulatory and investment decisions as well as research and development activities on a sustainable use of energy.

### 3.2.2 Scope and Modelling Requirements

The type of this study is an accounting LCA, more specifically a comparative life cycle impact assessment. The methodological specifications are determined according to DIN EN ISO 14040:2006 [7].

#### *Definition of the product system, its functions and the functional unit*

The product system's function in this study is the production of electricity and heat in a gas turbine substituting alternative gas in place of natural gas in the natural gas grid. The unit processes that form the product system are shown in Figure 2. The definition of unit processes for each pathway is based on the processes described in the theoretical basis.

The assessed alternative gas production pathways are the following:

- Biomethane from digestion of manure *bioCH$_4$_manure*, maize silage *bioCH$_4$_maize* and biowaste *bioCH$_4$_waste.*
- BioSNG from gasification of residual forest wood *SNG_RFW*, short rotation forestry wood *SNG_SRF*, straw *SNG_straw* and imported pellets from demolition wood *SNG_IP I* and *SNG_IP II.*
- Regenerative hydrogen from proton exchange membrane electrolysis *PtH_PEM*, high temperature electrolysis *PtH_SOEC* and steam reforming *PtH_SR* and subsequent regenerative methane from catalytic methanation *PtM_cat* and biological methanation *PtM_bio*.

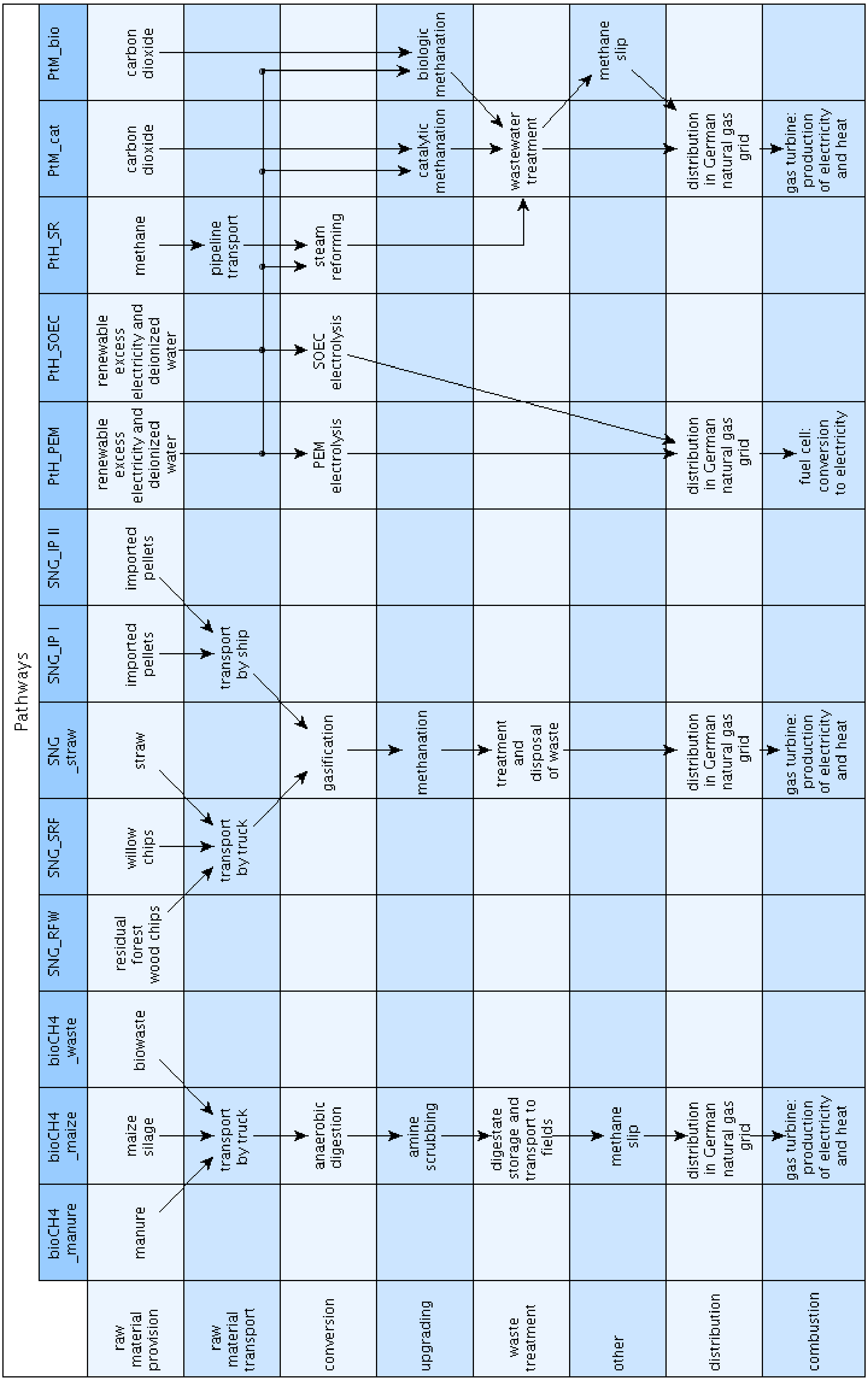


Figure 2: Pathways and unit processes to be assessed in this LCA

*Natural gas* is investigated as a reference pathway.

Functional unit is the production of 1 MWh of energy consisting of electricity and heat.

The production of regenerative hydrogen and of regenerative methane are assessed in a more general way than the other pathways as can be seen in the implementation.

### *System boundary*

As shown in the flow chart in Figure 2, the process begins with producing the raw materials. In case they are waste products, the process begins with processing these waste products. These steps represent the cradle of the raw materials. During the process, the raw materials are transported, converted and upgraded into regenerative gas and distributed in the natural gas grid. The process ends with burning the regenerative gas in a gas turbine to produce electricity and heat or with converting it into electricity in a fuel cell. As no recycling and further waste treatment follow this step, the electricity and heat production represent the grave of the assessed process.

The system boundary excludes construction and maintenance of equipment and plants and the conversion of land to industrial land. Dismantling the plant and renaturation of the land are excluded, too. Co-products like waste heat are not considered.

Datasets taken from the international LCA database ecoinvent are adjusted to this system boundary individually. If this is not possible, deviations from the defined system boundary are marked.

### *Allocation procedures*

This study is conducted as an accounting LCA. Therefore, the preferred allocation procedure is partitioning. For data taken from ecoinvent, the system model “Allocation, cut-off by classification” is chosen [35, p. 1222 f.]. In this modelling type, primary production is allocated to primary use. Thus, recyclable materials enter recycling processes burden-free and their outputs bear only the environmental impacts of the recycling process.

### *Impact categories, methodology of impact assessment, interpretation to be used*

The relevant impact category for this study is climate change. The corresponding impact indicator is the Global Warming Potential for a time horizon of 100 years (GWP 100) measured as kg $CO_{2,\,eq.}$ This is consistent with the goal of the study of identifying the least GHG intensive alternative gas producing pathway. According to IPCC 2007 [33], this study considers the substances in Table 2.

Table 2: Considered substances and corresponding GWP 100

| *Substance* | *GWP 100* |
|---|---|
| Carbon dioxide $CO_2$ | 1 |
| Methane $CH_4$ | 25 |
| Dinitrogen monoxide $N_2O$ | 298 |

Other substances and impact categories like eutrophication and acidification are neglected. No distinction is made between biogenic or fossil substances.

The impact assessment is implemented with the software openLCA. The impact category climate change and the impact indicator GWP 100 are provided by openLCA in the methodology of impact assessment ILCD 2011 midpoint (v1.0.10) based on IPCC 2007 [36, p. 3].

The interpretation of the results is made after the characterization of the LCI results. For further evaluation of the results, a Monte Carlo simulation is implemented. Furthermore, the LCA results are interpreted in comparison with literature.

### *Data requirements and initial data quality requirements*

The data used in this study is required to be secondary data from ecoinvent datasets and other LCA studies. For this accounting LCA, representative average values are chosen through an intense literature study. As climate change is the relevant impact category, only GHG related data and values are considered. Thus, emissions apart from $CO_2$, $CH_4$ and $N_2O$ are neglected.

To ensure data quality, the following requirements must be fulfilled:

- Time-related coverage: Data is not older than 15 years, while data not older than 10 years is preferred. Technologies developed in this period are considered contemporary.
- Geographical coverage: Data comes primarily from studies treating German sites. Due to a lack of data, the geographical range is expanded to Western Europe. For the pathways *SNG_IP I* and *SNG_IP II* data from Northern America is considered.
- Technology coverage: Data from studies treating processes in a similar scale as in the assessed pathways is preferred.

For sufficient precision and reproducibility of the data, only publicly accessible data is used, and all sources are declared. Processes for which completeness cannot be achieved, e.g. due to lack of data, are indicated.

### *Assumptions and Limitations*

The following general assumptions and limitations are valid for all pathways:

- All transportation is carried out by the same means of transport: road transport according to ecoinvent dataset "transport, freight, lorry >32 metric ton, EURO5, RER"[1], rail transport according to "market for transport, freight train, CN"[2], sea transport according to ecoinvent dataset "transport, freight, sea, transoceanic ship, GLO"[3]. These datasets include construction of equipment and are used without being adapted. Therefore, they cause a discrepancy from the defined system boundary. This discrepancy is compensated by using the same datasets for all pathways.
- For reasons of simplification and consistency, covered storage of raw materials is assumed for all pathways. Potential developing gases are discharged as weak gases. Thus, storage of raw materials is free from emissions.
- The use of electricity from the medium and low voltage grid results in the same amount of GHG emissions.
- The performance and operation of all units and plants is ideal. Thus, no further emissions occur due to improper handling, ageing or lack of maintenance.
- Every unit process is examined at rated operation. Part-load behavior, startup and shutdown processes are neglected.

Pathway specific assumptions and limitations are indicated in the relevant sections.

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[1] transport, freight, lorry >32 metric ton, EURO5, RER, Allocation, cut-off by classification, ecoinvent database version 3.4

[2] Treyer, K., market for transport, freight train, CN, Allocation, cut-off by classification, ecoinvent database version 3.4

[3] Spielmann, M., transport, freight, sea, transoceanic ship, GLO, Allocation, cut-off by classification, ecoinvent database version 3.4

### *Type of critical review*

No critical review is required.

### *Type and format of the report required for the study*

This study is reported in this master thesis.

## 3.3 Reference Pathway *natural gas*

Reference for all pathways is the production, distribution and combustion of natural gas. For the reference pathway, inventory analysis and impact assessment are carried out in a shortened form. Monte Carlo simulation and comparison with literature are not implemented.

### 3.3.1 Inventory Analysis

The inventory analysis for the pathway *natural gas* is limited to the step of natural gas production in general, natural gas distribution in the German natural gas grid and the combustion of natural gas in a gas turbine.

***Natural gas provision***

The provision of natural gas is calculated according to the ecoinvent dataset "market for natural gas, high pressure, DE"[4]. This dataset combines the datasets for the production of natural gas in Germany and in the exporting countries Netherlands, Norway and Russia. It includes the energy requirements and emissions of the high-pressure distribution network in Germany. As they are to be assessed separately and the consideration of the pipeline construction exceeds the system boundary, the construction of the pipeline and the distribution in the high-pressure network are subtracted from the given emissions. In total, the provision of natural gas in Germany leads to 40.203 kg $CO_{2,eq}$/MWh natural gas.

***Distribution***

Alamia [15, p. 448] reports 0.13% of leakage/1000 km in the Swedish high-pressure grid for long distance transport. Based on this, 0.2% leakage/1000 km in the German grid with a standard transport distance of 500 km are determined. These determinations result in 0.001 kg $CH_4$ losses/kg natural gas in the grid.

***Combustion***

Table 3 shows the data basis and corresponding calculations for the combustion of product gas in a gas turbine.

Table 3: Data basis for combustion of product gas in a gas turbine

| *natural gas, burned in micro gas turbine, 100kWe, CH* | | *Referred to 1 m³ gas input* | *Referred to 1 MWh total energy output* |
|---|---|---|---|
| ***Input*** | | | |
| Natural gas, low pressure [m³] | 0.026 | 1 | 123.077 |
| ***Output*** | | | |
| Heat, central or small-scale, natural gas [$MW_{th}$] | 0.460 MJ* | 0.005 | |
| Electricity, low voltage [$MWh_{el}$] | 0.081 kWh* | 0.003 | |
| Total energy output [MWh] | | 0.008 | 1 |
| Resulting emissions [kg $CO_{2,eq}$] | 0.056 | 2.201 | 270.863 |

** original unit from ecoinvent deviating from unit given in first column for further calculations*

[4] Jungbluth, N., market for natural gas, high pressure, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

Combustion is calculated based on ecoinvent dataset "natural gas, burned in micro gas turbine, 100kWe, CH"[5]. This data set was chosen, as it was the only dataset from ecoinvent treating natural gas being burnt in a gas turbine for no other reason than producing electricity to be fed into the grid and heat. This dataset includes the fuel input, infrastructure, emissions to air and working materials for operation. This is a discrepancy from the defined system boundary, which excludes construction of equipment. Therefore, the deviating parameters are excluded to compensate the discrepancy.

### 3.3.2 Impact Assessment

According to the scope definition, climate change is the only relevant impact category in this LCA and the corresponding impact indicator is the Global Warming Potential for a time horizon of 100 years (GWP 100) measured as kg $CO_{2,\,eq.}$ The impact assessment is implemented with the software openLCA.

The results from the implementation of the impact assessment for the biomethane pathways are shown in Table 4.

Table 4: Results impact assessment of pathway *natural gas*

| *Process* | *Natural gas* |
|---|---|
| Natural gas provision [kg $CO_{2,\,eq}$/MWh natural gas] | 40.203 |
| Distribution [kg $CO_{2,\,eq}$/MWh natural gas] | 1.726 |
| Combustion [kg $CO_{2,\,eq}$/MWh energy] | 270.863 |
| Total after distribution and combustion [kg $CO_{2,\,eq}$/MWh energy] | 329.867 |

[5] Primas, A., natural gas, burned in micro gas turbine, 100kWe, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

## 3.4 Biomethane from Anaerobic Digestion

This thesis assesses the production of biomethane from manure, maize silage and biowaste. The corresponding pathways are

- biomethane from digestion of manure *bioCH₄_manure*,
- biomethane from maize silage *bioCH₄_maize* and
- biomethane from biowaste *bioCH₄_waste*.

According to the guidelines, inventory analysis and impact assessment are conducted first. The subsequent interpretation and evaluation are completed by a Monte Carlo simulation and a comparison with literature data.

### 3.4.1 Inventory Analysis

For the steps of data collection and data calculation some general data and factors are necessary, for example as conversion factors. They are stated in Table 14 (annex A.1). If they are used in calculations, they are not mentioned explicitly.

For the inventory analysis, data is collected for every unit process presented in Figure 2 according to the scope definition. The biomethane pathways are based on the characteristics in Table 5.

Table 5: Characteristics biomethane pathways

| *Characteristic parameter* | *bioCH$_4$_manure* | *bioCH$_4$_maize* | *bioCH$_4$_waste* |
|---|---:|---:|---:|
| Input substrate [MW] | 2.5 | 10 | 10 |
| Input substrate [t/h] | 10.000 | 5.625 | 11.250 |
| Process efficiency (incl. digestion and upgrading) [%] | 52.90 | 63.40 | 58.00 |
| Output bioCH$_4$ [MW] | 1.323 | 6.340 | 5.800 |
| Output bioCH$_4$ [Nm$^3$/h] | 132.648 | 635.908 | 581.745 |
| Full load hours [h/a] | 8,000 | 8,000 | 8,000 |
| Lower heating value substrate [kWh/t] | 250.000 | 1777.778 | 888.889 |
| Lower heating value substrate [MJ/kg] | 0.900 | 6.400 | 3.200 |
| Moisture substrate [%] | - | 65.000 | - |

#### *Raw material provision*

***bioCH$_4$_manure*** uses manure from swine and cattle in general as a substrate. Dairy manure is excluded due to its low methane content.

The provision of manure is assessed in a simplified way excluding the machinery for collection of the manure. As mentioned in the theoretical basis, the processing of manure in a biomethane process avoids the emissions occurring by conventional storage of manure. As a mean value from literature data in Table 15 (annex A.1.1), 0.053 kg $CO_{2,eq}$/kg wet manure are chosen as credits for avoiding conventional manure storage.

***$bioCH_4$_maize*** uses maize silage as a substrate.

The provision of maize silage is calculated according to ecoinvent dataset “maize silage production, organic, CH”[6]. This dataset includes the production of maize silage with a moisture content of 72% at storage, machine operations, the corresponding machine infrastructure and sheds and direct field emissions. Due to lack of comparable datasets, this discrepancy with the system boundary and the determined characteristics is accepted. Calculation with openLCA results in -0.4083 kg $CO_{2,\,eq}$/kg maize silage for cultivation and ensiling of maize.

This value differs from literature values shown in Table 21 (annex A.1.2), as it considers the carbon uptake into the maize during growth. Many studies do not consider the carbon uptake as it is compensated later by combustion of the produced biomethane. The ecoinvent dataset considers a carbon uptake of 0.457 kg $CO_2$/kg maize silage during the growing of the maize. Excluding the carbon uptake results in 0.0487 kg $CO_2$/kg maize silage.

To calculate the provision of biowaste as substrate for ***$bioCH_4$_waste***, biowaste is assumed to consist of potato residues. Comparing several ecoinvent datasets with the reference product "potato" "potato, organic" leads to a mean carbon uptake of 0.312 kg $CO_{2,\,eq}$/kg potato. This value is reduced by the operations necessary to produce the potato. According to ecoinvent dataset “potato production, organic, CH”[7], the total emissions of potato production account for -0.20473 kg $CO_{2,\,eq}$/kg potato, including the carbon uptake. Excluding the carbon uptake results in 0.107 kg $CO_2$/kg biowaste.

The following general characteristics are determined according to Giuntoli et al. [10, p. 61]:

- Moisture content of biowaste: 76.3%
- Lower heating value of biowaste: 20.7 MJ/kg biowaste, dry

### *Raw material transport*

For ***$bioCH_4$_manure***, the German Chambers of Agriculture [37] report the amount of manure produced by different classifications of cattle. On average, 0.796 $m^3$ manure are produced by an average cow per month. 1 kg/l density of manure [13, p. 39], leads to 9,555 kg manure/a*cow. The characteristics of the pathway *$bioCH_4$_manure* define an input of 10 t manure/h at 8,000 full load hours per year. To meet this demand, 8,372.5798 cows are necessary. According to the German Federal Statistical Office [38], there are 12.37 million cows in Germany on the country’s area of 357,385.71 $km^2$ [39]. That yields in 34.612 cows/$km^2$ and an area of 241.894 $km^2$ to meet the required demand. This results in a transport distance of 0.00877 tkm/kg manure. For comparison, Table 16 (annex A.1.1) shows the literature values for the transport of manure.

In accordance with the presented calculations and with literature data, a transport distance of 10 km by truck was chosen. This distance corresponds to 0.01 tkm/kg wet manure.

For ***$bioCH_4$_maize***, literature provides the data in Table 22 (annex A.1.2). By further calculations, a transport distance of 0.093 tkm/kg maize silage by truck was chosen.

The transport distance of **biowaste** is determined based on Table 24. As transport distances in the USA are considered generally higher than in Germany, 0.02 tkm/kg biowaste transport distance by truck is stated.

[6] Kägi, T., maize silage production, organic, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

[7] Kägi, T., potato production, organic, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

### *Conversion*

Conversion of **manure** to raw biogas via anaerobic digestion is calculated based on the ecoinvent dataset "anaerobic digestion of manure, CH"[8]. To adapt the dataset to the defined characteristics, relevant input and output values are referred to the total manure input. From the share of 55% $bioCH_4$ in raw biogas (see *Upgrading*) arises the ratio of 24.118 $Nm^3$ raw biogas/t manure. Subsequently with this ratio, the values are referred to 1 $Nm^3$ raw biogas output. The corresponding results are presented in Table 17 (annex A.1.1).

Digester sludge accounted for as a negative input value corresponds to the produced digestate during anaerobic digestion of manure.

As Figure 3 shows, the calculated values match the values for the digestion of manure given in different studies, see Table 18 (annex A.1.1).

Conversion of **maize silage** to raw biogas via anaerobic digestion is assumed to happen in a closed digester. Literature provides the values in Table 23 (annex A.1.2). To adapt the values to the defined characteristics, values are converted to refer to the maize silage input.

Values from Giuntoli et al. [10] seem to be a good middle course between the widespread literature data and show the best accordance with the defined characteristics. For this reason, electricity and heat input into the digestion process are calculated according to Giuntoli et al. The literature values correspond in terms of digestate production. Therefore, 0.7715 t digestate/t maize silage is used being the mean from Giuntoli et al., Dunkelberg et al. [13] and Stucki [40].

Assuming 52% $bioCH_4$ in raw biogas (see *Upgrading*), the characteristics of *$bioCH_4$_maize* require 4.5997 kg maize silage input/$Nm^3$ raw biogas. The resulting inputs for the digestion process are 0.476 $MJ_{el}/Nm^3$ raw biogas and 1.904 $MJ_{th}/Nm^3$ raw biogas. Furthermore, there is an output of 3.549 kg digestate/$Nm^3$ raw biogas.

Conversion of **biowaste** to raw biogas via anaerobic digestion is assumed to happen in a closed digester. Literature provides the values in Table 25. To adapt the values to the defined characteristics, they are converted to refer to the biowaste input.

Values from Giuntoli et al. [10], Billig [41], DiStefano [42] and ecoinvent show good accordance with each other. Therefore, mean values are used for calculation of the process:

- 0.111 $MJ_{el}$ input/kg biowaste from [10], [41], ecoinvent
- 0.264 $MJ_{th}$ input/kg biowaste from [10], [41], ecoinvent
- 140.2 $Nm^3$ raw biogas output/t biowaste from [10], [41], [42]
- 0.829 kg digestate output/kg biowaste from [10], [41], [42]

[8] Symeonidis, A., anaerobic digestion of manure, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

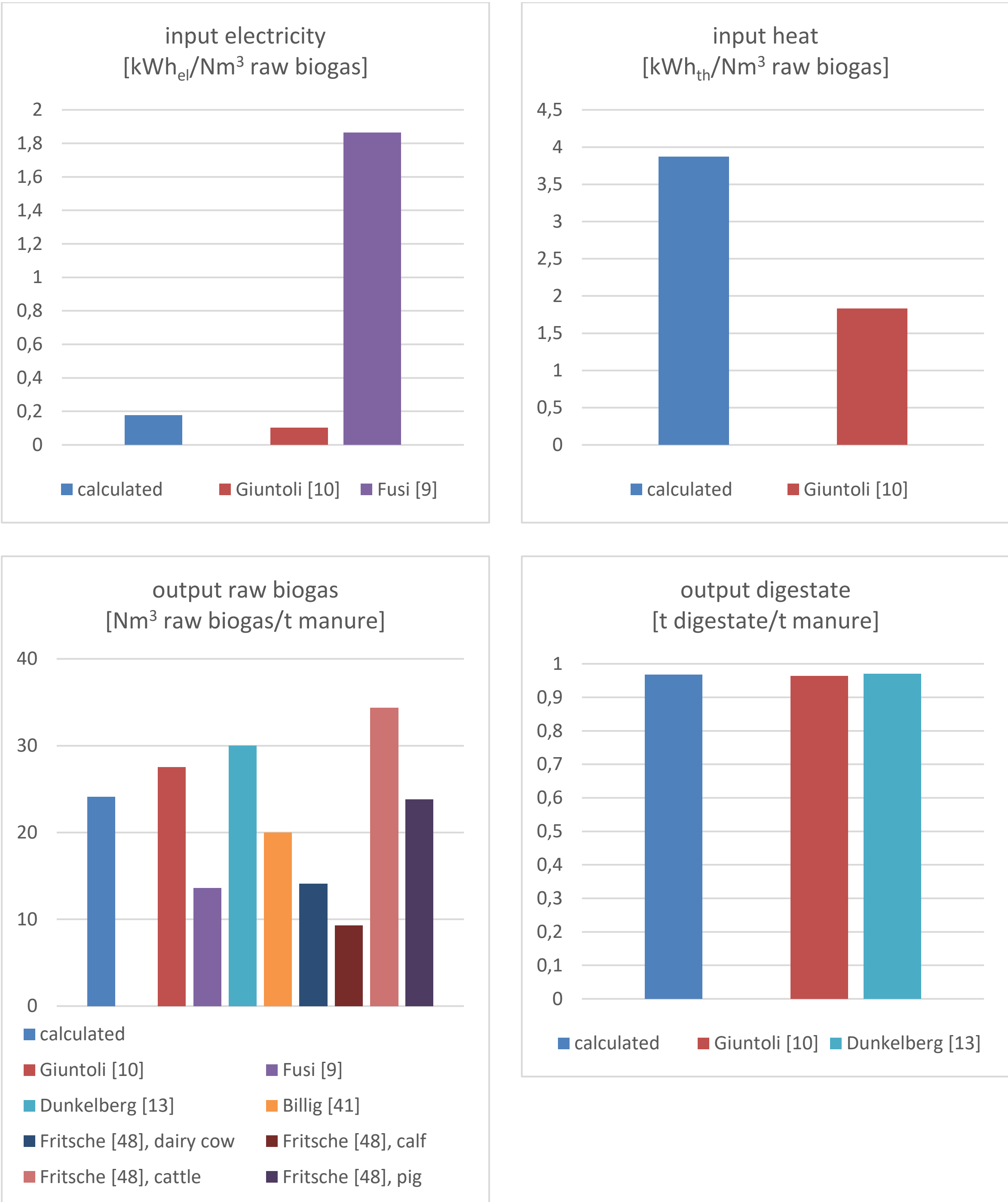


Figure 3: Anaerobic digestion of manure: Comparison of calculated values with literature data

### *Upgrading*

As mentioned in 2.1.1, there are several methods of biogas upgrading. For the different methods, Dunkelberg et al. [13] study especially the three factors electricity demand, heat demand and methane slipping. Amine scrubbing shows very low demand for electricity, but high demand for process heat. It is especially characterized by methane slipping lower than the maximum of 0.2%. This makes further weak gas treatment unnecessary [13, p. 51 f.]. Therefore, amine scrubbing is chosen as upgrading process for this LCA. Amine scrubbing is calculated according to Dunkelberg et al. [13, p. 46]. The data basis is presented in Table 19 (annex A.1.1).

For ***bioCH$_4$_manure*** a share of 55% bioCH$_4$ in raw biogas is assumed in accordance with literature.

According to literature, a share of 52% $bioCH_4$ in raw biogas is assumed for ***$bioCH_4$_maize***.

For the pathway ***$bioCH_4$_waste***, 0.0517 $Nm^3$ $bioCH_4$ output/kg biowaste are determined in accordance with the defined characteristics and the digestion process. That leads to a share of 36.88% $bioCH_4$ in raw biogas. Literature provides different values, presumably due to different plant sizes.

The data basis for the choice of the biomethane shares in raw biogas is presented in Table 6.

Table 6: Data basis for biomethane upgrading

| | *Methane in raw biogas* [vol%] | *Input raw biogas* [$Nm^3$ raw biogas/$Nm^3$ $bioCH_4$] | *Reference* |
|---|---|---|---|
| *$bioCH_4$_manure* | 51 | 1.961 | [10, p. 180] |
| | 56 | 1.786 | [9, p. 6] |
| | 60 | 1.667 | [41, p. 161] |
| | 60 | 1.667 | [43, p. 64] |
| | 55 | 1.818 | [13, p. 41] |
| *$bioCH_4$_maize* | 51.395 | 1.946 | [10, pp. 54, 180] |
| | 52 | 1.923 | [13, p. 41] |
| | 52.5 | 1.900 | [41, p. 165] |
| | 52.5<br>53 | 1.900 | [40, p. 16 f.] |
| | 54 | 1.850 | [44, p. 210] |
| *$bioCH_4$_waste* | 58.16 | 1.720 | [10, pp. 54, 180] |
| | 58.7 | 1.704 | [41, p. 164] |
| | Household biowaste: 60 | 1.667 | [41, p. 161] |
| | Municipal green waste: 43.33 | 2.308 | [41, p. 161] |
| | 55 | 1.818 | [42, p. 1098] |

### *Waste treatment: storage and transport*

Digestate is assumed to be stored in closed storage tanks to avoid unnecessary emissions. Due to lack of further data, digestate storage is calculated according to Dunkelberg et al. [13, p. 40], see Table 20 (annex A.1.1). Density of digestate is 1 kg/l according to Dunkelberg et al. [13, p. 39].

The calculation of the amounts of digestate per biomethane pathway is shown in Table 7.

Table 7: Digestate output from biomethane pathways

| | *$bioCH_4$_manure* | *$bioCH_4$_maize* | *$bioCH_4$_waste* |
|---|---|---|---|
| Output digestate from digestion [kg digestate/$Nm^3$ raw biogas] | 40.141 | 3.549 | 5.915 |
| Input raw biogas into upgrading [$Nm^3$ raw biogas/$Nm^3$ $bioCH_4$] | 1.818 | 1.923 | 2.711 |
| Total output digestate [kg digestate/$Nm^3$ $bioCH_4$] | 72.984 | 6.825 | 16.037 |

Based on Stucki [40, p. 21], 10.5 km transport distance is defined from the biogas plant to the field where the digestate is used as fertilizer. This distance is equivalent to 0.0105 tkm/kg digestate by truck.

#### *Other*

Gas Network Access Regulations (Gasnetzzugangsverordnung) [29], paragraph 36 (1) allows for a maximum of 0.2 vol% methane slip from the production of biomethane to be fed into the natural gas grid. Therefore, the equivalent of 0.00143 kg $CH_4$/$Nm^3$ bio$CH_4$ is considered.

#### *Distribution*

The produced biomethane is assumed to be distributed in Germany's natural gas grid with the same emissions as natural gas. These emissions account for 0.001 kg $CH_4$ losses/kg gas in the grid leading to 1.952 kg $CO_{2,\,eq}$/MWh bio$CH_4$

#### *Combustion*

Combustion is assumed equal to the combustion of natural gas. Thereof follow 270.863 kg $CO_{2,\,eq}$/MWh energy.

### 3.4.2 Impact Assessment

According to the scope definition, climate change is the only relevant impact category in this LCA and the corresponding impact indicator is the Global Warming Potential for a time horizon of 100 years (GWP 100) measured as kg $CO_{2,\,eq.}$ The impact assessment is implemented with the software openLCA.

The results from the implementation of the impact assessment for the biomethane pathways are summarized in Figure 4.

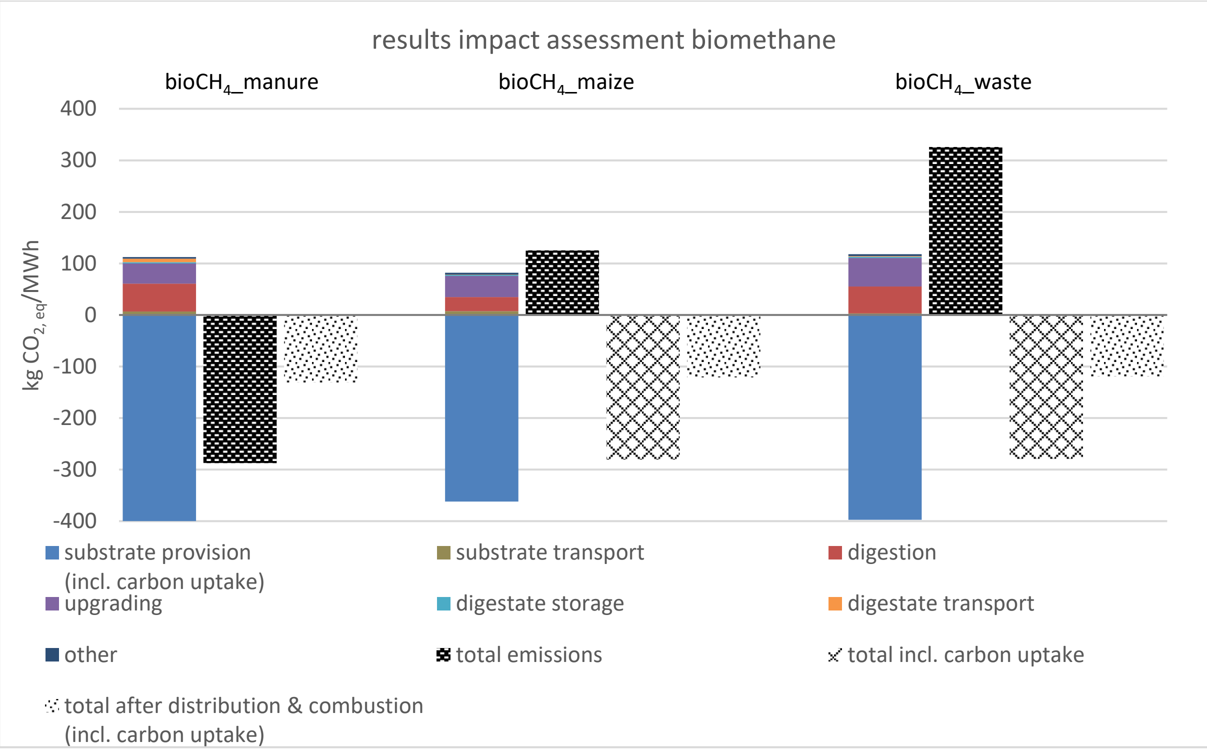


Figure 4: Results impact assessment biomethane pathways

The category "total emissions" provides the emissions of the pathways excluding the carbon uptake. For the pathways *bioCH$_4$_maize* and *bioCH$_4$_waste*, the calculation of the carbon uptake in the correct way is complex. During the growth of the substrates, carbon from the surrounding air is absorbed and stored. This carbon is accounted for as carbon dioxide uptake. During the digestion process, part of the absorbed carbon is converted into methane and part of it remains in the digestate. The share of carbon remaining in the digestate is not investigated in this study. The converted carbon in the biogas is released when the biogas is combusted. The defined process for combustion of biomethane does not distinguish between fossil and biogenic carbon being released. The remaining carbon in the digestate is released during further application of the digestate.

This LCA does not consider the further application of the digestate but does consider the combustion of the biomethane. As a result, the way of the carbon is assessed incompletely and out of balance. This imbalance leads to too low emissions. Tracing the path of the carbon exceeds the extent of this thesis. This problem is solved by neglecting the carbon uptake into the substrate as well as the combustion of the biomethane. Therefore, the value “total emissions”, excluding carbon uptake, distribution and combustion, is the target value for investigations in this study. This is a simplifying approach, as no distinction is made between biogenic and fossil carbon dioxide. To clarify this approach, it is illustrated in Figure 5.

For the pathway *bioCH$_4$_manure*, the credits for avoiding the manure storage do not represent an uptake of carbon into the substrate, but a credit received for avoiding the emission intensive storage the substrate. Therefore, they cannot be neglected.

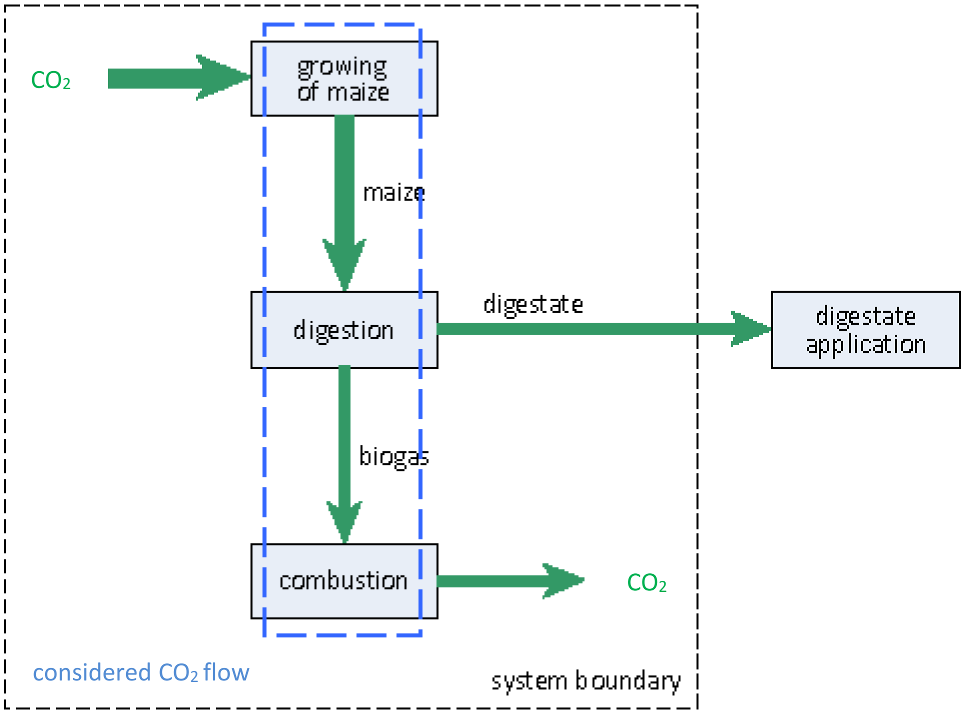


Figure 5: Approach carbon uptake

The construction of the plant for anaerobic digestion produces -2.208 kg $CO_{2,\ eq}$/MWh bioCH$_4$. As the share of this unit process only accounts for 0.762% of the total emissions, it is neglected for this and all other pathways. Table 8 shows the results of the impact assessment in detail.

Table 8: Results impact assessment biomethane pathways

| *Unit process* | *$bioCH_4$_manure* | *$bioCH_4$_maize* | *$bioCH_4$_waste* |
|---|---|---|---|
| Raw material provision (incl. carbon uptake) [kg $CO_{2,eq}$/MWh $bioCH_4$] | -399,928 | -362.253 | -397.105 |
| *Share total emissions [%]* | *139.159** | *129.107* | *142.164* |
| Raw material transport [kg $CO_{2,eq}$/MWh $bioCH_4$] | 6.537 | 7.166 | 3.354 |
| *Share total emissions [%]* | *-2.274** | *-2.554* | *-1.201* |
| Conversion [kg $CO_{2,eq}$/MWh $bioCH_4$] | 54.554 | 27.771 | 51.552 |
| *Share total emissions [%]* | *-18.983** | *-9.898* | *-18.455* |
| Upgrading [kg $CO_{2,eq}$/MWh $bioCH_4$] | 38.598 | 40.629 | 55.805 |
| *Share total emissions [%]* | *-13.431** | *-14.480* | *-19.978* |
| Waste treatment: storage [kg $CO_{2,eq}$/MWh $bioCH_4$] | 2.605 | 1.888 | 2.009 |
| *Share total emissions [%]* | *-0.906** | *-0.673* | *-0.719* |
| Waste treatment: transport [kg $CO_{2,eq}$/MWh $bioCH_4$] | 6.645 | 0.621 | 1.460 |
| *Share total emissions [%]* | *-2.312** | *-0.221* | *-0.523* |
| Other: methane slip [kg $CO_{2,eq}$/MWh $bioCH_4$] | 3.600 | 3.596 | 3.596 |
| *Share total emissions [%]* | *-1.243** | *-1.282* | *-1.287* |
| Total emissions [kg $CO_{2,eq}$/MWh $bioCH_4$] | 112.539 | 125.038 | 325.993 |
| Total incl. carbon uptake [kg $CO_{2,eq}$/MWh $bioCH_4$] | -287.389 | -280.583 | -279.330 |
| Total after distribution and combustion (incl. carbon uptake) [kg $CO_{2,eq}$/MWh energy] | -130.806 | -121.228 | -119.465 |

**construction excluded*

## 3.4.3 Monte Carlo Simulation

Parameters relevant for the Monte Carlo Simulation are determined by a sensitivity analysis. As the biomethane pathways only differ in terms of the substrate, the sensitivity analysis is carried out exemplarily for the pathway *$bioCH_4$_manure*. Relevant parameters for *$bioCH_4$_maize* and *$bioCH_4$_waste* are derived from this analysis. The sensitivity analysis and the Monte Carlo simulations refer to the total emissions without carbon uptake.

***Sensitivity Analysis***

For the sensitivity analysis of the pathway *$bioCH_4$_manure*, the parameters of all unit processes are varied one by one, while all other parameters of the process system stay constant. Variations are executed according to literature values in the inventory analysis. If considered appropriate, the variations from literature are complemented by stated variations. Figure 6 shows the results of the sensitivity analysis. The numbers at the end of the bars indicate the minimum or maximum variation of the parameters. The bars present the resulting change in total emissions.


Figure 6: Results sensitivity analysis $bioCH_4$_manure

Parameter variations leading to a high change of the total emissions are considered the most critical ones. For them, even small variations show a huge impact on the result. Thus, the input of manure into the digestion process, the credits for avoided manure storage, and the input of raw biogas into the upgrading process are considered the most critical ones. The credits' impact is multiplied by the manure input value. Same is valid for the raw biogas input multiplying the manure input. Therefore, the impact of these three parameters is the highest.

The parameter "methane slip" leads to a relatively high change in the total emissions despite a low gradient. Its influence can be traced back to the immense variation of the input parameter based on literature data. Same is valid for the input of electricity into the digestion process.

Only parameters whose variation results in a change in the final result of the *bioCH$_4$_manure* pathway of 5% or more are considered critical for the Monte Carlo simulation. This selection is necessary due to limited computing capacities.

### *Monte Carlo Simulation*

The critical parameters for the Monte Carlo simulation of the biomethane pathways are

- credits for avoiding manure storage (*bioCH$_4$_manure*), emissions from the provision of maize silage (*bioCH$_4$_maize*), emissions from the provision of biowaste (*bioCH$_4$_waste*),
- input of substrate into the digestion process,
- input of heat into the digestion process,
- input of raw biogas into the upgrading process and
- total methane slip.

For the pathway *bioCH$_4$_maize*, the transport distance of the raw material and the input of electricity into the digestion process are added because they show variations of 434.65% and 170.12%, respectively.

The input of electricity into the digestion process is added in the pathway *bioCH$_4$_waste* because it shows variations of up to 135.57% which result in a change in the final result of the *bioCH$_4$_waste* pathway of 15.3%.

For all pathways, the raw material provision is considered without carbon uptake. A summarizing presentation of the respective parameters can be found in Table 43 (*bioCH$_4$_manure*), Table 44 (*bioCH$_4$_maize*), Table 45 (*bioCH$_4$_waste*), all in annex B.1.1.

To avoid problems due to the limited computing capacities, the simulation is implemented in 35,000 simulation steps. That is equivalent to 8.106 variations per parameter for *bioCH$_4$_manure*, 4.458 variations for *bioCH$_4$_maize* and 5.719 variations for *bioCH$_4$_waste*.

Figure 7, Figure 8 and Figure 9 present the results of the Monte Carlo simulation summarized in Table 46 (annex B.1.1). For reasons of computing capacities, the graphic presentation of the results in the mentioned figures is only possible for 10,000 simulation steps. The figures show the results in kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$. Attention must be paid to the scale of the axes as they cannot be scaled consistently for reasons of presentation.

In the graphs, the 5% percentile, the median and the 95% percentile, the mean and the standard deviation and the result from the LCA calculations are indicated. Median and 5% percentile and 95% percentile are types of quantiles indicating the share of results lower or exactly as high as the corresponding value [45, p. 79]. The closer the values of the 5% percentile and 95% percentile are to the median's value, the more robust and explicit the result can be interpreted. The same is valid for the standard deviation being close to 0 as the standard deviation indicates the range of results including 68% of all values related to the mean value [46, p. 23]. A standard deviation close to 1 and mean and median values close to each other indicate a distribution resembling the normal distribution.

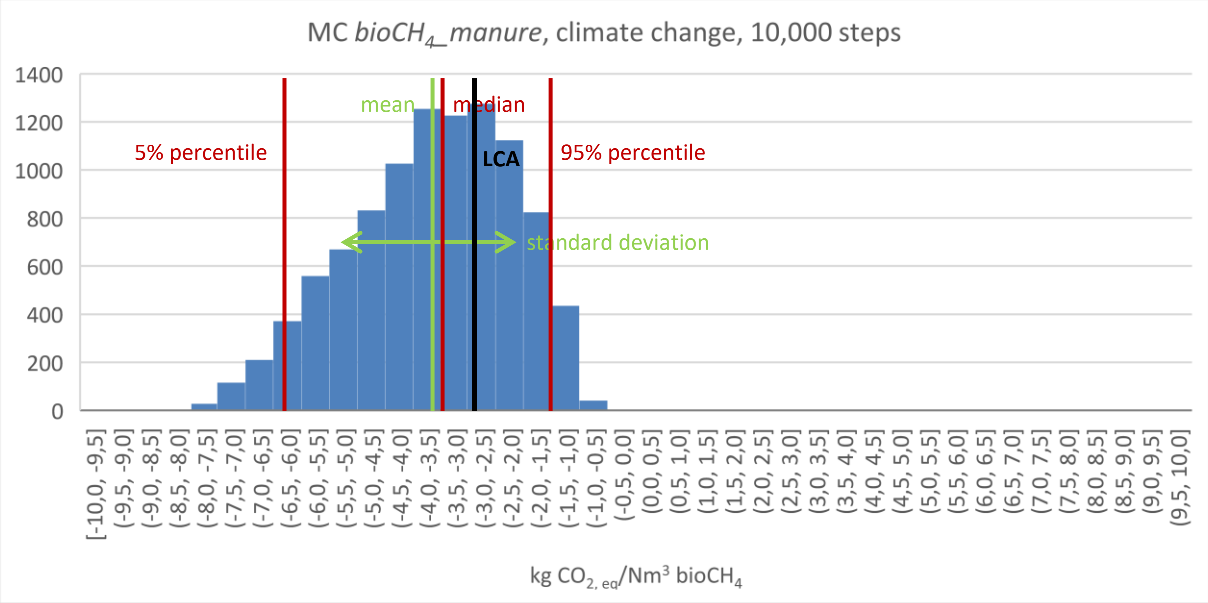


Figure 7: Results Monte Carlo simulation *bioCH$_4$_manure*, climate change, 10,000 simulation steps

For the pathway ***bioCH$_4$_manure***, the LCA result lies within the range of the standard deviation. Furthermore, mean and median value are very close to each other and the shape of the distribution resembles a lightly shifted normal distribution.

These factors indicate the robustness of the result and confirm the choice of the input parameters made in the inventory analysis.

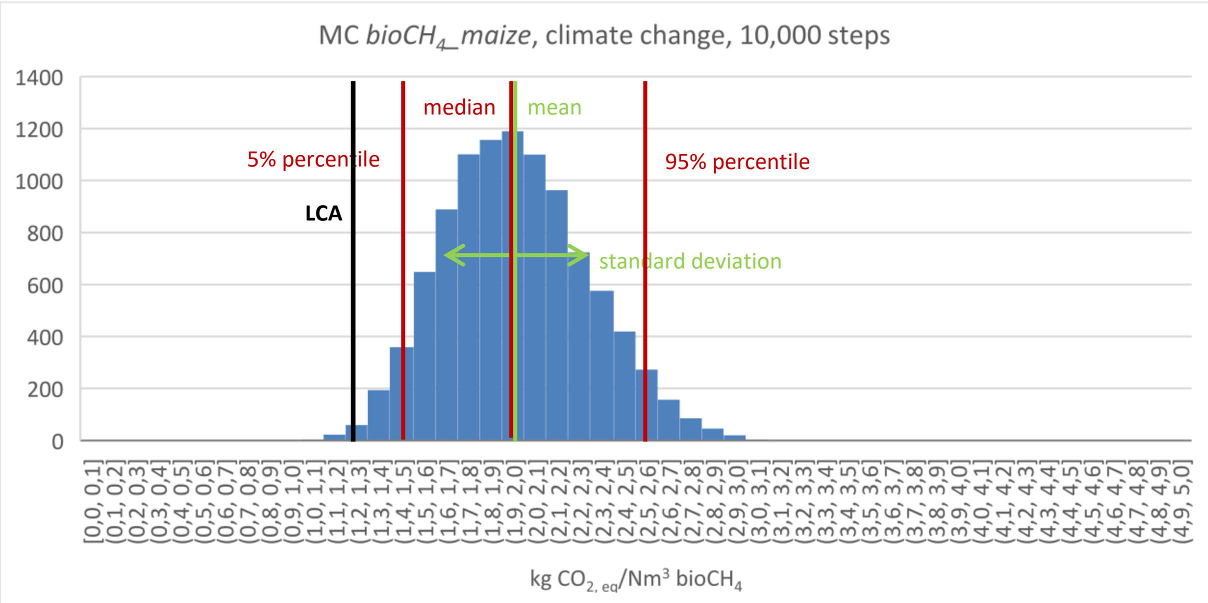


Figure 8: Results Monte Carlo simulation *bioCH$_4$_maize*, climate change, 10,000 simulation steps

For ***bioCH$_4$_maize***, the LCA result lies out of the rage of the standard deviation. However, mean and median value are very close to each other. The distribution appears to be a normal distribution. The LCA result being very low in comparison to the results from the Monte Carlo simulation is assumed to be cause by high variations of the input parameters, to some extend higher than 100%.

Tu ensure robustness and in further assessments, the choice of input parameters made in the inventory analysis should be reconsidered and further investigation should be done.

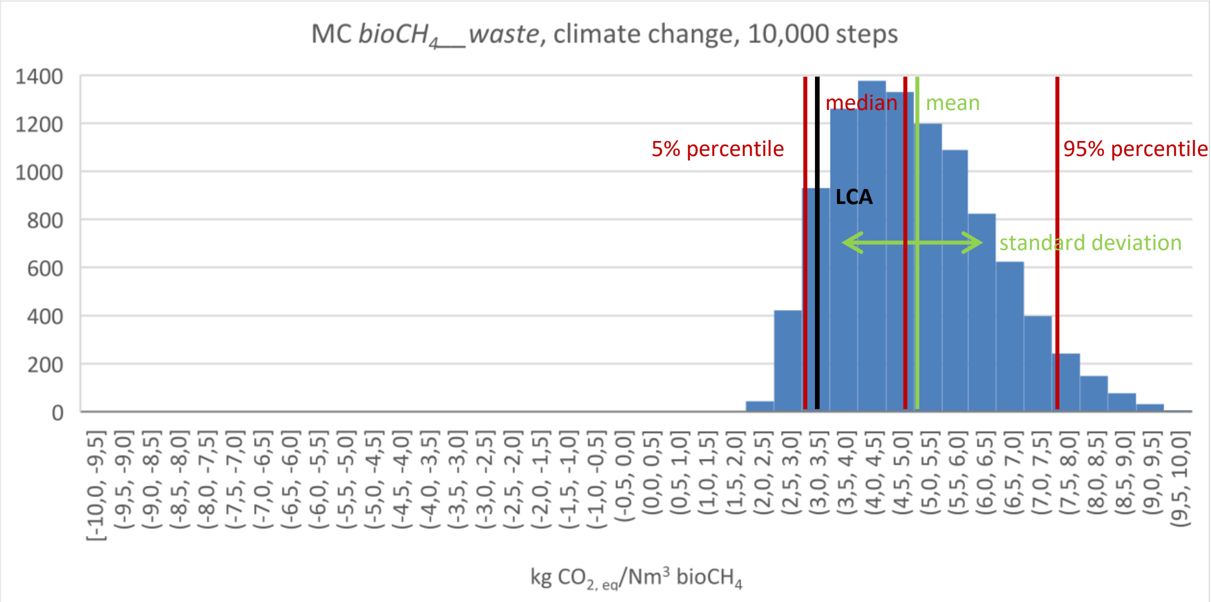


Figure 9: Results Monte Carlo simulation *bioCH$_4$_waste*, climate change, 10,000 simulation steps

The LCA results of the pathway ***bioCH$_4$_waste*** lies just out of the range of the standard deviation. This irregularity is assumed to be a result of the range of input parameters. The sensitivity analysis for *bioCH$_4$_manure* stated the high impact of the credits for the avoided manure storage. In the pathway *bioCH$_4$_waste*, these credits correspond to the emissions from the biowaste provision. This explains the deviation of the simulation results to higher values compared to the LCA result. Furthermore, it causes the shape of the distribution resembling a normal distribution slightly shifted to lower values.

Like for *bioCH$_4$_maize*, further investigation should be done on the choice of input parameters for the inventory analysis in further investigations. Special attention should be paid to the raw material provision.

### 3.4.4 Comparison with Literature

Figure 10 shows the LCA results of the biomethane pathways in comparison with literature data. The corresponding references can be found in Table 47 (*bioCH$_4$_manure*), Table 48 (*bioCH$_4$_maize*) and Table 49 (*bioCH$_4$_waste*), all in annex B.1.2. The error bar at the total emissions represents the standard deviation according to the Monte Carlo simulation.

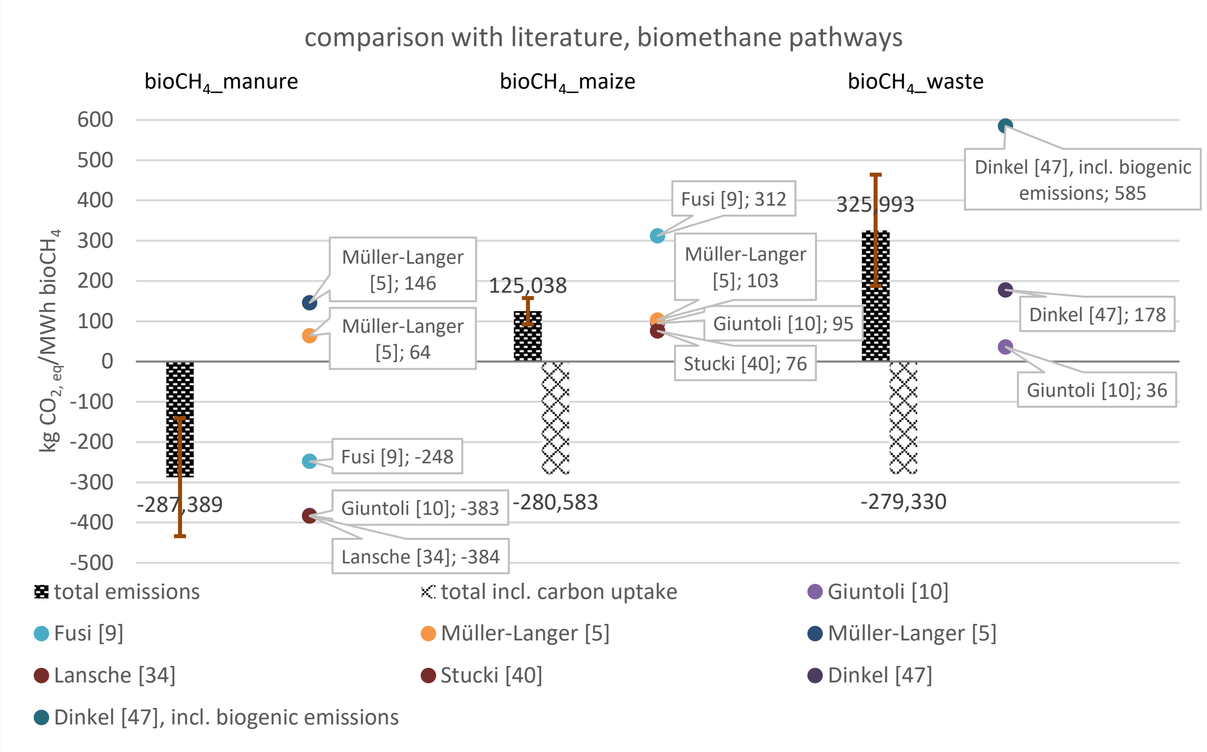


Figure 10: Comparison with literature, biomethane pathways

For the pathway ***bioCH$_4$_manure***, the LCA result of -287.389 kg $CO_{2,\,eq}$/MWh bioCH$_4$ lies between the results from Giuntoli et al. [10], Fusi [9] and Lansche [34]. Deviations can be traced back to differences in credits for the avoided storage of manure, the manure and heat input into the digestion process and the input of raw biogas into the upgrading process.

Exemplarily compared to this LCA, Giuntoli et al. [10] accounts for higher credits for the avoided storage of manure, which is one of the most critical parameters according to the sensitivity analysis. A lower amount of manure and heat input into the digestion process further reduce the emissions. This reduction cannot be reversed by a higher amount of raw biogas input.

As Müller-Langer et al. [5] do not provide detailed information on the unit processes, reasons for the immense deviations can only be assumed. Often, studies do not consider biogenic carbon dioxide for the calculation of credits. They consider biogenic carbon dioxide carbon neutral and the credits are compensated with the carbon dioxide released during combustion. Neglecting the credits for the avoided storage of manure, this LCA would result in 112.539 kg $CO_{2,\,eq}$/MWh bioCH$_4$ what fits the values from Müller-Langer et al. That confirms the assumption that Müller-Langer et al. do not consider credits for the avoided storage of manure.

The LCA result of 125.038 kg $CO_{2,\,eq}$/MWh bioCH$_4$ from the pathway ***bioCH$_4$_maize*** is higher than the results from Giuntoli et al. [10], Stucki et al. [40]and Müller-Langer et al. [5]. Considering the standard deviation, the LCA result matches the literature data. Fusi [9] assumes a higher demand for heat for the digestion process and furthermore a lower efficiency. These differences lead to higher emissions than the LCA result.

For the pathway ***bioCH$_4$_waste***, the LCA result of 325.993 kg $CO_{2,\,eq}$/MWh bioCH$_4$ lies between the results from Dinkel et al. [47] and exceeds the result from Giuntoli et al. [10]. An exemplarily comparison with Giuntoli et al. reveals, among others, differences in the process efficiencies causing this deviation.

Summarizing, the total emissions excluding the carbon uptake match the values from literature. That confirms the approach described in 3.4.2.

## 3.5 BioSNG from Gasification Processes

To produce biologic synthetic natural, this thesis assesses residual forest wood, short rotation forestry wood, straw and imported pellets from demolition wood as substrates. The corresponding pathways are

- bioSNG from gasification of residual forest wood *SNG_RFW*,
- bioSNG from gasification of short rotation forestry wood *SNG_SRF*,
- bioSNG from gasification of straw *SNG_straw*,
- bioSNG from gasification of imported pellets from demolition wood *SNG_IP I* with 1 MW raw material input, and
- bioSNG from gasification of imported pellets from demolition wood *SNG_IP II* with 100 MW raw material input.

According to the guidelines, inventory analysis and impact assessment are implemented. The subsequent interpretation and evaluation are completed by a Monte Carlo simulation and a comparison to literature data.

### 3.5.1 Inventory Analysis

General data and conversion factor necessary for the steps of data collection and data calculation are stated in Table 26 (annex A.2). They are not mentioned explicitly if they are used in further calculations.

For the inventory analysis, data is collected for every unit process presented in Figure 2 according to the scope definition.

The bioSNG pathways are based on the characteristics in Table 9.

Table 9: Characteristics bioSNG pathways

| *Characteristic parameter* | *SNG_RFW* | *SNG_SRF* | *SNG_straw* | *SNG_IP I* | *SNG_IP II* |
|---|---|---|---|---|---|
| Input substrate [MW] | 30 | 30 | 1 | 1 | 100 |
| Input substrate [t dry/h] | 5.684 | 5.870 | 0.209 | 0.189 | 18.947 |
| Process efficiency (regarding LHV) [%] | 67.252 | 63.913 | 53.321 | 57.155 | 71.444 |
| Output bioSNG [MW] | 20.176 | 19.174 | 0.533 | 0.572 | 71.444 |
| Output bioSNG [$Nm^3/h$] | 2023.641 | 1923.145 | 53.481 | 57.327 | 7165.867 |
| Full load hours [h/a] | 7,500 | 7,500 | 7,500 | 7,500 | 7,500 |
| Lower heating value substrate [kWh/t dry] | 5277.780 | 5111.110 | 4777.780 | 5277.780 | 5277.780 |
| Lower heating value substrate [MJ/kg] | 19.000 | 18.400 | 17.200 | 19.000 | 19.000 |
| Moisture substrate [%] | 9.000 | 35.000 | 8.000 | 9.000 | 9.000 |

### *Raw material provision*

***SNG_RFW*** uses residual forest wood (RFW) as a substrate.

Wood chips from residual forest wood are defined according to the following characteristics:

- Lower heating value: 19 MJ/kg dry, according to the defined characteristics and confirmed by [22, p. 77], [48, p. 100]
- Moisture after harvest: 50%, according to [16, p. 152], [22, p. 77], [48, p. 100]
- Moisture after drying: 9%, according to the defined characteristics and confirmed by [41, p. 162]
- Average density: 545.564 kg dry/$m^3$

The density was determined from the ecoinvent datasets "hardwood forestry, mixed species, sustainable forest management, CH"[9] stating 640 kg dry/$m^3$ hardwood and "softwood forestry, mixed species, sustainable forest management, CH"[10] stating 440 kg dry/$m^3$ softwood. Calculated from ecoinvent dataset "hardwood forestry, oak, sustainable forest management, DE"[11], German wood chips production consists of 52.782% hardwood and 47.218% softwood. Thereof results the average density.

The residual forest wood needs to be processed for application in the gasification process. The provision of wood chips is calculated according to the same datasets and in the same way as the density. This leads to emissions of -1.778 kg $CO_{2,\,eq}$/kg wood chips. Literature values do not consider the carbon uptake into the wood and result in positive emissions, see Table 27 (annex A.2.1). Calculated from the ecoinvent datasets, the carbon uptake accounts for 1.811 kg $CO_2$/kg wood. Excluding this uptake results in emissions for the provision of wood chips of 0.033 kg $CO_{2,\,eq}$/kg RFW chips.

The pathway ***SNG_SRF*** uses short rotation forestry (SRF) wood from willow as a substrate.

Wood chips from willow are defined according to the following characteristics:

- Lower heating value: 18.4 MJ/kg dry, according to the defined characteristics and confirmed by [5, p. 153], [49, p. 387]
- Moisture after harvest: 50%, according to [5, p. 153], [22, p. 89], [41, p. 162]
- Moisture after drying: 35%, according to the defined characteristics and confirmed by [5, p. 153], [41, p. 162]

The willow chips need to be processed for application in the gasification process. The provision of willow chips is calculated according to the ecoinvent dataset "willow production, short rotation coppice, DE"[12] and leads to emissions of -1.701 kg $CO_{2,\,eq}$/kg willow chips. To provide consistency with the other bioSNG pathways, the carbon uptakes are investigated separately. According to the ecoinvent dataset, 1.759 kg $CO_2$ absorbed by willow during its growth. The emissions for the provision of willow chips excluding this absorption account for 0.058 kg $CO_{2,\,eq}$/kg SRF chips.

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[9] Werner, F., hardwood forestry, mixed species, sustainable forest management, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

[10] Werner, F., softwood forestry, mixed species, sustainable forest management, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

[11] Werner, F., hardwood forestry, oak, sustainable forest management, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[12] Schnetzer, J., willow production, short rotation coppice, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

Literature often does not consider carbon uptake during the growth of the willow plants. Therefore, the comparable literature value differs from the chosen values, see Table 32 (annex A.2.2).

Straw as substrate for the pathway ***SNG_straw*** is defined according to the following characteristics:

- Lower heating value: 17.2 MJ/kg, according to the defined characteristics
- Moisture: 8%, according to the defined characteristics

Simplifying, the production of straw is calculated according to the ecoinvent dataset "market for straw, organic, GLO"[13], leading to -0.174 kg $CO_{2,\,eq}$/kg straw. Assessing the individual datasets forming this market, reveals a carbon uptake into the straw of 0.207 kg $CO_2$/kg straw. Thereof emissions of 0.033 kg $CO_{2,\,eq}$/kg straw occur during the production of straw excluding the carbon uptake. The pelletization of straw is considered equal to the production of wood pellets and is calculated according to Zhang et al. [50], resulting in 0.035 kg $CO_{2,\,eq}$/kg pellets.

This thesis assesses the very specific case of wood pellets being produced from demolition wood and imported to Germany as a substrate in the pathways ***SNG_IP I*** and ***SNG_IP II***. Demolition wood is assumed to origin from natural disasters destroying wooden houses in the US. The remaining wood is transported to palletization plants, and the pellets are transported to Germany by ship to be gasified.

Pellets from demolition wood are defined according to the following characteristics:

- Lower heating value: 19 MJ/kg dry, according to the defined characteristics and confirmed by [50]
- Moisture: 9%, according to the defined characteristics and confirmed by [16, p. 152]

The raw material provision is calculated in the following steps:

1. Provision of demolition wood:

The $CO_2$ emissions coming along with the demolition wood are based on the ecoinvent dataset "market for cleft timber, measured as dry mass, RoW"[14]. The carbon uptake during the growth of the wood is reduced by the processing of wood to cleft timber. Cleft timber is assumed to be the feedstock of building houses. During a building's lifetime, the remaining carbon balance of the wood does not change, so demolition wood comes with an absorbed "carbon content" of 1.746 kg $CO_{2,\,eq}$/kg cleft timber.

2. Transport of demolition wood to the palletization plant:

To be economically, the transport distance of the demolition wood should not be too large. A transport distance of 200 km by truck is defined.

3. Pellet production process:

The pelletization is calculated according to Zhang et al. [50], resulting in 0.035 kg $CO_{2,\,eq}$/kg pellets. As shown in Table 34, this value corresponds with further literature data.

4. Transport of pellets to harbor for international shipping:

A transport distance of 500 km by train is defined.

### *Raw material transport*

Residual forest wood as substrate to ***SNG_RFW*** is defined as waste product from forestry remaining unused in the forest [22, p. 82]. According to the Federal Ministry of Food and Agriculture [51, p. 35],

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[13] Bourgault, G., market for straw, organic, GLO, Allocation, cut-off by classification, ecoinvent database version 3.4

[14] market for cleft timber, measured as dry mass, RoW, Allocation, cut-off by classification, ecoinvent database version 3.4

20.2 million $m^3$ harvesting residues and bark and 10.4 million $m^3$ dead wood remain in the forests. This leads to 8.566E-05 $m^3$ residual forest wood/$km^2$ on an area of 35,720,780 ha [51, p. 0], equivalent to 11,673.458 $km^2/m^3$ residual forest wood. This corresponds to a radius of 60,957 km/$m^3$ wood. Kaltschmitt et al. [22, p. 183] recommend extending the linear distance by factor 1.5 for transport by truck. Considering the wood's moisture after harvest and after drying, a total transport distance of 0.335 km by truck/kg dry wood, equivalent to 3.352E-04 tkm/kg dry wood chips is determined.

For the pathway ***SNG_SRF***, the raw material transport is calculated as follows. In Germany, short rotation forestry was cultivated on 5,968.5 ha in 2014 [52]. This value is considered current. Annually, 5 to 10 t willow are harvested/ha. Assuming 50% of the cultivated short rotation forestry is willow, these values lead to an amount of 22,381.875 t willow cultivated annually in Germany. With Germany's size of 357,358.71 $km^2$ [39] there are 0.063 t willow/$km^2$. Extending the linear distance by factor 1.5 for transport by truck according to Kaltschmitt et al. [22, p. 183], results in a total transport distance of 3.382E-03 km by truck/kg wood, equivalent to 3.382E-06 tkm/kg willow wood chips. This value is confirmed by Müller-Langer et al. [5, p. 172].

A raw material transport distance of 20 km is defined for ***SNG_straw*** based on Kaltschmitt et al. [22, p. 183]. Extending the linear distance by factor 1.5 for transport by truck, leads to a transport distance of 0.03 tkm/kg straw.

For the pathways ***SNG_IP I*** and ***SNG_IP II***, the pellets are shipped from the US to Germany. Exemplary transport distances from New York and Miami to Hamburg account for 6,698.684 km and 8,132.132 km, respectively [53]. A mean distance of 7.415 tkm by ship/kg pellet is determined.

### *Conversion and Upgrading*

Conversion and upgrading are considered the same for all bioSNG pathways. For *SNG_straw* this is a simplification caused by insufficient data and the straw gasification process still being at the stage of development [41, p. 186]. Technically, the gasification of straw is more complicated than the gasification of wood. The low ash melting temperature leads to the development of agglomerates and tar [22, p. 612]. This can be improved by adding additives. Corrosive chlorine further complicates the gasification process [41, pp. 184, 186].

Conversion and upgrading are summarized in one unit process based on the ecoinvent dataset "methane production, 96% by volume, from synthetic gas, wood, fluidised technology, CH"[15]. As described in 2.1.2, Kaltschmitt et al. [22, p. 621] recommend a fluidized bed gasifier for the gasification of wood. Therefore, the technology assessed in the dataset fits the pathway's demands. The dataset describes the gasification and methanation of wood chips with a share of 94% $CH_4$ in the produced bioSNG. The process begins with the transport of wood and required equipment to the production site. Drying and comminuting the wood chips and their gasification follow. The process ends with the treatment and conditioning of the product gas, its methanation and compression of methane to natural gas network pressure.

To enable the adaption of the ecoinvent process to the required characteristics and the system boundary, the data were referred to the wood input as shown in Table 28 (annex A.2.1). Furthermore, the industrial furnace and the synthetic gas factory are neglected due to their low influence on the emissions of the unit process.

The data is converted to refer on the substrate input for all pathways. The resulting inputs are summarized in Figure 11 according to Table 29 (annex A.2.1). For comparison, values from literature are given, if available, in Table 30 (*SNG_RFW*), Table 33 (*SNG_SRF*), and Table 35 (*SNG_IP I*), all in annex A.2.1 to A.2.3.

[15] Del Duce, A., methane production, 96% by volume, from synthetic gas, wood, fluidised technology, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

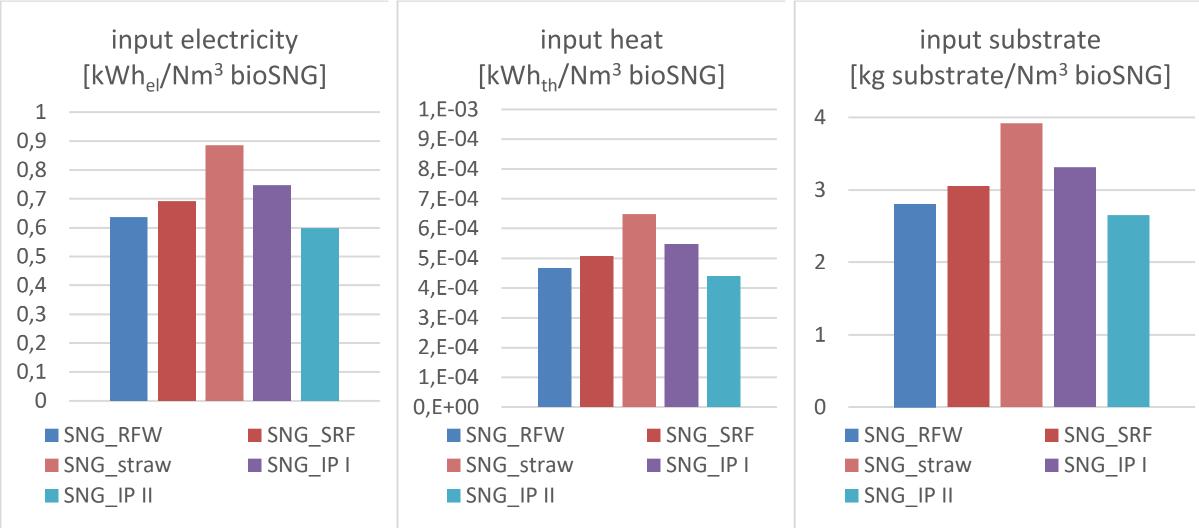


Figure 11: BioSNG - input values gasification and upgrading

### *Waste treatment*

Waste treatment is modelled according to the ecoinvent datasets given in Table 31 (annex A.2.1). Market datasets are chosen in accordance with the activities given in dataset "methane production, 96% by volume, from synthetic gas, wood, fluidised technology, CH" (see *Conversion and Upgrading*).

The respective amounts of waste for every pathway are summarized in Table 31 as well.

### *Other*

No other unit processes or emissions are considered.

### *Distribution*

The produced bio$CH_4$ is assumed to be distributed in Germany's natural gas grid with the same emissions as natural gas. This leads to 0.001 kg $CH_4$ losses/kg gas in the grid, equivalent to 1.952 kg $CO_{2,\,eq}$/MWh bioSNG.

### *Combustion*

The combustion process is considered equal to the combustion of natural gas with 270.863 kg $CO_{2,\,eq}$ emissions/MWh energy.

## 3.5.2 Impact Assessment

The impact assessment for bioSNG from gasification processes is implemented with the software openLCA. Climate change is the only relevant impact category in this LCA, the corresponding impact indicator is the Global Warming Potential for a time horizon of 100 years (GWP 100) measured as kg $CO_{2,\,eq}$.

The results from the implementation of the impact assessment for the bioSNG pathways are summarized in Figure 12 and shown in Table 10. Carbon uptakes are treated equally to the biomethane pathways.

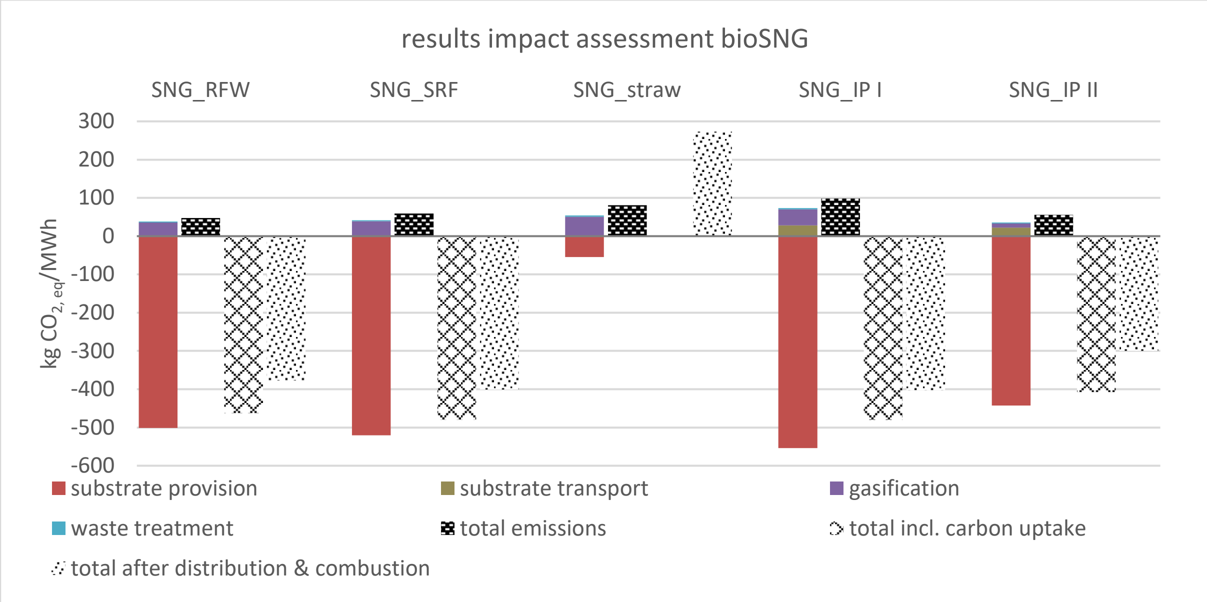


Figure 12: Results impact assessment bioSNG pathways

Table 10: Results impact assessment bioSNG pathways

| *Unit process* | *SNG_RFW* | *SNG_SRF* | *SNG_straw* | *SNG_IP I* | *SNG_IP II* |
|---|---|---|---|---|---|
| Raw material provision, incl. credits, carbon uptake [kg $CO_{2,\,eq}$/MWh bioSNG] | -501.028 | -520.764 | -54.584 | -553.751 | -443.001 |
| *Share total emissions [%]* | *108.281* | *108.687* | *28492.147* | *115.202* | *108.746* |
| Raw material transport [kg $CO_{2,\,eq}$/MWh bioSNG] | 0.008 | 8.949E-05 | 1.018 | 27.995 | 22.395 |
| *Share total emissions [%]* | *-0.002* | *1.87E-05* | *-531.414* | *-5.824* | *-5.497* |
| Conversion and upgrading [kg $CO_{2,\,eq}$/MWh bioSNG] | 35.698 | 38.788 | 49.736 | 42.004 | 10.776 |
| *Share total emissions [%]* | *-7.715* | *-8.095* | *-25961.78* | *-8.738* | *-2.645* |
| Waste treatment [kg $CO_{2,\,eq}$/MWh bioSNG] | 2.611 | 2.837 | 3.628 | 3.072 | 2.457 |
| *Share total emissions [%]* | *-0.564* | *-0.592* | *-1.898.953* | *-0.639* | *-0.603* |
| Total emissions [kg $CO_{2,\,eq}$/MWh bioSNG] | 47.596 | 59.294 | 81.185 | 98.280 | 55.796 |
| Total incl. carbon uptake [kg $CO_{2,\,eq}$/MWh bioSNG] | -462.711 | -479.139 | -0.191 | -480.680 | -407.372 |
| Total after distribution and combustion [kg $CO_{2,\,eq}$/MWh energy] | -377.521 | -400.639 | 273.341 | -402.807 | -299.647 |

### 3.5.3 Monte Carlo Simulation

Parameters relevant for the Monte Carlo Simulation are determined by a sensitivity analysis. As the bioSNG pathways are assumed to differ only in terms of the substrate, the sensitivity analysis is carried out exemplary for the pathway *SNG_RFW*. Relevant parameters for the other bioSNG pathways are derived from this analysis. The sensitivity analysis and the Monte Carlo simulations refer to the total emissions without carbon uptake.

#### *Sensitivity Analysis*

The sensitivity analysis for *SNG_RFW* is based on the literature data in annex A.2.1. The parameters of all unit processes are varied according to their range in literature. If that range is not considered sufficient, stated variations are added to variations from literature. All other parameters of the process system stay constant. The sensitivity analysis is implemented for the wood chips provision excluding the carbon uptake.

Figure 13 shows the results of the sensitivity analysis. The numbers at the end of the bars indicate the minimum or maximum variation of the parameters. The bars present the resulting change in total emissions.

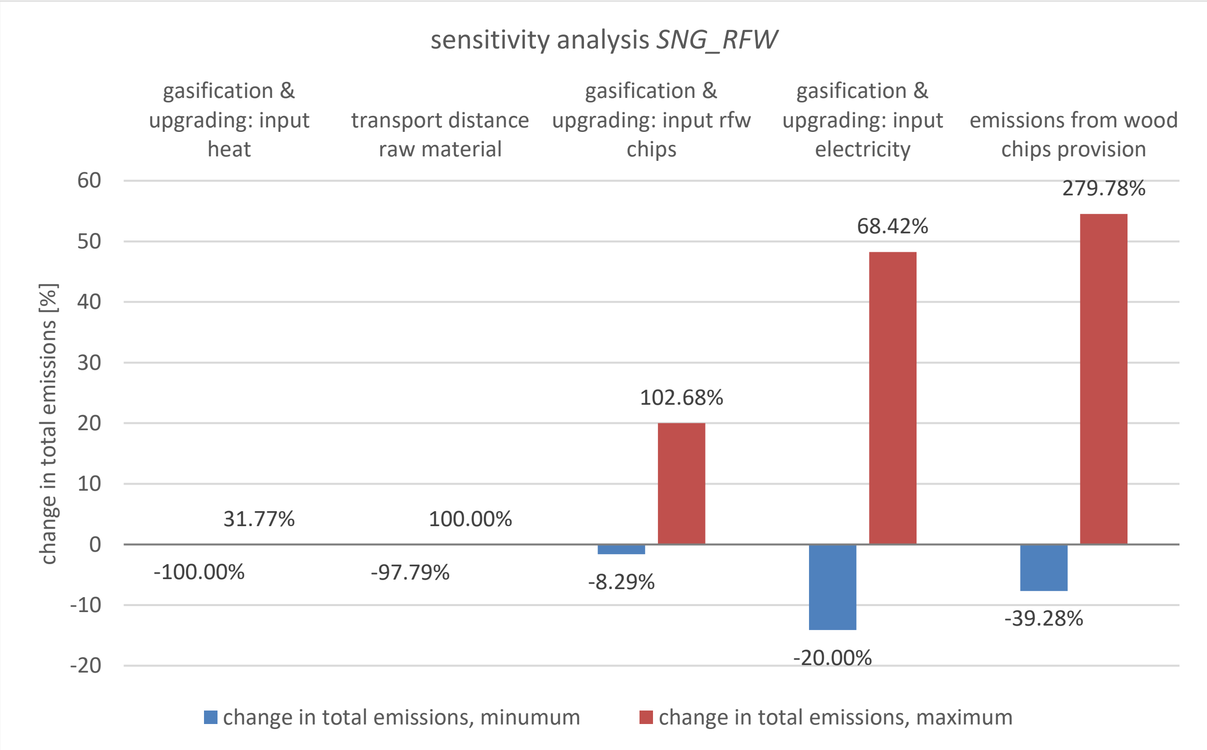


Figure 13: Results sensitivity analysis *SNG_RFW*

The most critical parameters leading to a high change of the total emissions are the emissions from the wood chips provision and the parameter "input electricity" into the gasification process. The input of the residual forest wood into the gasification process is also a critical value.

#### *Monte Carlo Simulation*

The critical parameters for the Monte Carlo simulation of the bioSNG pathways are

- emissions from substrate provision,
- input of substrate into the gasification process, and
- input of electricity into the gasification process.

Caused by lack of literature data for *SNG_straw*, the variations of the input parameters were defined based on the variations for *SNG_RFW* and *SNG_SRF*.

As the transport of the pellets by ship at the pathways *SNG_IP I* and *SNG_IP II* is responsible for 5.824% and 5.497% of the total emissions, respectively, an analysis for variations of -20% and +20% was implemented. The variations of -20% and +20% result in a change of the total emissions of only -1.16% and +1.16%. Therefore, the transport distance is not included in the Monte Carlo simulation.

A summarizing presentation of the respective parameters can be found in Table 50 (*SNG_RFW*), Table 51 (*SNG_SRF*), Table 52 (*SNG_straw*), Table 53 (*SNG_IP I*) and Table 54 (*SNG_IP II*), all in annex B.2.1.

To avoid problems due to the limited computing capacities, the simulation is implemented in 35,000 simulation steps. That is equivalent to 32.711 variations per parameter.

Figure 14 to Figure 18 present the results of the Monte Carlo simulation summarized in Table 55 (annex B.2.1). For reasons of computing capacities, the graphic presentation of the results in the mentioned figures is only possible for 10,000 simulation steps and the figures show the results in kg $CO_{2,\,eq}/Nm^3$ bioSNG. In the graphs, 5% percentile, median and 95% percentile, mean and standard deviation and the result from the LCA calculations are indicated.

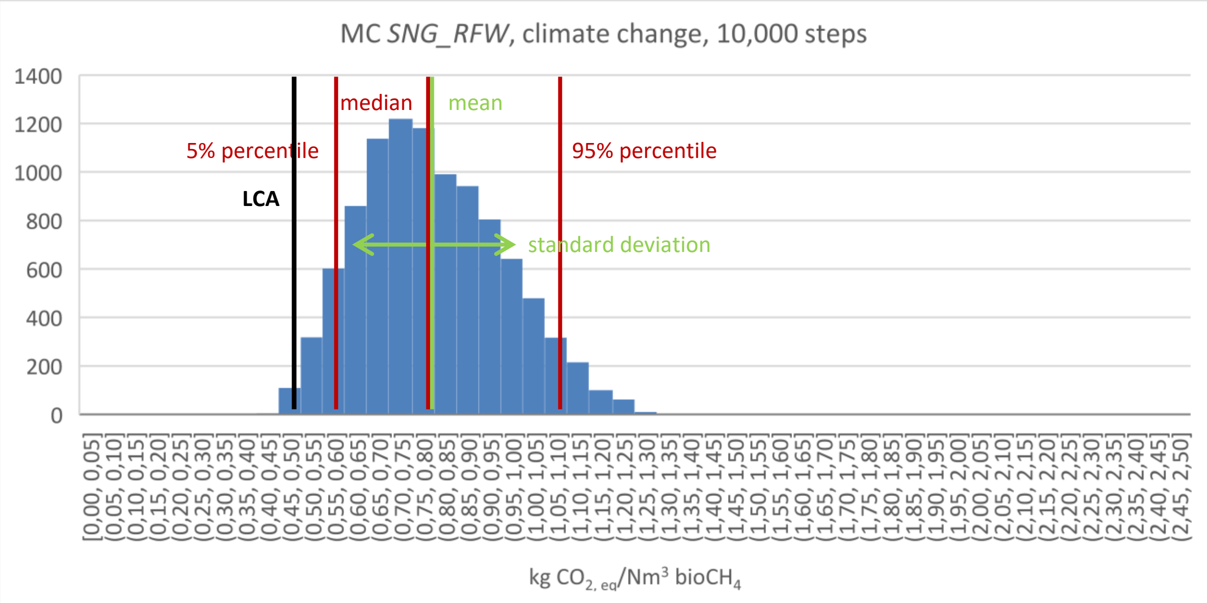


Figure 14: Results Monte Carlo simulation *SNG_RFW*, climate change, 10,000 simulation steps

For ***SNG_RFW***, the distribution is considered a normal distribution. The LCA result is even lower than the value of the 5% percentile. This is caused by enhanced variations of the input parameters to higher values. Especially the variation of +279.78% of the emissions from the wood chips provision shift the distribution away from the LCA result. This needs to be considered for further investigations.

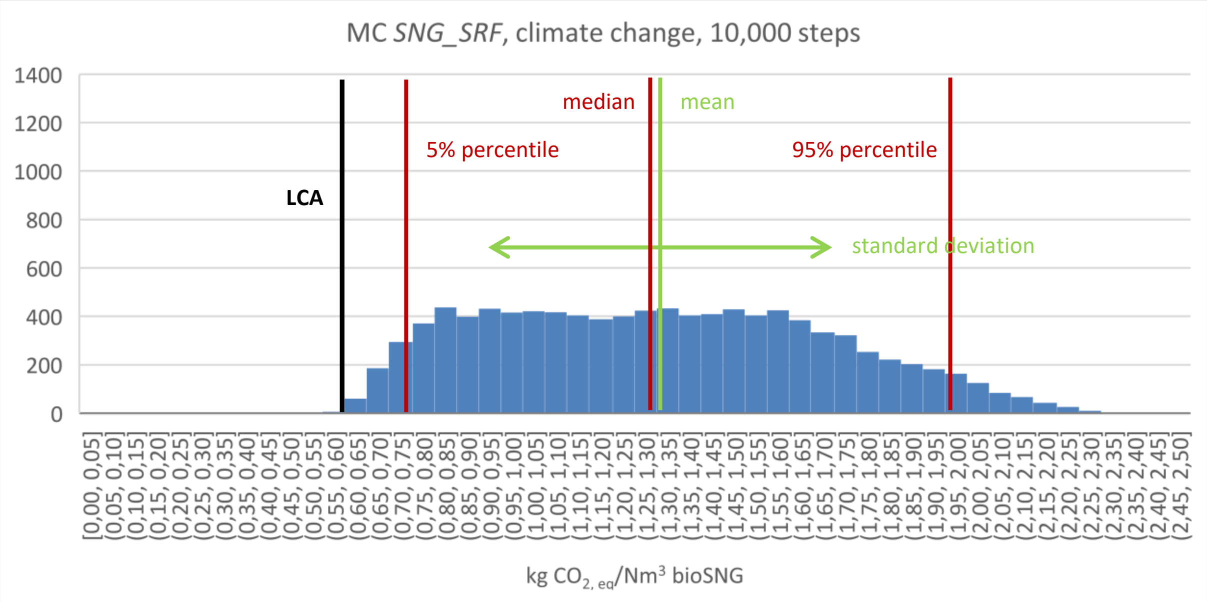


Figure 15: Results Monte Carlo simulation *SNG_SRF*, climate change, 10,000 simulation steps

For ***SNG_SRF***, the LCA result is only a little higher than the minimum value. Like for *SNG_RFW*, this is caused by the variations of the input parameters. Emissions from substrate provision and input of electricity into the gasification process are the most critical parameters. For them, no negative variations are calculated. Therefore, the simulation results in higher emissions than the LCA calculation and the shape of the distribution does not resemble the normal distribution.

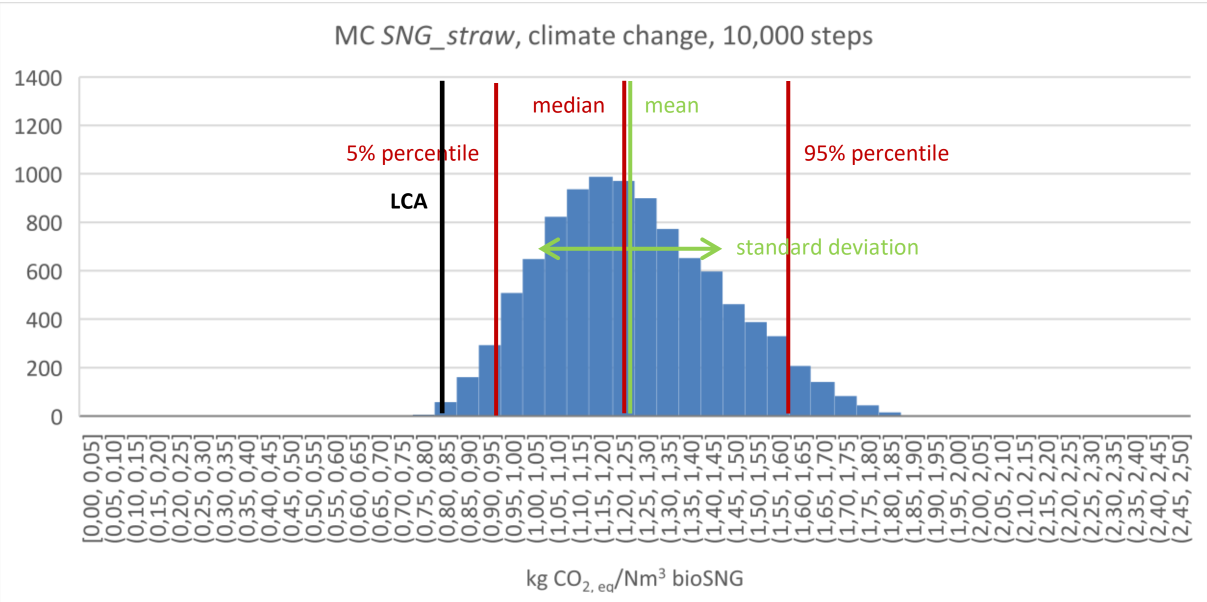


Figure 16: Results Monte Carlo simulation *SNG_straw*, climate change, 10,000 simulation steps

As the variations for ***SNG_straw*** are defined based on the variations from *SNG_RFW* and *SNG_SRF*, the LCA result is lower than the simulation results as well and the shape of the distribution resembles the normal distribution. As the values for the variations are not derived from literature, no further statements can be made.

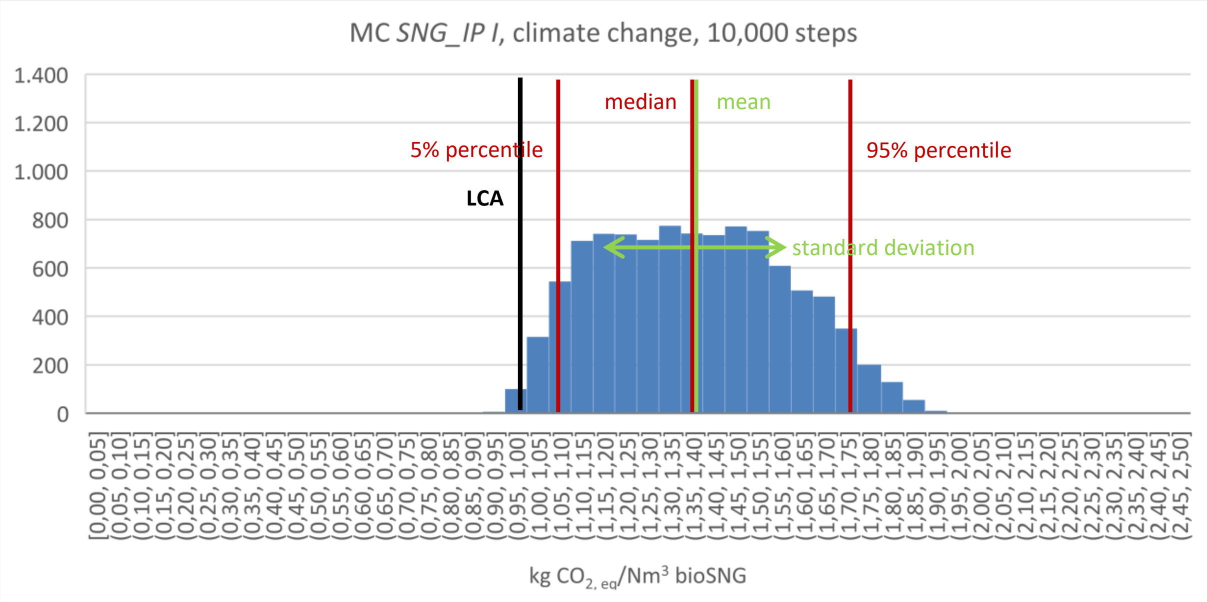


Figure 17: Results Monte Carlo simulation *SNG_IP I*, climate change, 10,000 simulation steps

For ***SNG_IP I***, the shape of the distribution resembles a drawn apart normal distribution without the typical peak. This can be traced back to the variations of the input parameters being uneven to lower and higher values. Like for the other bioSNG pathways, the extreme variations of the emissions from the substrate provision of more than 500% shift the simulation results to higher values than the LCA result.

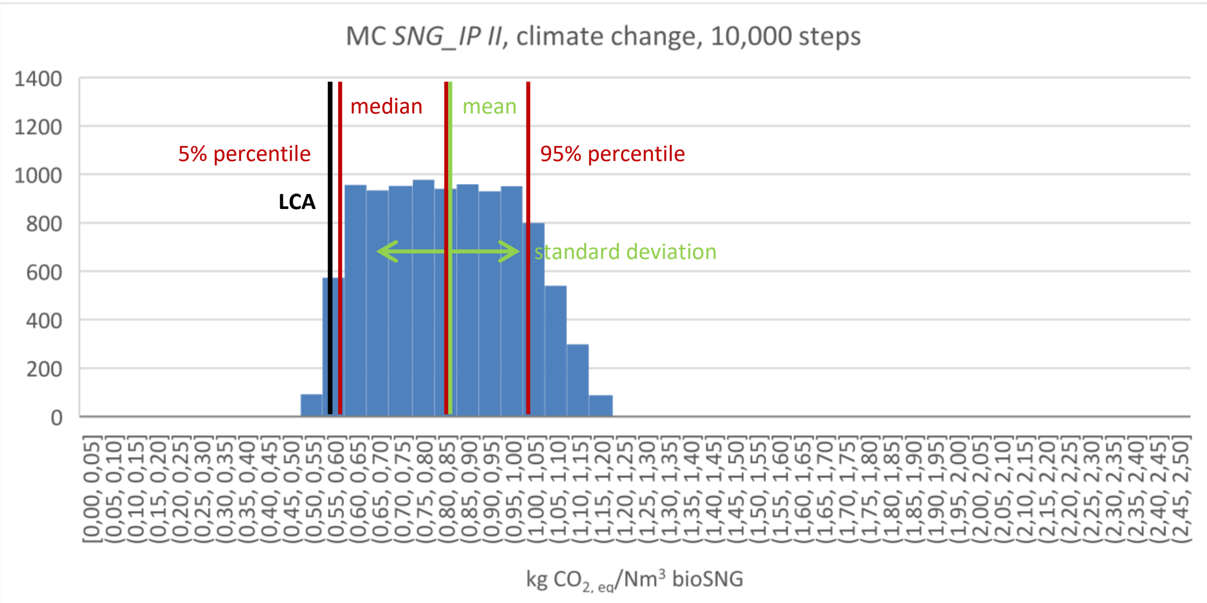


Figure 18: Results Monte Carlo simulation *SNG_IP II*, climate change, 10,000 simulation steps

The LCA result of ***SNG_IP II*** is the closes to the 5% percentile compared to the other results of the bioSNG pathways. The shape of the distribution is very similar to the shape of *SNG_IP I*. And the LCA being low compared to the simulation results can be traced back on the same variation of the emissions for the substrate provision as for *SNG_IP I*.

Summarizing, the Monte Carlo simulations of the bioSNG pathways confirm the tremendous impact of the variations of the emissions from substrate provision and of the input of electricity into the digestion process. In further investigations, especially the emissions from the substrate provision should be assessed more in detail.

### 3.5.4 Comparison with Literature

Figure 19 shows the LCA results of the bioSNG pathways in comparison with literature data if available. The corresponding references can be found in Table 56 (*SNG_RFW*), Table 57 (*SNG_SRF*) and Table 58 (*SNG_IP I*), all in annex B.2.2. The error bar at the total emissions represents the standard deviation according to the Monte Carlo simulation.

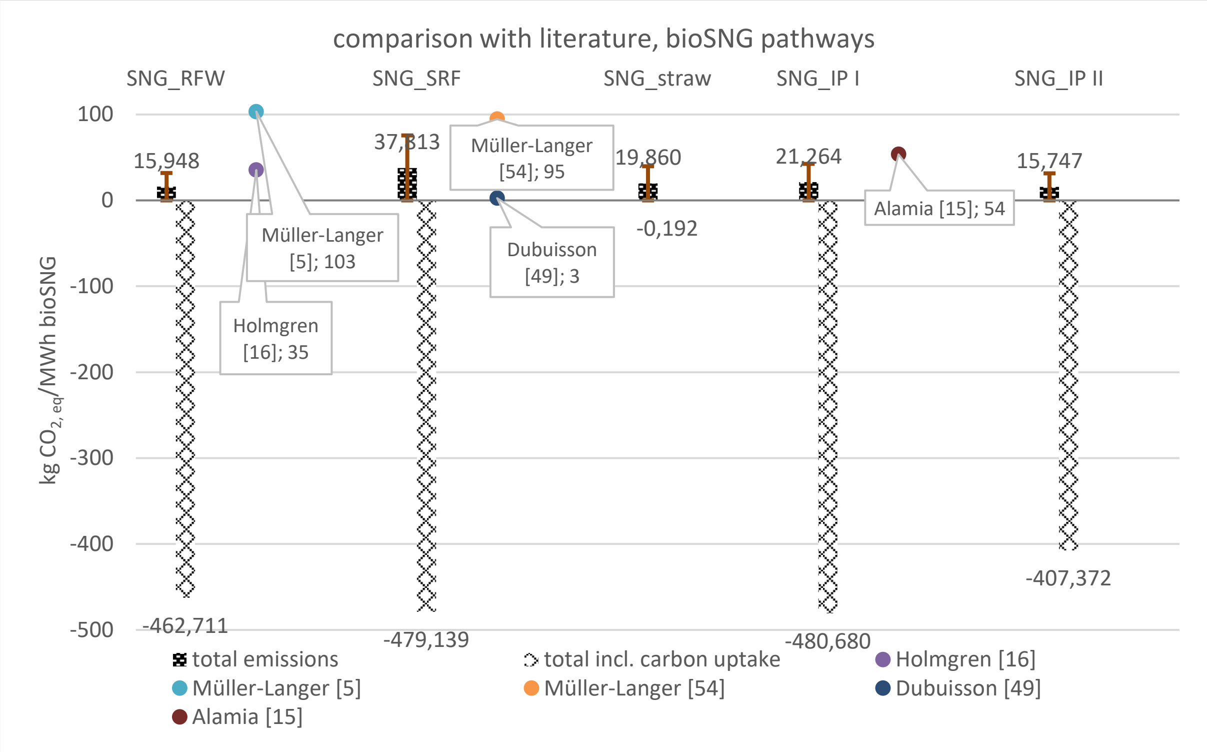


Figure 19: Comparison with literature, bioSNG pathways

Compared to the biomethane pathways, less literature is available for comparison with the bioSNG pathways.

The LCA result of 15.948 kg $CO_{2,\,eq}$/MWh bioSNG from the pathway ***SNG_RFW*** is lower than the literature value provided by Holmgren et al. [16]. Nevertheless, the range of the standard deviation matches literature.

For the pathway ***SNG_SRF***, the LCA result of 37.815 kg $CO_{2,\,eq}$/MWh bioSNG lies between the values provided by Müller-Langer [54] and Dubuisson and Sintzoff [49]. Müller-Langer assumes significantly higher emissions for the provision of the SRF chips resulting in the higher total emissions. The value from Dubuisson and Sintzoff is extremely low. They give their results in kg C instead of kg $CO_{2,\,eq.}$ The conversion from C to $CO_{2,\,eq}$ appears to be insufficient and is assumed to be the reason for the extreme value. Nevertheless, no further references concerning the conversion from C to $CO_{2,\,eq}$ could be found.

No reference was found providing comparable information for the pathway ***SNG_straw***.

The LCA result of 21.264 kg $CO_{2,\,eq}$/MWh bioSNG from the pathway ***SNG_IP I*** is half of the result from Alamia et al. [15]. Compared in detail, Alamia et al. use higher emissions for the pellet production, but do not provide any information about the transport of the required wood and the produced pellets. This is assumed to be a reason for the differences between the literature value and the LCA result.

The pathway ***SNG_IP II*** assesses a scale of pellet gasification plants that is not implemented yet. Therefore, not literature data for comparison was found.

## 3.6 Power to X

This thesis assesses the production of regenerative hydrogen (reg$H_2$) and methane (reg$CH_4$) from excess renewable electricity. The corresponding pathways are

- reg$H_2$ via proton exchange membrane electrolysis *PtH_PEM*,
- reg$H_2$ via high-temperature electrolysis *PtH_SOEC*,
- reg$H_2$ via steam reforming *PtH_SR*,
- reg$CH_4$via catalytic methanation *PtM_cat,* and
- reg$CH_4$ via biological methanation *PtM_bio*.

According to the guidelines, inventory analysis and impact assessment are implemented. Monte Carlo simulation and the comparison with literature data complete the interpretation and evaluation.

### 3.6.1 Inventory Analysis

General data and conversion factors necessary for the steps of data collection and data calculation are stated in Table 36 (annex 0). If they are used in further calculations, they are not mentioned explicitly. In the mentioned annex, the values for regenerative excess electricity and deionized water are deduced in detail.

For the inventory analysis, data is collected for every unit process presented in Figure 2 according to the scope definition. Compared to the biomethane and bioSNG pathways, the PtX pathways are assessed in a more general way. Basis for the assessment is the process efficiency in connection with the inputs and outputs. Preceding and follow-up processes are treated shallower. The PtX pathways are characterized as shown in Table 11.

Table 11: Characteristics PtX pathways

| *Characteristic parameter* | *PtH_PEM* | *PtH_SOEC* | *PtH_SR* | *PtM_cat* | *PtM_bio* |
|---|---|---|---|---|---|
| Input electricity [$MW_{el}$] | 1 | 0.1 | 0.5 | 6 | 1 |
| Input $CH_4$ [kmol/h] | - | - | 3.010 | - | - |
| Input $CO_2$ [kmol/h] | - | - | - | 13.796 | 2.104 |
| Input $H_2O$ [t/h] | 0.158 | 0.024 | 0.271[16] | 0.941 | 0.152 |
| Process efficiency [%] | 58.800 | 87.700 | 62.358 | 46.000 | 45.400 |
| Output reg$H_2$ [MW] | 0.588 | 0.0877 | 0.730 | - | - |
| Interim output reg$H_2$[17] [kmol/h] | | | | 52.209 | 8.416 |
| Output reg$CH_4$ [MW] | - | - | - | 2.760 | 0.454 |
| Output $H_2O$ [t/h] | - | - | 0.171[18] | 0.47 | 0.076 |
| Output $CO_2$ [kmol/h] | - | - | 2.525 | 1.379 | 0.063 |

[16] equivalent to 15.048 kmol/h

[17] The determined output of the electrolysis is used as input for the methanation process.

[18] equivalent to 9.501 kmol/h

### *Raw material provision*

For the pathways ***PtH_PEM*** and ***PtH_SOEC***, raw materials are excess renewable electricity and deionized water. Their respective emissions are already defined.

Additionally, the pathway ***PtH_SR*** requires a methane input which is assumed to be derived from natural gas. Natural gas is provided according to the reference pathway.

The pathways ***PtM_cat*** and ***PtM_bio*** require excess renewable electricity and deionized water as well. Further raw material is $CO_2$ considered a waste product from amine scrubbing of raw biogas. In accordance with the defined allocation methods, the $CO_2$ is assumed free from preceding burdens and emissions.

### *Raw material transport*

For all pathways, water is received from tap and treated at the PtH plant causing the emissions mentioned above. No further transport is required. Electricity is received from the grid. No further transport is required, too.

The natural gas required for ***PtH_SR*** is assumed to be delivered by pipeline. The corresponding emissions are calculated according to the distribution of natural gas in the reference pathway.

From the consideration of $CO_2$ required for the pathways ***PtM_cat*** and ***PtM_bio*** being a waste product from amine scrubbing of raw biogas follows the assumption that the PtM processes take place closely to the biogas plant. Therefore, no transport is required.

### *Conversion*

The PEM electrolysis in ***PtH_PEM*** is calculated according to the defined characteristics. The required inputs are 5.102 $kWh_{el}/m^3$ $regH_2$ and 0.806 kg $H_2O/m^3$ $regH_2$.

For comparison, values from literature are given in Table 38 (annex A.3.1).

For the pathway ***PtH_SOEC***, the SOEC electrolysis is calculated according to the defined characteristics, too. The required inputs are 3.421 $kWh_{el}/m^3$ $regH_2$ and 0.821 kg $H_2O/m^3$ $regH_2$. Based on Lewandowska-Bernat and Desideri [23, p. 4570], Schiebahn [28, p. 4287] and Götz [26, p. 1373], an operation temperature of 850 °C is determined. The corresponding heat demand for heating up the water is estimated with the following equations [55, p. 30 ff.]:

$$\Delta Q = m \cdot c \cdot \Delta T \tag{1}$$

$$c\Big|_{T_1}^{T_2} = \frac{c\Big|_{T_0}^{T_2} \cdot (T_2 - T_0) - c\Big|_{T_0}^{T_1} \cdot (T_1 - T_0)}{T_2 - T_1} \tag{2}$$

- $\Delta Q$ indicates the heat demand in $kJ$
- $m$ indicates the mass to be heated in $kg$
- $c$ indicates the specific thermal capacity of the material to be heated in $\frac{kJ}{kg \cdot K}$
- $\Delta T$ indicates the required temperature difference in $K$

The underlying values and results are summarized in Table 12. Literature data providing comparable values could not be found.

Table 12: Calculation of heat demand for SOEC electrolysis

| *Parameter* | *Value* | *Reference* |
|---|---|---|
| Mass $\mathbf{m}$ $[\mathbf{kg\ H_2O}]$ | 1 | |
| Temperature $\mathbf{T_1}$ $[\mathbf{K}]$ | 298.150 | |
| Specific thermal capacity $c\Big\|_{T_0}^{T_1}$ of water $[\frac{kJ}{kg \cdot K}]$ | 1.8615 | [56, p. 624] |
| Temperature $\mathbf{T_2}$ $[\mathbf{K}]$ | 1123.150 | [23, p. 4570], [28, p. 4287], [26, p. 1373] |
| Specific thermal capacity $c\Big\|_{T_0}^{T_2}$ of water $[\frac{kJ}{kg \cdot K}]$ | 2.0913 | Interpolated according to [56, p. 624] |
| Temperature difference $\Delta T = T_2 - T_1$ $[\mathbf{K}]$ | 825 | |
| Specific thermal capacity $c\Big\|_{T_1}^{T_2}$ $[\frac{kJ}{kg \cdot K}]$ | 2.0856 | |
| Heat demand $\frac{\Delta Q}{m}$ $[\frac{kJ}{kg\ H_2O}]$ | 1720.639 | |

Steam reforming in ***PtH_SR*** according to the defined characteristics requires 2.055 $kWh_{el}/m^3$ $regH_2$, 0.198 kg $CH_4/m^3$ $regH_2$ and 1.114 kg $H_2O/m^3$ $regH_2$ as inputs. Resulting outputs are 7.034E-4 $m^3$ $H_2O/m^3$ $regH_2$ and 0.457 kg $CO_2/m^3$ $regH_2$. In this scenario, the total energy demand is met by excess renewable electricity.

For comparison, values from literature are given in Table 39 (annex A.3.2).

As described in the theoretical basis, the methanation in the pathways ***PtM_cat*** and ***PtM_bio*** usually follows an electrolysis. Therefore, the input and output values defined in the characteristics must be separated between the two processes. The separation is shown in Table 40 (annex A.3.3) and Table 42 (annex A.3.4). The electrolysis is assumed to be a PEM electrolysis according to *PtH_PEM*. The excess regenerative hydrogen produced is neglected for the calculations.

For the pathway *PtM_bio*, scarcely any literature data was found. For *PtM_cat*, literature data is given in Table 41 (annex A.3.3).

### *Upgrading*

No upgrading is required, as pure hydrogen is produced at the pathways ***PtH_PEM***, ***PtH_SOEC*** and ***PtH_SR***.

For the pathways ***PtM_cat*** and ***PtM_bio***, the methanation is considered the upgrading process.

### *Waste treatment*

For the pathways ***PtH_PEM*** and ***PtH_SOEC***, no waste treatment is required, as water is assumed to be converted into hydrogen completely.

The pathway ***PtH_SR*** requires the wastewater treatment of 7.034E-04 $m^3$ $H_2O/m^3$ $regH_2$. The wastewater treatment is calculated according to the ecoinvent dataset “market for wastewater, from residence, RoW”[19].

The wastewater treatment of 1.6982E-03 $m^3$ $H_2O/m^3$ $regCH_4$ and 1.669E-03 $m^3$ $H_2O/m^3$ $regCH_4$ for ***PtM_cat*** and ***PtM_bio*** is calculated according to the same dataset.

#### *Other*

No other unit processes or emissions are considered for ***PtH_PEM***, ***PtH_SOEC*** and ***PtH_SR***.

For the pathways ***PtM_cat*** and ***PtM_bio***, the maximum methane slip according to Gas Network Access Regulations [29], paragraph 36 (1) is considered. This leads to a methane slip of 0.00143 kg $CH_4/m^3$ $regCH_4$.

#### *Distribution*

The produced $regH_2$ is distributed in Germany’s natural gas grid. It is assumed that only $regH_2$ is in the grid. As hydrogen emitted to the atmosphere has no environmental impact according to IPCC 2007 [33], no $CO_2$ emissions occur from the distribution of hydrogen at the pathways ***PtH_PEM***, ***PtH_SOEC*** and ***PtH_SR***.

The produced $regCH_4$from ***PtM_cat*** and ***PtM_bio*** is assumed to be distributed in Germany’s natural gas grid with the same emissions as natural gas. These emissions account for 0.001 kg $CH_4$ losses/kg gas in the grid, equivalent to 1.8 kg $CO_{2,\,eq}$/MWh $regCH_4$.

#### *Combustion*

The pathways ***PtH_PEM***, ***PtH_SOEC*** and ***PtH_SR*** consider the conversion of regenerative hydrogen to electricity in a fuel cell. A fuel cell with an efficiency of 55% is defined [57]. Resulting from this determination, 1.818 MWh $regH_2$ are required to produce 1 MWh electricity.

Combustion of $regCH_4$is assumed equal to the combustion of natural gas. Thereof follow 270.863 kg $CO_{2,\,eq}$/MWh energy for the pathways ***PtM_cat*** and ***PtM_bio***.

### 3.6.2 Impact Assessment

As for the biomethane and the bioSNG pathways, climate change is the only relevant impact category in this LCA and the corresponding impact indicator is the Global Warming Potential for a time horizon of 100 years (GWP 100) measured as kg $CO_{2,\,eq.}$ The impact assessment is implemented with the software openLCA.

The results from the implementation of the impact assessment for the biomethane pathways are summarized in Figure 20 and shown in Table 13.

[19] market for wastewater, from residence, RoW, Allocation, cut-off by classification, ecoinvent database version 3.4

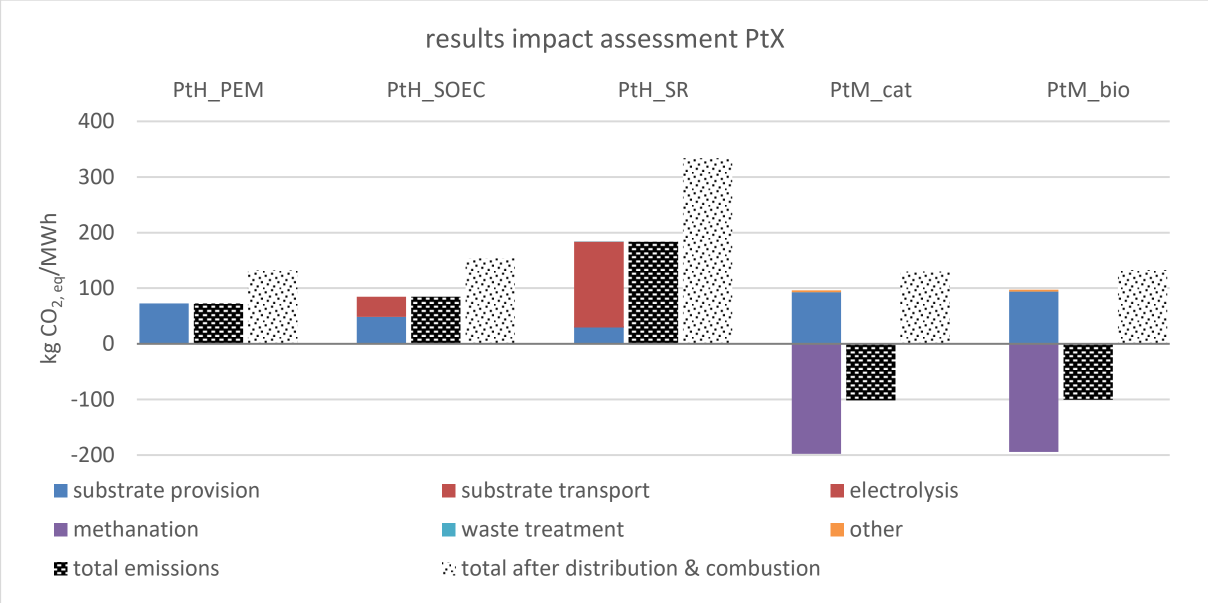


Figure 20: Results impact assessment PtX pathways

For the pathway *PtH_SR*, the value indicated with "electrolysis" corresponds to the emissions from the steam reforming.

Contrary to the other pathways, the total emissions after distribution and combustion are the target values for *PtM_cat* and *PtM_bio*. For the biomethane and bioSNG pathways, the absorbed carbon is not considered to maintain a balance of carbon dioxide being taken up and being released. Corresponding to this balance, the combustion of the regenerative methane must be considered for the Power to Methane pathways. During the combustion, $CO_2$ being released compensates the $CO_2$ entering the process as input into the methanation.

Table 13: Results impact assessment PtX pathways

| *Unit process* | *PtH_PEM* | *PtH_SOEC* | *PtH_SR* | *PtM_cat* | *PtM_bio* |
|---|---|---|---|---|---|
| Raw material provision [kg $CO_{2,\ eq}$/MWh regX] | 72.453 | 48.707 | 29.533 | 92.613 | 93.823 |
| *Share total emissions [%]* | 100.000 | 57.525 | 16.086 | 991.108 | 93.541 |
| Raw material transport [kg $CO_{2,\ eq}$/MWh regX] | 0 | 0 | 1.653 | 0 | 0 |
| *Share total emissions [%]* | 0 | 0 | 0.901 | 0 | 0 |
| Conversion: electrolysis [kg $CO_{2,\ eq}$/MWh regX] | 0 | 35.967 | 152.227 | 0 | 0 |
| *Share total emissions [%]* | 0 | 42.479 | 82.914 | 0 | 0 |
| Upgrading: methanation [kg $CO_{2,\ eq}$/MWh regX] | - | - | - | -197.995 | -194.333 |
| *Share total emissions [%]* | - | - | - | -194.777 | -193.75 |
| Waste treatment [kg $CO_{2,\ eq}$/MWh regX] | - | - | 0.110 | 0.133 | 0.131 |
| *Share total emissions [%]* | - | - | 0.100 | 0.131 | 0.131 |
| Other [kg $CO_{2,\ eq}$/MWh regX] | - | - | - | 3.595 | 3.595 |
| *Share total emissions [%]* | - | - | - | 3.537 | 3.584 |
| Total emissions [kg $CO_{2,\ eq}$/MWh regX] | 72.453 | 84.670 | 183.597 | -101.652 | -100.301 |
| Total after distribution and combustion [kg $CO_{2,\ eq}$/MW energy] | 131.733 | 153.945 | 333.812 | 130.35 | 132.252 |

### 3.6.3 Monte Carlo Simulation

Parameters relevant for the Monte Carlo simulation are determined by a sensitivity analysis. The PtH pathways differ only in terms of the amount of input parameters. Therefore, the sensitivity analysis is carried out exemplary for the pathway *PtH_PEM* and relevant parameters for the other PtH pathways are derived from this analysis. Another sensitivity analysis is implemented for the pathway *PtM_cat*, exemplary for the PtM pathways.

***Sensitivity Analysis***

The sensitivity analysis for *PtH_PEM* is based on the literature data in annex A.3.1 and on the literature data in annex A.3.3 for *PtM_cat*. The parameters of all unit processes are varied according to their range in literature. Stated variations are added to variations from literature if that range is not considered sufficient. All other parameters of the process system stay constant. Figure 21 and Figure 22 show the results of the sensitivity analysis. The numbers at the end of the bars indicate the minimum or maximum variation of the parameters. The bars present the resulting change in total emissions.

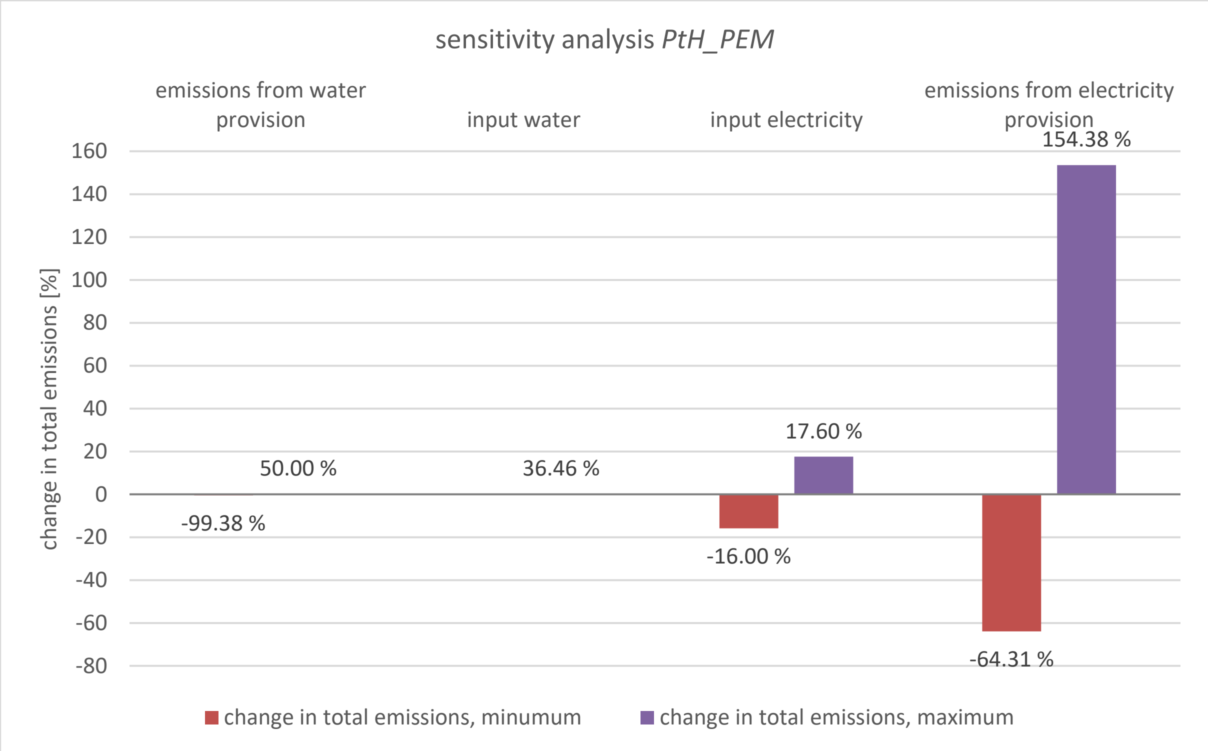


Figure 21: Results sensitivity analysis *PtH_PEM*

The most critical parameters for *PtH_PEM* are the emissions from electricity provision and subsequently the input of electricity into the electrolysis process. Concerning the emissions from electricity provision it is important to mention the occurrence of the huge variations. As described in the deviation of the emissions from electricity provision, this LCA considers a mixture of renewable fluctuating electricity. Other studies focus on only one source like wind or solar power. Therefore, the variations of the emissions from electricity provisions are defined according to single ecoinvent datasets. The corresponding datasets are the datasets used for the calculation of the renewable fluctuating electricity mixture.

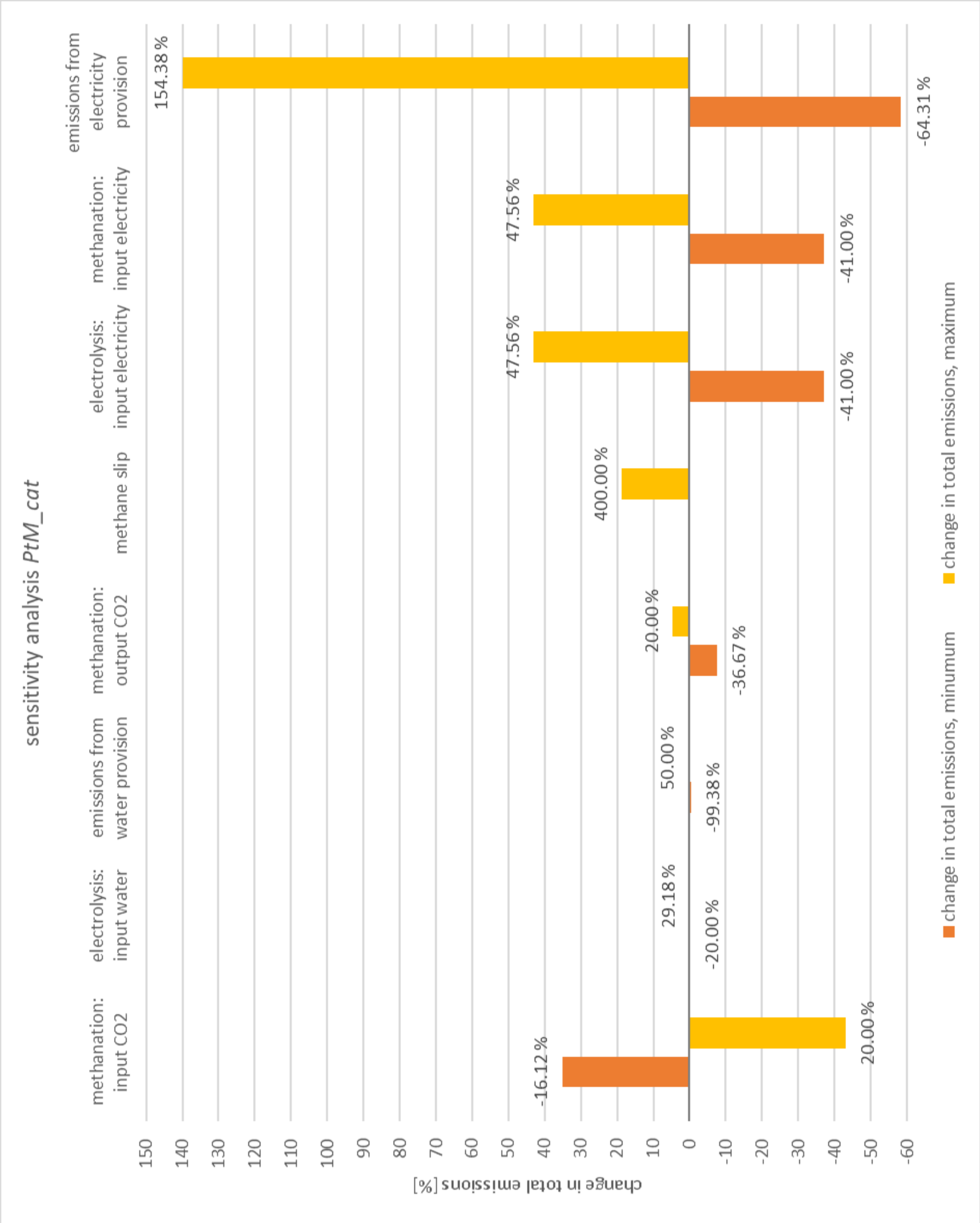


Figure 22: Results sensitivity analysis *PtM_cat*

The most critical parameters for *PtH_PEM* are the emissions from electricity provision and subsequently the input of electricity into the electrolysis and methanation processes. Furthermore, the methane slip and the input and output of $CO_2$ into and from the methanation process show an important influence.

### *Monte Carlo simulation*

The critical parameters for the Monte Carlo simulation of the PtH pathways are

- emissions from renewable electricity provision and
- input of electricity into the electrolysis process.

For *PtH_SOEC*, the input of heat into the electrolysis process is considered, too. For *PtH_SR*, the output of $CO_2$ is added, as literature states variations of up to 75.18% resulting in a change of emissions of 62.33%.

The critical parameters for the PtM pathways are

- emissions from renewable electricity provision,
- input of electricity into the electrolysis process,
- input of electricity into the methanation process,
- methane slip,
- input of $CO_2$ into the methanation process, and
- output of $CO_2$ from the methanation process.

A summarizing presentation of the respective parameters can be found in Table 59 to Table 63 (annex B.3.1).

To avoid problems due to the limited computing capacities, the simulation is implemented in 35,000 simulation steps. That is equivalent to 187.083 variations per parameter for *PtH_PEM,* 32.711 variations per parameter for *PtH_SOEC* and *PtH_SR* and 5.719 variations per parameter for *PtM_cat* and *PtM_bio.*

Figure 23 to Figure 27 present the results of the Monte Carlo simulation summarized in Table 64 (annex B.3.1). For reasons of computing capacities, the graphic presentation of the results in the mentioned figures is only possible for 10,000 simulation steps and the figures show the results in kg $CO_{2,\,eq}$/Nm$^3$ regX. To provide meaningful and interpretable diagrams, a uniform scaling of the axis is not possible. In the graphs, 5% percentile, median and 95% percentile, mean and standard deviation and the result from the LCA calculations are indicated.

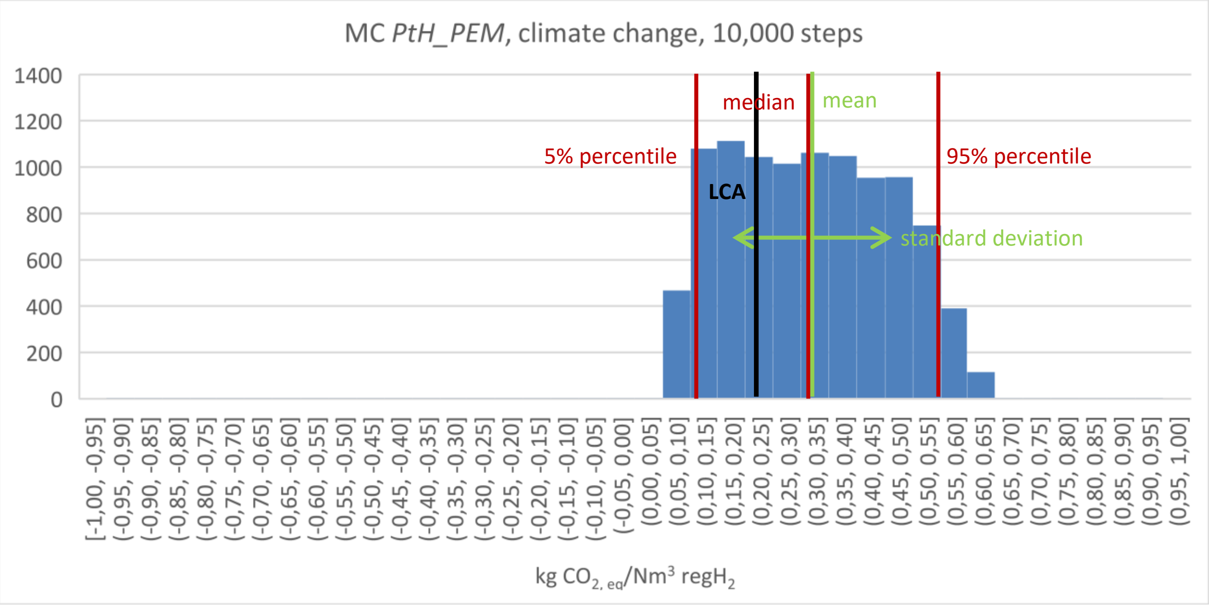


Figure 23: Results Monte Carlo simulation *PtH_PEM*, climate change, 10,000 simulation steps

The LCA result of ***PtH_PEM*** lies within the range of the standard deviation. Mean and median are almost equal. The distribution is shifted to lower values and does not resemble the normal distribution.

This deviation is caused by the immense influence of the emissions from the electricity provision causing an expansion of the normal distribution.

To ensure robustness it is recommendable to further define the renewable electricity source.

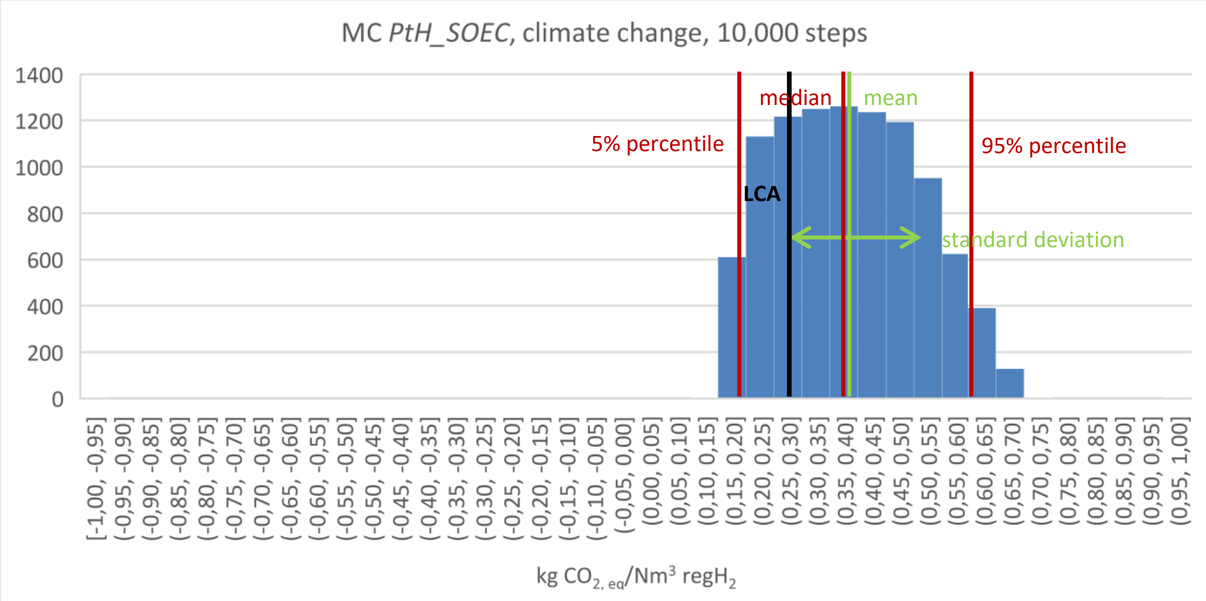


Figure 24: Results Monte Carlo simulation *PtH_SOEC*, climate change, 10,000 simulation steps

The distribution of the Monte Carlo simulation of ***PtH_SOEC*** resembles the normal distribution more than the one from *PtH_PEM* and mean and median value are almost equal. Nevertheless, the LCA result lies out of the range of the standard deviation. This is caused by the uneven variation of the input of electricity into the electrolysis process. The variation was defined based on the range of efficiency of 54 to 77% according to Lewandowska-Bernat and Desideri [23, p. 4570]. These efficiencies require a higher input of electricity into the electrolysis process than the defined representative process with an efficiency of 87.7%.

Compared to literature values, the reliability of the LCA result can be questioned. However, this LCA considers a certain predefined process whose result can be assumed solid.

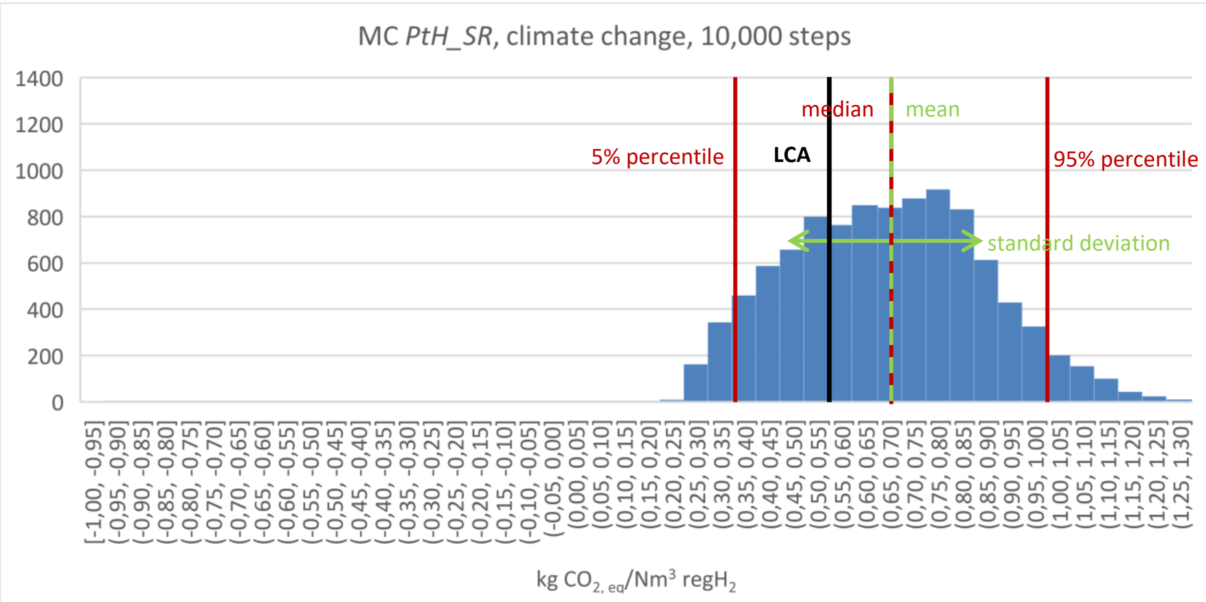


Figure 25: Results Monte Carlo simulation *PtH_SR*, climate change, 10,000 simulation steps

For the pathway ***PtH_SR***, the distribution of the results from the Monte Carlo simulation must be treated separated. For values higher than median and mean, the shape of the distribution corresponds to the normal distribution. For lower values, the distribution is shifted to lower results.

Nevertheless, median and mean value are equal and the LCA result lies sufficiently within the range of the standard deviation to confirm a robust result.

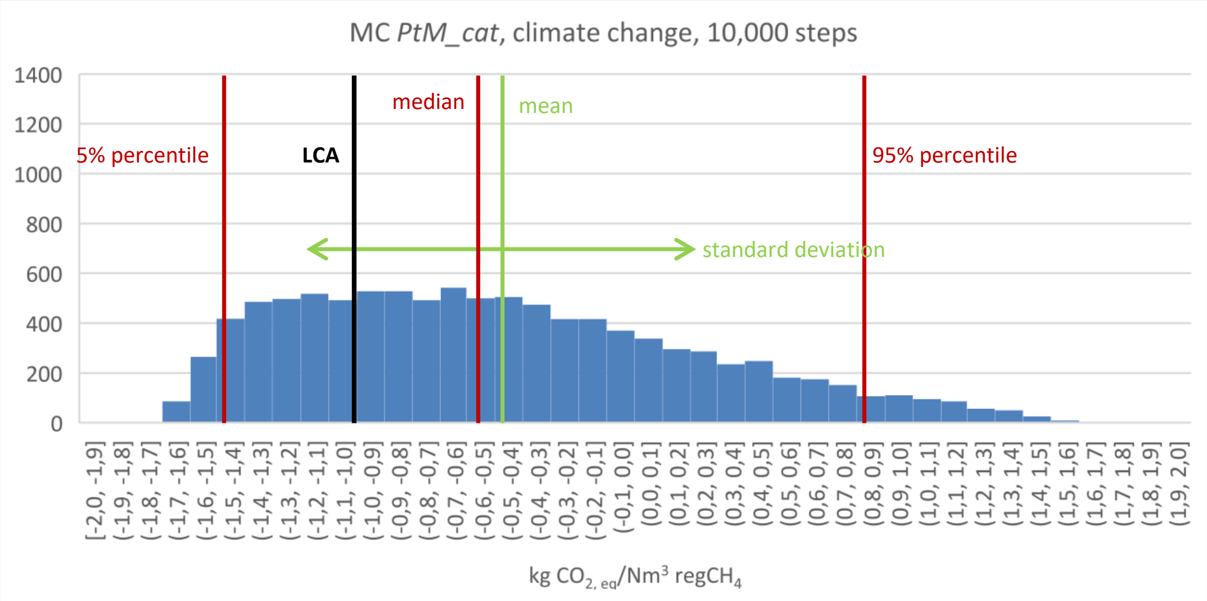


Figure 26: Results Monte Carlo simulation *PtM_cat*, climate change, 10,000 simulation steps

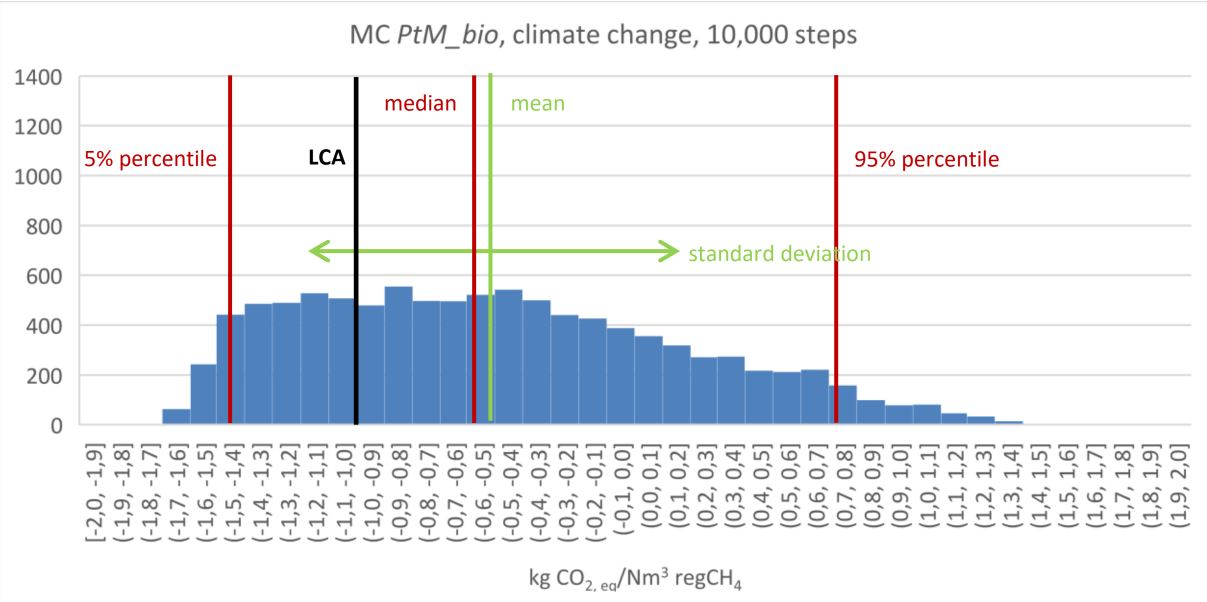


Figure 27: Results Monte Carlo simulation *PtM_bio*, climate change, 10,000 simulation steps

The shape of the distribution of the results from the Monte Carlo simulation of ***PtM_cat*** and ***PtM_bio*** are very similar. The characteristic values for 5% percentile and 95% percentile, mean and median value and standard deviation are nearly equal. This similarity can be traced back to the variations of the *PtM_bio* pathway being defined according to the variations of *PtM_cat* due to lack of comparable literature data. Therefore, both pathways are treated together.

Considering the scaling of the axes in the diagrams, mean and median values can be assumed to be almost equal. The LCA results lie within the ranges of the standard deviations. The shapes of the distributions resemble a flat normal distribution.

### 3.6.4 Comparison with Literature

Figure 28 and Figure 29 show the LCA results of the PtH and PtM pathways in comparison with literature data if available. The corresponding references can be found in Table 65 (*PtH_PEM*), Table 66 (*PtH_SR*) and Table 67 (*PtM_cat*), all in annex B.3.2. The error bar at the total emissions from the PtH pathways represents the standard deviation according to the Monte Carlo simulation. For the PtM pathways, they refer to the target value "total emissions after distribution and combustion".

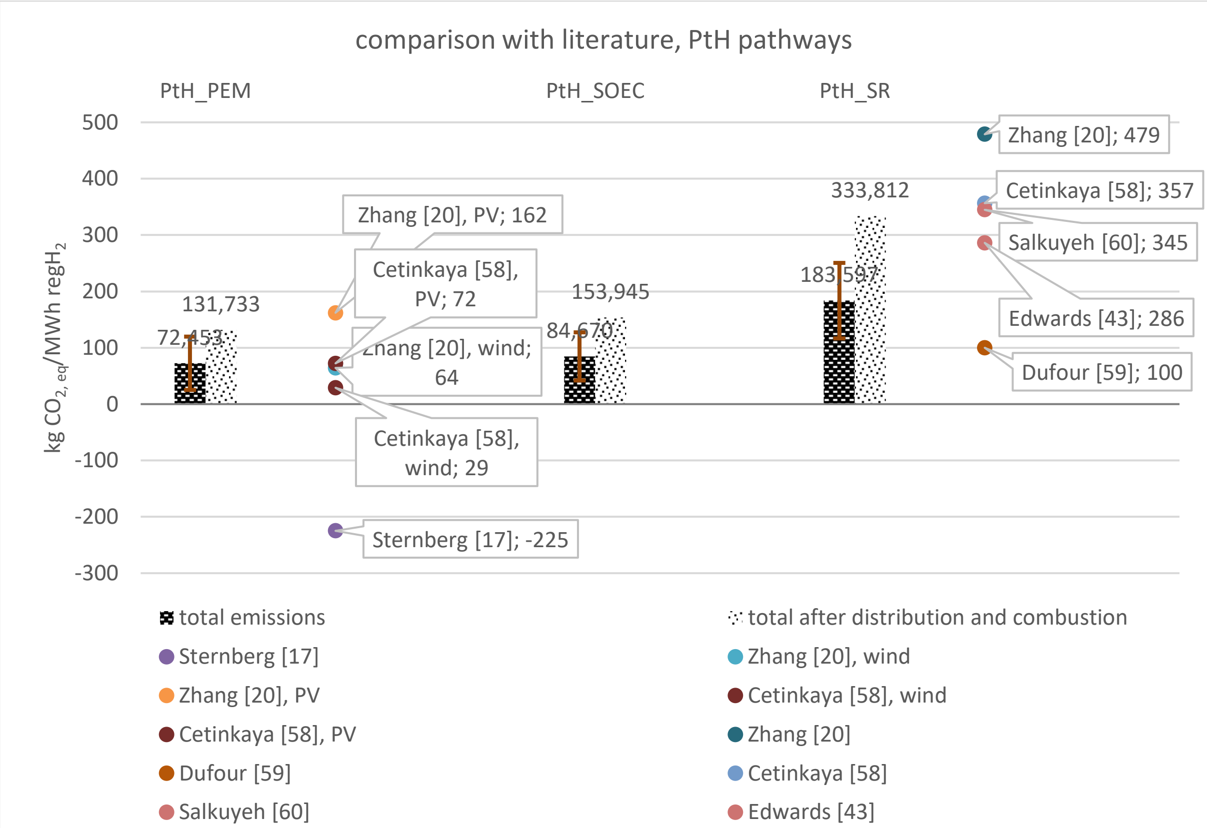


Figure 28: Comparison with literature, PtH pathways

The LCA result from the pathway ***PtH_PEM*** with 72.453 kg $CO_{2,\,eq}$/MWh $regH_2$ is consistent with the range that Zhang et al. [20] and Cetinkaya et al. [58] indicate for electricity from wind and solar power. The LCA result exceeds some of their results and is lower than the others, as they do not consider a mix of the energy sources but every source individually. Results from Zhang et al. and Edwards et al. [43] considering the general electricity mix in the EU show significantly higher results than this LCA. They are not shown in this figure. The value from Sternberg [17] cannot be compared, as it calculates the savings from the application of PtH processes and not the process itself. None of the considered studies assesses the reconversion of hydrogen to electricity. Therefore, the result of 131.733 kg $CO_{2,\,eq}$/MWh energy including distribution and energy production cannot be compared.

Summarizing, the literature values confirm the LCA result. Apart from that, they show the influence of the energy source for electricity supply on the total emissions.

No reference was found providing comparable information for the pathway ***PTH_SOEC***.

The LCA result of 183.597 kg $CO_{2,\,eq}$/MWh $regH_2$ from ***PTH_SR*** lies in the range of the values from Edwards et al. [43] and Dufour et al. [59]. Edwards et al. result in higher emissions because a higher electricity demand is assumed for the steam reforming. The opposite applies for Dufour et al. Cetinkaya et al. [58] and Salkuyeh et al. [60] confirm the result of 333.812 kg $CO_{2,\,eq}$/MWh energy after distribution and conversion into energy assuming they consider the reconversion of hydrogen to electricity. However, this assumption is not confirmed, and the high emissions are assumed to result from a higher steam output at Cetinkaya et al. Salkuyeh et al. and Zhang et al. [20] do not provide further information.

The literature values match the LCA results in cases where the same characteristic, process specific parameters are assumed.

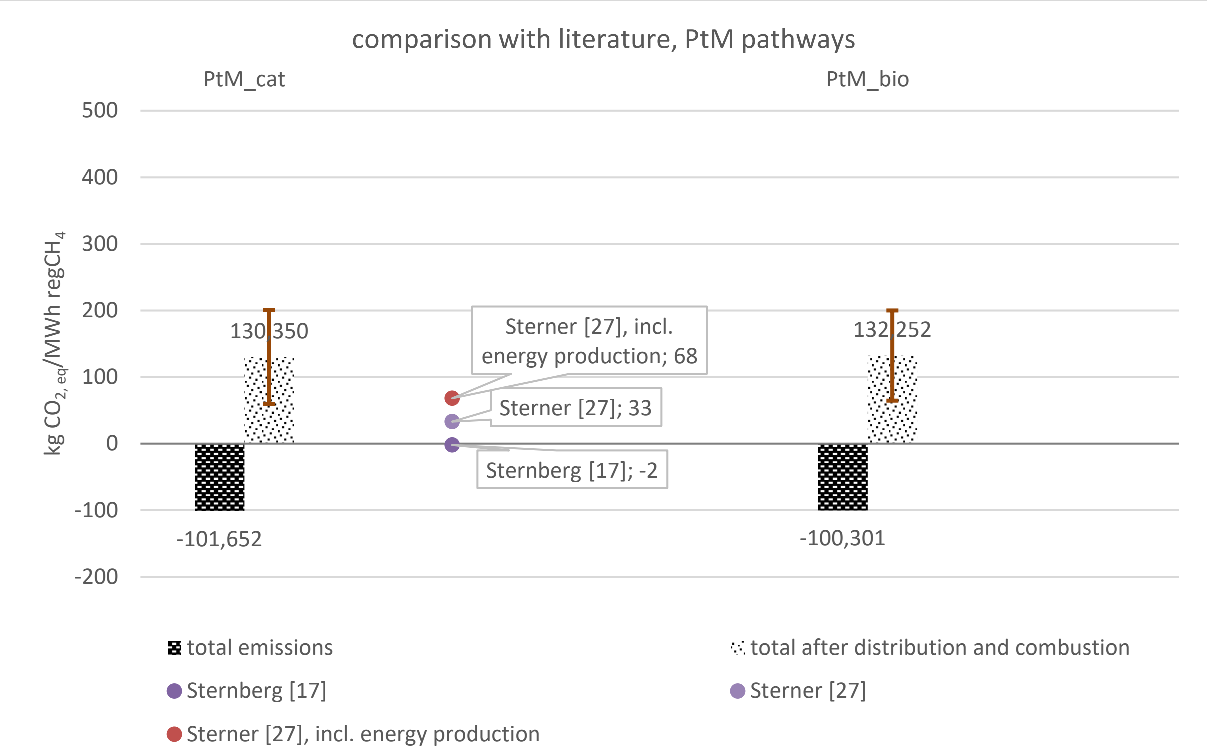


Figure 29: Comparison with literature, PtM pathways

As mentioned in the impact assessment, the target value for the PtM pathways are the total emissions after distribution and combustion.

The result from ***PtM_cat*** is higher than the values from Sternberg and Bardow [17] and from Sterner [27]. Sternberg and Bardow only investigate the methanation and exclude the electrolysis. Therefore, the demand for electricity is nearly 100 times lower. Sterner does not provide any further information. The difference in the resulting emissions is assumed to be caused by different handling of the $CO_2$ input and output.

For the pathway ***PtM_bio***, no reference was found providing comparable information.

## 3.7 Summarizing Evaluation

For a comprehensive evaluation and comparison of all pathways, the results are summarized in Figure 30. The error bars at the total emissions represent the standard deviation according to the Monte Carlo simulation.

For the PtX pathways and the pathway *natural gas*, the category "total incl. carbon uptake" represents the emissions after distribution and combustion. These emissions are the target values for the pathways *PtM_cat* and *PtM_bio*. As the combustion is indirectly included in the other pathways, it also must be considered for the comparison with natural gas. The category "raw material provision" includes the carbon uptakes.

Comparing the values from the biomethane pathways, reveals *bioCH$_4$_manure* being the less greenhouse gas emission intensive pathway with -287.389 kg $CO_{2,\,eq}$/MWh bio$CH_4$. This is caused by the credits for the avoided manure storage. It must be stated that this result is achieved by a simplified approach in this LCA excluding the further treatment and application of the digestate. *bioCH$_4$_waste* shows the highest emissions of the biomethane pathways with 325.993 kg $CO_{2,\,eq}$/MWh bio$CH_4$. Compared to the pathway *bioCH$_4$_maize* with 125.038 kg $CO_{2,\,eq}$/MWh bio$CH_4$, this can be traced back to the high demand for biowaste as input into the digestion process, the high digestate outcome and the low amount of $CH_4$ in the raw biogas. These factors lead to increased total emissions. Excluding the raw material provision, upgrading and conversion contribute most to the total emissions.

The bioSNG pathways show results in the same order of magnitude. *SNG_RFW* and *SNG_SRF* investigate substrates with nearly equal lower heating values and similar process efficiencies. Therefore, they result in similar total emissions of 47.596 kg $CO_{2,\,eq}$/MWh bioSNG and 59.294 kg $CO_{2,\,eq}$/MWh bioSNG, respectively. The gasification of straw is not as effective as the gasification of residual forest wood and wood from short rotation forestry. A lower energy content requires a higher amount of substrate input and further increases the emissions of the pathway *SNG_straw* to 81.185 kg $CO_{2,\,eq}$/MWh bioSNG. Despite the same substrate and the same transport distances, the pathways *SNG_IP I* and *SNG_IP II* show a significant difference in the total emissions with 98.280 kg $CO_{2,\,eq}$/MWh bioSNG and 55.796 kg $CO_{2,\,eq}$/MWh bioSNG, respectively. This difference is caused by the higher process efficiency of the 100 times larger facility assumed for *SNG_IP II*. The pathways *SNG_IP I* and *SNG_IP II* are the only pathways showing a significant influence of the substrate transport. Nevertheless, the emissions from *SNG_IP II* are nearly as low as the emissions from *SNG_SRF* and *SNG_straw*. Most crucial contributor to the emissions from the bioSNG pathways is the gasification process itself.

A comparison of the PtX pathways shows the hydrogen production via electrolysis being the most environmentally friendly option concerning greenhouse gases with 72.453 kg $CO_{2,\,eq}$/MWh reg$H_2$. Despite the lower demand for electricity, *PtH_SOEC* has higher emissions than *PtH*_PEM accounting for 84.670 kg $CO_{2,\,eq}$/MWh reg$H_2$. This is caused by the heat demand for the high temperature electrolysis. Another heat source could change this result. *PtH_SR* with even lower emissions from substrate provision and transport results in the highest emissions of all PtX pathways. 183.597 kg $CO_{2,\,eq}$/MWh reg$H_2$ derive from the steam reforming operating over stoichiometrically and releasing a significant amount of $CO_2$. Using $CO_2$ from a renewable origin and distinguishing between biogenic and fossil emissions would lead to *PtH_SR* showing the lowest emissions of all PtX pathways. *PtM_cat* and *PtM_bio* are nearly equal with 130.350 kg $CO_{2,\,eq}$/MWh energy and 132.252 kg $CO_{2,\,eq}$/MWh energy. Neglecting the distribution and combustion of the regenerative methane would even result in negative emissions due to the high amount of $CO_2$ required for the methanation. Their emissions derive mainly from the electricity and water supply for the electrolysis. Considering the distribution and combustion and by that the release of the $CO_2$, they lie between the electrolysis processes and the steam reforming. The electricity supply for the PtX pathways contributes most to the total emissions.

In total, the bioSNG pathways show the lowest overall emissions of all pathways. Compared to the biomethane pathways, the bioSNG pathways do not consider methane slip. Methane slip is not relevant for the bioSNG pathways as retention times of substrates and gases in huge, not entirely gas tight units are significantly lower than for the biomethane production.

Natural gas being burnt in a gas turbine is the reference process for all pathways resulting in 329.867 kg $CO_{2,\,eq}$/MWh energy. As expected, most of the pathways lead to emissions lower than the reference process. *bioCH₄_waste* shows total emissions nearly as high as *natural gas*. However, the total emissions do not include the carbon uptake and the combustion of the biomethane. That would reduce the emissions from this pathway. *PtH_SR* exceeds the reference value in case distribution and combustion are considered. A higher efficiency of the fuel cell could reduce the overall emissions of this pathway.

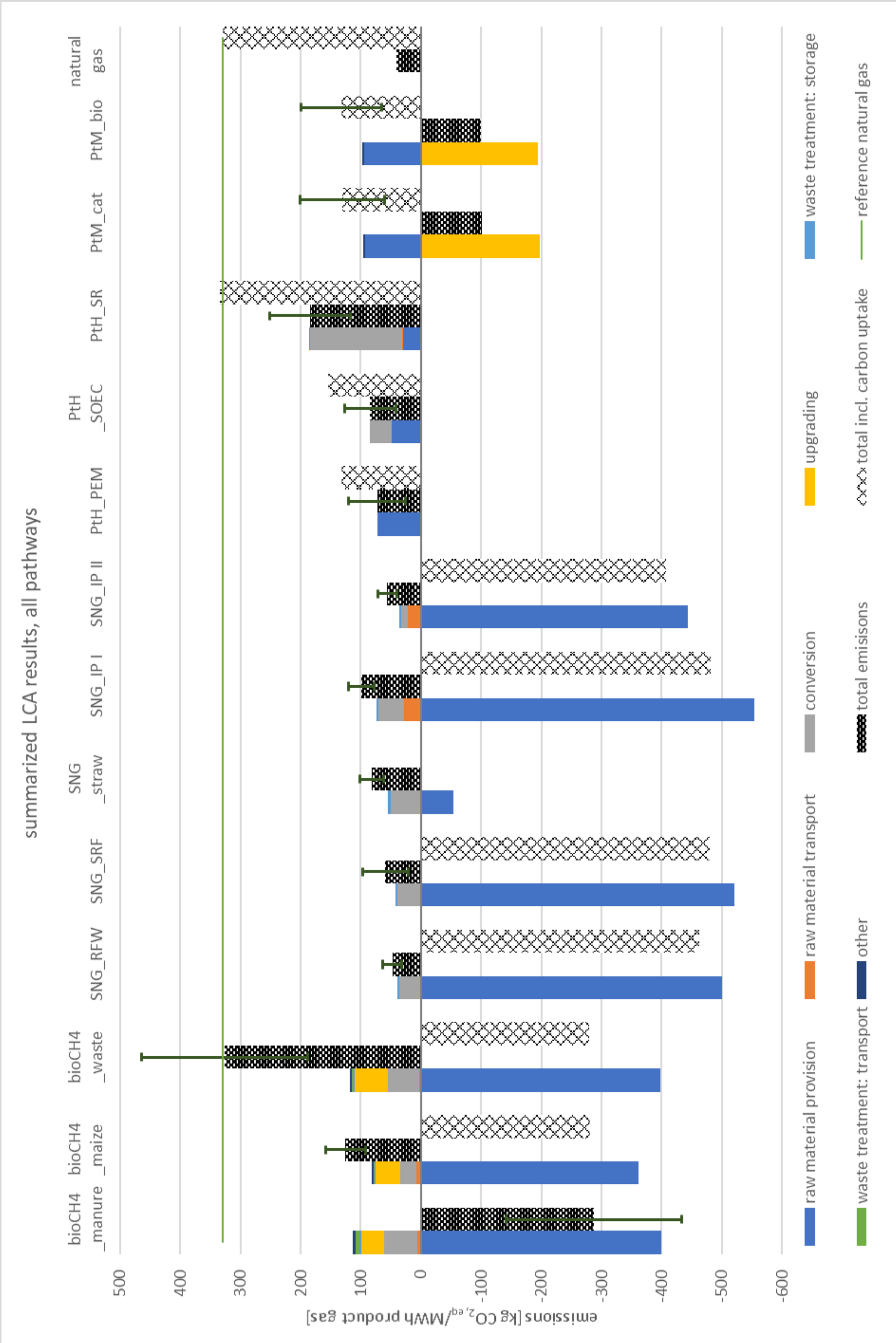


Figure 30: Summarized LCA results of all pathways, incl. error bars from Monte Carlo simulation

# 4 Conclusion and Opportunities

In this thesis, emissions from alternative gas production technologies are investigated. Preliminarily, a literature review of studies investigating the emissions incurred by alternative gas production is executed. The LCAs are implemented consistently according to the guidelines DIN EN ISO 14040:2006 [7] and 14044:2006 [8] to achieve comparable results. These results are further evaluated by a Monte Carlo simulation and compared with data from literature. Finally, the least emission intensive technology is identified.

The literature review reveals difficulties in comparing different technologies with varying substrates due to methodological inequalities. Differences in individual system boundaries and fundamental assumptions prevent a meaningful comparison of the studies. This thesis compares renewable gas production technologies with varying substrates in a consistent way. This enables the comparison of the respective environmental performance.

In this thesis, LCAs are implemented for thirteen different pathways. First, for the production of biomethane from anaerobic digestion of manure, maize silage and biowaste; second, for the production of synthetic natural gas from the gasification of residual forest wood, short rotation forestry wood, straw and imported pellets; third, for the production of hydrogen and methane via Power to X technologies from excess renewable electricity. Natural gas production, distribution and combustion was chosen as mutual reference pathway.

The results generated by this study show that 12 out of 13 assessed alternative gas production technologies have the potential to reduce greenhouse gas emissions compared to natural gas. The production of synthetic natural gas via gasification of biomass shows the highest potential. For this technology, the use of residual forest wood as substrate is the best option with 47.596 kg $CO_{2,\,eq}$/MWh bioSNG. The second-best option is the use of imported pellets in a 100 MW facility resulting in 55.796 kg $CO_{2,\,eq}$/MWh bioSNG. The highest emissions of 183.597 kg $CO_{2,\,eq}$/MWh $regH_2$ arise from steam reforming of methane to produce hydrogen. This pathway is the only one resulting in slightly higher emissions than the reference pathway. Steam reforming is followed by 325.993 kg $CO_{2,\,eq}$/MWh $bioCH_4$ occurring from the anaerobic digestion of biowaste. The most crucial contributors to the greenhouse gas emissions are the conversion and upgrading processes of anaerobic digestion and gasification. For example, together they account for up to 40% of the total emissions from anaerobic digestion (these calculations include carbon uptake). Design-related improvements would further reduce the total emissions from these processes. For producing gases from excess renewable electricity, the electricity supply shows the highest impact on emissions as excess renewable electricity is the main substrate in these processes. For further processing of the results from this study, it must be considered that electricity is assumed to be supplied by a renewable fluctuating electricity mix.

The evaluation via Monte Carlo simulation shows huge changes in the total emissions by variations of input parameters. Especially the substrate provision and the substrate input into the conversion process are found to be crucial. Nevertheless, the comparison with data from literature confirms the chosen input parameters but also reveals the need for further assessment of the substrate provision and of the carbon uptake approach.

For this study it was decided to exclude the carbon uptake into the substrate and the combustion of the product gas. This is a simplification that cannot be neglected. Further investigation should especially focus on the raw material provision as this unit process shows the highest variations in literature and the highest potential to improve the carbon uptake approach.

Interesting outcomes can be expected from further investigation of a possible regenerative gas import. Alternative gas can be produced at sites with excellent natural conditions. For example, biomethane can be produced in nations cultivating immense amounts of energy crops or with strong agroindustry producing an excess of manure. Regenerative hydrogen and methane can be produced in nations with a high potential for wind and solar power. The product gases can be compressed and shipped or transported by pipeline to sites with a high demand for gas. The additional transport is expected to raise the total emissions. Further studies should assess this increase and the general potential of regenerative gas import.

With the detection of the greenhouse gas emission occurring during the production of biogas, important contributors to the ecological consequences and to the social acceptance of alternative gas production technologies are investigated. The findings of this study are available for further application in the project *SustainableGas* and in the ABBY-Net project “Challenges and opportunities of alternative gas technologies in Germany and Alberta”*.* This study extends the strategies from *SustainableGas* by an important factor and is expected to inform for discussions and decision-making.

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# Annex A: Inventory Analysis

## A.1 LCI Biomethane

Table 14: Basic data for the inventory analysis of biomethane from anaerobic digestion

| *Category* | *Parameter* | *Value* | *Reference* |
|---|---|---|---|
| *Electricity and heat supply* | Emissions from electricity supply [kg $CO_{2,\,eq}$/$kWh_{el}$] | 0.527 | [61, p. 9] |
| | Emissions from heat supply, from biogas [kg $CO_{2,\,eq}$/$MJ_{th}$] | 0.03902 | ecoinvent dataset "heat and power co-generation, biogas, gas engine, DE"[20] |
| *Methane* | Density [kg/Nm$^3$] | 0.717 | [10, p. 179] |
| | Lower heating value [MJ/m$^3$] | 35.900 | [10, p. 179] |
| | Lower heating value [MJ/kg] | 50.000 | [10, p. 179], [19, p. 288] |
| *bio$CH_4$* | Density [kg/Nm$^3$] | 0.750 | [10, p. 180] |
| | Lower heating value [MJ/m$^3$] | 35.892 | [41, p. 194 ff.] |
| | Lower heating value [MJ/kg] | 46.100 | [10, p. 180] |
| | Methane content [m$^3$ $CH_4$/m$^3$ bio$CH_4$] | 0.970 | [10, p. 180] |
| | Carbon dioxide content [m$^3$ $CO_2$/m$^3$ bio$CH_4$] | 0.030 | [10, p. 180] |

[20] Treyer, K., heat and power co-generation, biogas, gas engine, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

### A.1.1 LCI *bioCH$_4$_manure*

Table 15: Data basis for *bioCH$_4$_manure* - raw material provision

| *Credits for avoided manure storage* | *Conversion factors* | *Result* *[kg $CO_{2,\ eq}$/kg manure]* | *Reference* |
|---|---|---|---|
| 36.8 g $CO_{2,\ eq}$/MJ manure from avoided $CH_4$ emissions + 8.3 g $CO_{2,\ eq}$/MJ manure from avoided $N_2O$ emissions | • Lower heating value dry manure: 12 MJ/kg dry manure<br>• moisture content manure: 90% | 0.054 | [10, pp. 59, 180] |
| 32 kg avoided $CH_4$ emissions from slurry storage per 21 t cow slurry | • GWP 100 of $CH_4$ | 0.038 | [9, p. 8] |
| 1.8 kg $CH_4$ emissions/$m^3$ manure + 0.1% $N_2O$ emissions per total nitrogen in manure, reduced by 85% by covered storage | • density of manure: 1 kg/l<br>• GWP 100 of $N_2O$<br>• 0.48 t nitrogen/t manure | 0.066 | [13, p. 39 f.] |

Table 16: Literature data for *bioCH$_4$_manure* - raw material transport

| *Transport distance* | *Conversion factors* | *Result* *[tkm/kg manure]* | *Reference* |
|---|---|---|---|
| • 0.0045 tkm/MJ manure<br>• 5 km one way | • Lower heating value dry manure: 12 MJ/kg dry manure<br>• moisture content manure: 90% | 0.0054 | [10, pp. 56, 180] |
| 10 km | - | - | [43, p. 79] |
| 5 km | - | - | [13, p. 39] |

Table 17: Data basis for anaerobic digestion of manure

| *anaerobic digestion of manure, CH*[21] | | *Referred to 1 kg manure input* | *Converted to 1 Nm³ raw biogas output* |
|---|---|---|---|
| ***Input*** | | | |
| Anaerobic digestion plant, agriculture, with methane recovery [items] | 2.86E-07 | 7.691E-09 | 3.189E-07 |
| Digester sludge [kg] | -36.000 | -0.968 | -40.141 |
| Electricity, low voltage [$kWh_{el}$] | 0.158 | 0.004 | 0.176 |
| Heat, central or small-scale, other than natural gas [$MJ_{th}$] | 3.470 | 0.093 | 3.869 |
| Manure, liquid, cattle [kg] | 20.452 | | |
| Manure, liquid, swine [kg] | 12.271 | 1.000 | 41.463 |
| Manure, solid, cattle [kg] | 4.462 | | |
| ***Output*** | | | |
| Ammonia [kg] | 0.004 | 1.1E-04 | 0.005 |
| Biogas [$m^3$] | 1.000 | 26.892 | 1.000 |
| Carbon dioxide, biogenic [kg] | 0.007 | 1.9E-04 | 0.008 |
| Dinitrogen monoxide [kg] | 5E-05 | 1.385E-06 | 6E-05 |
| Hydrogen sulfide [kg] | 4.128E-05 | 1.11E-06 | 4.602E-05 |
| Methane, biogenic [kg] | 0.001 | 2.851E-05 | 0.001 |

[21] Symeonidis, A., anaerobic digestion of manure, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

Table 18: Literature data for *bioCH$_4$_manure* - conversion

| *Digestion characteristics* | *Conversion factors* | *Input electricity* *[kWh$_{el}$ /Nm$^3$ raw biogas]* | *Input heat* *[MJ$_{th}$ /Nm$^3$ raw biogas]* | *Output raw biogas* *[Nm$^3$ raw biogas /t manure]* | *Output digestate* *[t digestate /t manure]* | *Reference* |
|---|---|---|---|---|---|---|
| Input:<br>• 2.38 MJ manure/MJ biogas<br>• 0.1 MJ heat/MJ biogas<br>• 0.2 MJ electricity/MJ biogas | • 42% efficiency of the conversion process, regarding energy content<br>• Lower heating value biogas: 18.3 MJ/Nm$^3$ biogas | 0.102 | 1.830 | 27.541 | | [10, p. 56 f., f.180] |
| • 285 Nm$^3$ biogas from 21 t cow slurry<br>Input:<br>• 0.11 MWh electricity/MWh electricity output | • Lower heating value biogas: 18.3 MJ/Nm$^3$ biogas<br>• Assumption: 30% conversion efficiency biogas to electricity | 1.864 | - | 13.571 | | [9, p. 8], [10] |
| 20 Nm$^3$ biogas/t manure | - | - | - | 20.000 | | [41, p. 161] |
| • Dairy cow: 14.1 Nm$^3$ biogas/t manure<br>• Calf: 9.3 Nm$^3$ biogas/t manure<br>• Cattle: 34.4 Nm$^3$ biogas/t manure<br>• Pig: 23.8 Nm$^3$ biogas/t manure | - | - | - | 9.300 - 34.400 | | [48, p. 87] |
| • 30 Nm$^3$ biogas/t manure<br>Output:<br>• 0.97 t digestate/t manure | - | - | - | 30.000 | 0.970 | [13, p. 40 f.] |

Table 19: Data basis for amine scrubbing

| *Amine scrubbing, according to* [13, p. 46] | | *Referred to 1 Nm$^3$ raw biogas input* | *Converted to 1 Nm$^3$ bioCH$_4$ output* bioCH$_4$_manure | bioCH$_4$_maize | bioCH$_4$_waste |
|---|---|---|---|---|---|
| Raw biogas input [Nm$^3$ raw biogas/Nm$^3$ bioCH$_4$] | 2.34 | 1.000 | 1.818 | 1.923 | 2.711 |
| Heat demand [kWh$_{th}$/Nm$^3$ bioCH$_4$] | 1.81 | 0.774 | 1.406 | 1.488 | 2.097 |
| Electricity demand [kWh$_{el}$/Nm$^3$ bioCH$_4$] | 0.37 | 0.158 | 0.287 | 0.304 | 0.429 |
| Methane slip [kg CH$_4$/Nm$^3$ bioCH$_4$] | 0.2 vol% | 0.2 vol% | 1.434E-03 | 1.434E-03 | 1.434E-03 |

Table 20: Data basis for closed digestate storage

| *Emissions from digestate storage* | *Conversion factors* | *Resulting emissions* | *Reference* |
|---|---|---|---|
| • 0.1% methane emissions regarding total produced bioCH$_4$<br>• 0.1% dinitrogen monoxide emissions regarding total amount of nitrogen in digestate, reduced by 90% at gas tight storage | 0.0037 t nitrogen/t digestate | • 9.824E-06 kg CH$_4$/kg digestate<br>• 3.7E-07 kg N$_2$O/kg digestate | [13, p. 40] |

## A.1.2 LCI *bioCH₄_maize*

Table 21: Literature data for *$bioCH_4$_maize* - raw material provision

| *Emissions from cultivation and ensiling of maize* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$ /kg maize silage]* | *Reference* |
|---|---|---|---|
| 17.3 g $CO_{2, eq}$/MJ $bioCH_4$ | • 1.429 MJ maize silage input/MJ raw biogas<br>• Lower heating value maize silage: 16 MJ/kg maize silage, dry<br>• Moisture content maize silage: 65%<br>• 1.03 MJ raw biogas input/MJ $bioCH_4$<br>• Lower heating value raw biogas: 19 MJ/$Nm^3$ raw biogas | 0.071 | [10, pp. 49, 54, 136, 180] |
| • 54.41 g $CO_{2, eq}$/kWh $bioCH_4$<br>• -10.68 g $CO_{2, eq}$/kWh $bioCH_4$ credits for manure treatment | • Biomass = 10% manure + 90% maize silage<br>• Input: 1.87 t biomass, dry/h<br>• Output: 500 $m^3$ $bioCH_4$/h, equivalent to 5 MW $bioCH_4$<br>• Assumption according to characteristics: 65% moisture content maize silage | 0.041 | [5, pp. 35, 43, 111] |

Table 22: Data basis for *$bioCH_4$_maize* - raw material transport

| *Transport distance* | *Conversion factors* | *Result* *[tkm/kg maize silage]* | *Reference* |
|---|---|---|---|
| • 0.0035 tkm/MJ maize silage<br>• 20 km one way | • Lower heating value maize silage: 16 MJ/kg dry maize silage<br>• Moisture content maize silage: 65% | 0.021 | [10, p. 49] |
| • 3.2 tkm/$Nm^3$ raw biogas<br>• 50 km, probably one way | • 156.1 $Nm^3$ raw biogas/t maize silage, wet | 0.500 | [40, pp. 50, 55] |
| 50 km | - | - | [44, p. 211] |
| • Up to 100 km<br>• 5.18 g $CO_{2, eq}$/kWh $bioCH_4$ | • Input: 1.87 t biomass, dry/h<br>• Output: 500 $m^3$ $bioCH_4$/h, equivalent to 5 MW $bioCH_4$<br>• Assumption according to characteristics: 65% moisture content maize silage<br>• 0.0622 kg $CO_{2, eq}$/tkm | 0.078 | [5, pp. 35, 43, 81, 111] ecoinvent dataset “transport, freight, lorry >32 metric ton, EURO5, RER” |

Table 23: Literature data for *bioCH$_4$_maize* - conversion

| *Digestion characteristics* | *Conversion factors* | *Input electricity* *[MJ$_{el}$ /t maize s.]* | *Input heat* *[MJ$_{th}$ /t maize s.]* | *Output raw biogas* *[Nm$^3$ r. b. /t maize s.]* | *Output digestate* *[t digestate /t maize s.]* | *Reference* |
|---|---|---|---|---|---|---|
| Input<br>• 1.429 MJ maize silage/MJ raw biogas<br>• 0.025 MJ electricity/MJ raw biogas<br>• 0.1 MJ heat/MJ raw biogas | • LHV maize silage: 16 MJ/kg dry maize silage<br>• Moisture content maize silage: 65%<br>• LHV raw biogas: 19 MJ/Nm$^3$ raw biogas<br>• Density raw biogas: 1.31 kg/Nm$^3$ raw biogas | 103.481 | 413.926 | 217.856 | 0.715 | [10, pp. 49, 180] |
| Output<br>• 200 Nm$^3$ raw biogas/t maize silage<br>• 0.78 t digestate/t maize silage | - | - | - | 200.000 | 0.780 | [13, p. 40 f.] |
| Output<br>• 200 Nm$^3$ raw biogas/t regrowing raw material | - | - | - | 200.000 | - | [41, p. 161] |
| Input per 1 MWh electricity<br>• 2.45 t maize silage<br>• 0.09 MWh electricity<br>• 0.38 MWh heat<br>Output per 1 MWh electricity<br>• 252 Nm$^3$ raw biogas | Density raw biogas: 1.31 kg/Nm$^3$ raw biogas | 132.245 | 558.367 | | - | [9, p. 8]<br>[10, p. 180] |
| Input<br>• 0.051 kWh electricity/m$^3$ raw biogas<br>• 1.2 MJ heat/m$^3$ raw biogas<br>Output<br>• 156.1 Nm$^3$ raw biogas/t maize silage<br>• 0.82 t digestate/t maize silage | - | 28.660 | 187.320 | 156.100 | 0.820 | [40, pp. 26, 50, 55] |
| Output<br>• 178.4 m$^3$ raw biogas/t maize silage | - | - | | 178.400 | - | [44, p. 210] |
| Input<br>• 1.87 t biomass, dry/h, equivalent to 9 MW biomass, dry<br>• 0.47 MW electricity<br>• 0.75 MW heat<br>Output<br>• 0.43 t digestate, dry | • Assumption according to characteristics: 65% moisture content maize silage<br>• 500 m$^3$ bioCH$_4$ output/h<br>• Assumption: 52% bioCH$_4$ in raw biogas, see Upgrading | 316.684 | 505.348 | 179.967 | - | [5, pp. 35, 43] |

### A.1.3 LCI *bioCH$_4$_waste*

Table 24: Data basis for *bioCH$_4$_waste* - raw material transport

| *Transport distance* | *Conversion factors* | *Result* *[tkm/kg biowaste]* | *Reference* |
|---|---|---|---|
| • 20 km, wet biowaste<br>• 0.0042 tkm/MJ biowaste, wet | - | 0.0206 | [10, p. 61] |
| • 100 miles, with return, US<br>• 18 t truck | • 1 mile = 1.60934 km<br>• Assumption: 27 t truck | 54.645 km, one way, 27 t truck | [42, p. 1099] |

Table 25: Data basis for *bioCH$_4$_waste* - conversion

| *Digestion characteristics* | *Conversion factors* | *Input electricity [MJ$_{el}$ /kg biowaste]* | *Input heat [MJ$_{th}$ /kg biowaste]* | *Output raw biogas [Nm$^3$ raw biogas /t biowaste]* | *Output digestate [kg digestate /kg biowaste]* | *Reference* |
|---|---|---|---|---|---|---|
| Input<br>• 1.45 MJ/biowaste/MJ raw biogas<br>• 0.03 MJ electricity/MJ biogas<br>• 0.1 MJ heat/MJ raw biogas<br>Output<br>• 0.1606 m$^3$ raw biogas/kg wet waste | • Lower heating value raw biogas: 21.5 MJ/Nm$^3$ raw biogas<br>• Density raw biogas: 1.22 kg/Nm$^3$ raw biogas | 0.104 | 0.345 | 160.6 | 0.804 | [3, pp. 62, 64, 180] |
| Input biogas plant with 700 Nm$^3$ raw biogas output<br>• 0.552 kWh electricity/Nm$^3$ raw biogas<br>• 0.502 kWh heat/Nm$^3$ raw biogas<br>Input biogas plant with 1400 Nm$^3$ raw biogas output<br>• 0.516 kWh electricity/Nm$^3$ raw biogas<br>• 0.475 kWh heat/Nm$^3$ raw biogas<br>Output<br>• 120 Nm$^3$ raw biogas/t biowaste | Biogas plant with 700 Nm$^3$ raw biogas output<br>• 48236 t biowaste input/a<br>• 8200 h/a<br>Biogas plant with 700 Nm$^3$ raw biogas output<br>• 96472 t biowaste input/a<br>• 8200 h/a<br>General<br>• Density raw biogas: 1.22 kg/Nm$^3$ raw biogas | 0.222 | 0.204 | 120.000 | 0.855 | [16, pp. 161, 166]<br>[3, p. 180] |
| Input<br>• 76E06 t municipal solid waste<br>Output<br>• 140 Nm$^3$ raw biogas/t municipal solid waste<br>• 63E06 t digestate | - | - | - | 140.000 | 0.829 | [17, p. 1098, 1101 ] |
| Input<br>• 2.14E-03 kWh electricity, low voltage<br>• 0.242 MJ heat, central or small-scale, other than natural gas<br>• -0.62 kg digester sludge<br>Output<br>• -1 kg biowaste<br>• 0.1 m$^3$ biogas | - | 0.008 | 0.242 | 100.000 | 0.620 | ecoinvent dataset "treatment of biowaste by anaerobic digestion, CH" [22] |

[22] Zschokke-Gohl, M., treatment of biowaste by anaerobic digestion, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

## A.2 LCI BioSNG

Table 26: Basic data for the inventory analysis of bioSNG from gasification

| *Category* | *Parameter* | *Value* | *Reference* |
|---|---|---|---|
| *Electricity and heat supply* | Emissions from electricity supply [kg $CO_{2,\,eq}$/$kWh_{el}$] | 0.527 | [61, p. 9] |
| | Emissions from heat supply, from biogas [kg $CO_{2,\,eq}$/$MJ_{th}$] | 0.03902 | ecoinvent dataset "heat and power co-generation, biogas, gas engine, DE"[23] |
| *Methane* | Density [kg/$Nm^3$] | 0.717 | [10, p. 179] |
| | Lower heating value [MJ/$m^3$] | 35.900 | [10, p. 179], [22, p. 619] |
| | Lower heating value [MJ/kg] | 50.000 | [10, p. 179], [19, p. 288] |
| *bioSNG* | Lower heating value [MJ/$Nm^3$] | 35.892 | [41, p. 194 ff.] |
| | Lower heating value [MJ/kg] | 46.100 | [10, p. 180] |
| | Upper heating value [MJ/$Nm^3$] | 39.860 | provided by the Chair of Energy Process Engineering of the Friedrich Alexander-University Erlangen-Nuremberg |
| *Carbon monoxide* | Lower heating value [MJ/$m^3$] | 12.600 | [22, p. 619] |
| *Hydrogen* | Lower heating value [MJ/$m^3$] | 10.800 | [22, p. 619] |

[23] Treyer, K., heat and power co-generation, biogas, gas engine, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

### A.2.1 LCI *SNG_RFW*

Table 27: Literature data for *SNG_RFW* - raw material provision

| *Emissions from wood chips provision* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$/kg RFW chips]* | *Reference* |
|---|---|---|---|
| Production and harvesting of raw material:<br>• 10.2 kg $CO_{2, eq}$/MWh wood chip<br>Transport to wood chip production site:<br>• 13.5 kg $CO_{2, eq}$/MWh wood chip | - | 0.125 | [16, p. 156] |
| Raw material provision:<br>• 11.385 g $CO_{2, eq}$/kWh bioSNG | • 12.24 t biomass input/h<br>• 2150 $Nm^3$ bioSNG output/h | 0.020 | [5, pp. 48, 111] |

Table 28: Data basis for methane production from wood

| *methane production, 96% by volume, from synthetic gas, wood, fluidised technology, CH*[24] | | *Referred to 1 kg wood chips input* |
|---|---|---|
| ***Input*** | | |
| Electricity, low voltage<br>+ electricity, medium voltage<br>[$kWh_{el}$] | 0.0082<br>+ 0.829<br>= 0.837 | 0.226 |
| Heat, central or small-scale, other than natural gas<br>(provided from process heat)<br>[$MJ_{th}$] | 6.13E-04 | 1.656E-04 |
| Industrial furnace, natural gas<br>[items] | 2.06E-08 | *Influence on emissions lower than 0.25%. Therefore neglected.* |
| Synthetic gas factory<br>[items] | 2.9E-09 | *Influence on emissions lower than 0.25%. Therefore neglected.* |
| Wood chips, dry, measured as dry mass<br>+ wood chips, wet, measured as dry mass<br>[kg RFW chips] | 0.814<br>+ 2.887<br>= 3.701 | 1 |
| Aluminum oxide [kg] | 4.294E-10 | 1.16E-10 |
| Charcoal [kg] | 0.020 | 0.005 |
| Dolomite [kg] | 0.040 | 0.011 |
| Nickel, 99.5% [kg] | 4.294E-10 | 1.16E-10 |
| Silica sand [kg] | 0.050 | 0.013 |
| Sodium hydroxide, without water [kg] | 0.003 | 8.727E-04 |
| Sulfuric acid [kg] | 0.013 | 0.003 |
| Tap water [kg] | 0.559 | 0.151 |
| Vegetable oil methyl ester[kg] | 0.015 | 0.004 |
| Zeolite, powder [kg] | 0.008 | 0.002 |
| Zinc [kg] | 0.002 | 5.051E-04 |
| Summarized as gasification inputs<br>[unit] | | 1 |
| ***Output*** | | |
| Synthetic methane (methane, 96% by volume)<br>[$m^3$] | 1 | 0.2702 |
| Inert waste<br>[kg] | 0.179 | 0.048 |
| Waste mineral oil<br>[kg] | 0.015 | 0.004 |
| Waste zeolite<br>[kg] | 0.008 | 0.002 |
| Wastewater, from residence<br>[$m^3$] | 0.001 | 2.91E-04 |
| Wood ash mixture, pure<br>[kg] | 0.035 | 0.009 |

[24] Del Duce, A., methane production, 96% by volume, from synthetic gas, wood, fluidised technology, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

Table 29: Data basis for bioSNG gasification and upgrading

| *Gasification and upgrading according to table 28* | *Referred to 1 kg wood chips input* | *Converted to 1 Nm³ bioSNG output* SNG_RFW | SNG_SRF | SNG_straw | SNG_IP I | SNG_IP II |
|---|---|---|---|---|---|---|
| ***Input*** | | | | | | |
| Electricity [$kWh_{el}$] | 0.226 | 0.635 | 0.69 | 0.885 | 0.747 | 0.598 |
| Heat [$MJ_{th}$] | 1.656E-04 | 4.652E-04 | 5.055E-04 | 6.482E-04 | 5.474E-04 | 4.379E-04 |
| Substrate [kg] | 1 | 2.8089 [RFW chips] | 3.052 [SRF chips] | 3.914 [straw pellets] | 3.305 [pellets] | 2.644 [pellets] |
| gasification inputs [unit] | 1 | 2.8089 | 3.052 | 3.914 | 3.305 | 2.644 |

Table 30: Literature data for *SNG_RFW* - conversion

| *Gasification characteristics* | *Conversion factors* | *Input RFW [kg RFW chips /Nm³ bioSNG]* | *Input electricity [$kWh_{el}$ /Nm³ bioSNG]* | *Input heat [$MJ_{th}$ /Nm³ bioSNG]* | *Reference* |
|---|---|---|---|---|---|
| Input<br>• 32.76 MW biomass, equivalent to 12.24 t/h<br>• 2.3 MW electricity<br>• No heat input.<br>Output<br>• 21.5 MW bioSNG, equivalent to 2150 Nm³/h | - | 5.693 | 1.070 | - | [5, p. 48] |
| *"SNG-1_wrh"*<br>Input<br>• 0.81 kWh electricity/Nm³ bioSNG<br>• 0 kWh heat/Nm³<br>Output<br>• 2055 Nm³ bioSNG/h<br><br>*"SNG-4_wrh"*<br>Input<br>• 1.12 kWh electricity/Nm³ bioSNG<br>• 0 kWh heat/Nm³<br>Output<br>• 1707 Nm³ bioSNG/h | 2023.641 Nm³ bioSNG output/h, according to characteristics | | 0.838 | 0 | [41, p. 178 f.] |

Table 31: Data basis for waste treatment bioSNG

| Type of waste | *Amount of waste* | | | | | *Ecoinvent dataset* |
|---|---|---|---|---|---|---|
| | *SNG_RFW* | *SNG_SRF* | *SNG_straw* | *SNG_IP I* | *SNG_IP II* | |
| Inert waste [kg] | 0.136 | 0.148 | 0.189 | 0.160 | 0.128 | market for inert waste, CH[25] |
| Waste mineral oil [kg] | 0.011 | 0.012 | 0.015 | 0.013 | 0.010 | market for waste mineral oil, CH[26] |
| Waste zeolite [kg] | 0.006 | 0.007 | 0.009 | 0.007 | 0.006 | market for waste zeolite, GLO[27] |
| Wastewater, from residence [$m^3$] | 8.173E-04 | 8.88E-04 | 0.001 | 9.616E-04 | 7.693E-04 | market for wastewater, from residence, RoW[28] |
| Wood ash mixture, pure [kg] | 0.027 | 0.029 | 0.037 | 0.031 | 0.025 | market for wood ash mixture, pure, CH[29] |

[25] Levova, T., market for inert waste, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

[26] Levova, T., market for waste mineral oil, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

[27] Bourgault, G., market for waste zeolite, GLO, Allocation, cut-off by classification, ecoinvent database version 3.4

[28] market for wastewater, from residence, RoW, Allocation, cut-off by classification, ecoinvent database version 3.4

[29] Levova, T., market for wood ash mixture, pure, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

### A.2.2 LCI *SNG_SRF*

Table 32: Literature data for *SNG_SRF* - raw material provision

| *Emissions from wood chips provision* | *Conversion factors* | *Result* *[kg $CO_{2,\ eq}$/kg SRF chips]* | *Reference* |
|---|---|---|---|
| Emission from land use change: 35 kg $CO_{2,\ eq}$/GJ bioSNG | Lower heating value bioSNG: 50 MJ/kg | 0.429 | [5, pp. 109, 154] |

Table 33: Literature data for *SNG_SRF* – conversion

| *Gasification characteristics* | *Conversion factors* | *Input SRF* *[kg SRF chips /Nm³ bioSNG]* | *Input electricity* *[$kWh_{el}$ /Nm³ bioSNG]* | *Input heat* *[$MJ_{th}$ /Nm³ bioSNG]* | *Reference* |
|---|---|---|---|---|---|
| Input<br>• 8852 kg short rotation forestry wood/h<br>• 2292 kWh electricity/h<br>Output<br>• 1564 kg bioSNG/h | Density of bioSNG: 0.72 kg/m³ | 4.075 | 1.060 | - | [5, pp. 154, 159] |
| *"SNG-1_KUP"*<br>Input<br>• 0.81 kWh electricity/Nm³ bioSNG<br>• 0 kWh heat/Nm³<br>Output<br>• 2055 Nm³ bioSNG/h<br><br>*"SNG-4_KUP"*<br>Input<br>• 1.12 kWh electricity/Nm³ bioSNG<br>• 0 kWh heat/Nm³<br>Output<br>• 1707 Nm³ bioSNG/h | 1923.145 Nm³ bioSNG output/h, according to characteristics | - | 0.927 | 0 | [41, p. 178 f.] |

### A.2.3 LCI *SNG_IP I* and *SNG_IP II*

Table 34: Literature data for *SNG_IP I and SNG_IP II* - raw material provision

| *Emissions from pelletization* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$/kg pellet]* | *Reference* |
|---|---|---|---|
| 4.39 g $CO_{2, eq}$/MJ bioSNG | 1.54 MJ biomass/MJ bioSNG | 0.054 | [15, p. 449 f.] |
| | - | 0.231 | [16, p. 156] read off and averaged from Fig. 5 |
| 39,560 g $CO_{2, eq}$/ODT pellet | - | 0.040 | [50, p. S23] |

Table 35: Literature values for *SNG_IP I* - conversion

| *Gasification characteristics* | *Conversion factors* | *Input pellets* *[kg pellets /Nm³ bioSNG]* | *Input electricity* *[kWh$_{el}$/Nm³ bioSNG]* | *Input heat* *[MJ$_{th}$ /Nm³ bioSNG]* | *Reference* |
|---|---|---|---|---|---|
| Input<br>• 0.074 MJ electricity/MJ bioSNG<br>• 32 MW pellets<br>Output<br>• 20.5 MW bioSNG | - | 2.919 | 0.738 | - | [15, p. 449] |

## A.3 LCI Power to X

Table 36: Basic data for the inventory analysis of Power to X

| *Category* | | *Value* | *Reference* |
|---|---|---|---|
| *Electricity and heat supply* | Emissions from regenerative excess electricity [kg $CO_{2,\,eq}$/$kWh_{el}$] | 0.04239 | See *Regenerative excess electricity.* |
| | Emissions from heat supply, general [kg $CO_{2,\,eq}$/$MJ_{th}$] | 0.07638 | ecoinvent dataset "market for heat, central or small-scale, other than natural gas, CH"[30] |
| *Water supply* | Emissions from deionized water supply [kg $CO_{2,\,eq}$/kg $H_2O$] | 0.00135 | See *Deionized water.* |
| *Methane* | Density [kg/Nm$^3$] | 0.717 | [10, p. 179] |
| | Lower heating value [MJ/m$^3$] | 35.9 | [10, p. 179], [22, p. 619] |
| | Lower heating value [MJ/kg] | 50 | [10, p. 179], [19, p. 288] |
| | Molar mass [g/mol] | 16.04246 | Calculated from molar masses of C and H. |
| *Hydrogen* | Density [kg/m$^3$] | 0.0899 | [27, p. 333] |
| | Lower heating value [MJ/m$^3$] | 10.8 | [22, p. 619] |
| | Lower heating value [kWh/kg] | 33 | [27, p. 333] |
| | Molar mass $H_2$ [g/mol] | 2.0158 | [27, p. 333] |
| | Molar mass H [g/mol] | 1.00794 | [62] |
| *Carbon* | Molar mass [g/mol] | 12.0107 | [62] |
| *Carbon monoxide* | Lower heating value [MJ/m$^3$] | 12.6 | [22, p. 619] |
| *Carbon dioxide* | Molar mass [g/mol] | 16.04246 | Calculated from molar masses of C and O. |
| | Density [kg/m$^3$] | 1.96359 | Calculated from molar mass. |
| *Water* | Molar mass [g/mol] | 18.01528 | [62] |
| *Oxygen* | Molar mass O [g/mol] | 15.9994 | [62] |

[30] Treyer, K., market for heat, central or small-scale, other than natural gas, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

### *Regenerative excess electricity*

In 2017, renewable electricity generation in Germany was composed as shown in Figure 31.

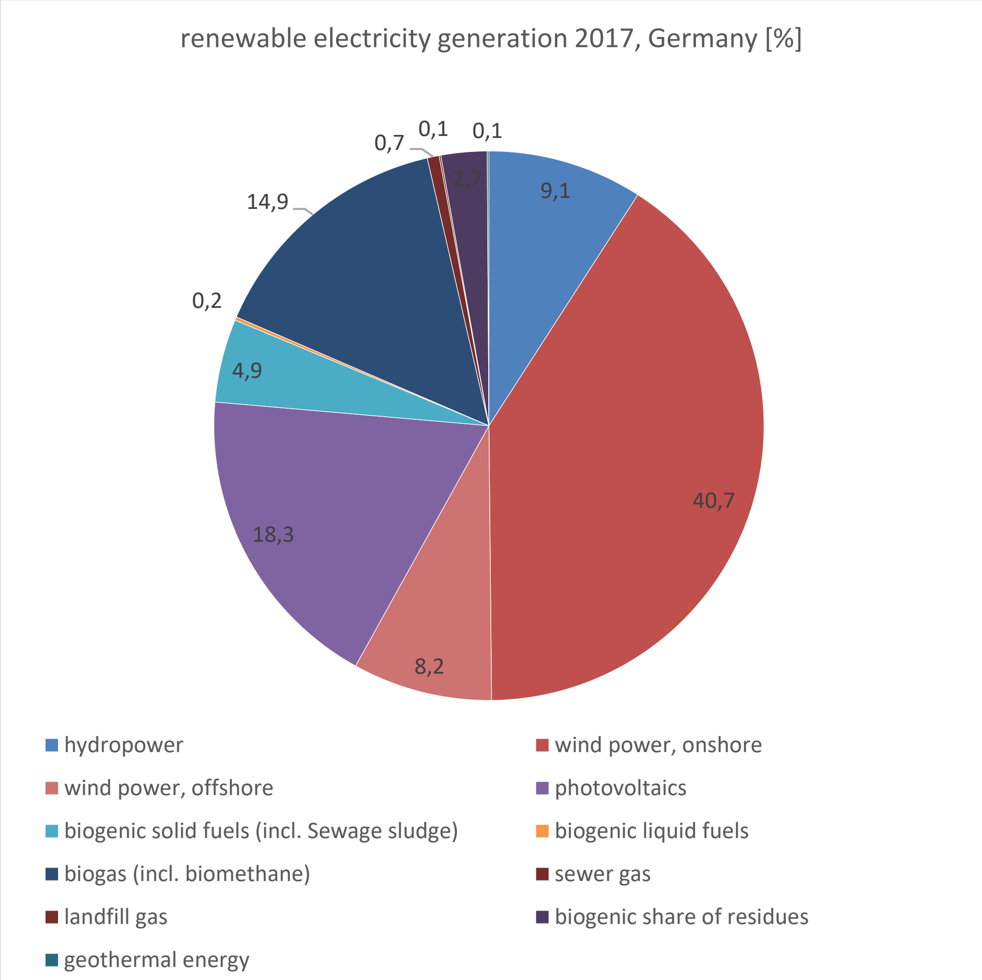


Figure 31: Renewable electricity generation 2017, Germany, based on [63]

Excess electricity is considered to arise only from energy sources which are subject to fluctuations. This assumption leads to a composition of excess renewable electricity as shown in Table 37. The resulting emissions were calculated from ecoinvent datasets, respectively, and are summarized in Table 37.

### *Deionized water*

Water to be used in electrolyzers needs to be deionized. In accordance with Zhang et al. [64, L. 120], the water provision is calculated as mean value from the ecoinvent datasets "market for water, deionised, from tap water, at user, CH"[31] and "market for water, deionised, from tap water, at user, RoW"[32]. Subsequently, the emissions from deionized water provision account for 0.00135 kg $CO_2$/kg $H_2O$.

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[31] Levovoa, T., market for water, deionised, from tap water, at user, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

[32] market for water, deionised, from tap water, at user, RoW, Allocation, cut-off by classification, ecoinvent database version 3.4

Table 37: Emissions from excess renewable electricity

| *Energy source* | *Share [%]* | *Corresponding emissions [kg $CO_{2,eq}$/$kWh_{el}$]* | *Reference dataset, ecoinvent* |
|---|---|---|---|
| Hydropower | 11.927 | 0.02742 | Mean of "electricity production, hydro, reservoir, non-alpine region, DE"[33] and "electricity production, hydro, run-of-river, DE"[34] |
| Wind power, onshore | 53.342 | 0.02180 | Mean of "electricity production, wind, <1MW turbine, onshore, DE"[35], "electricity production, wind, 1-3MW turbine, onshore, DE"[36] and "electricity production, wind, >3MW turbine, onshore, DE"[37] |
| Wind power, offshore | 10.747 | 0.01513 | "electricity production, wind, 1-3MW turbine, offshore, DE"[38] |
| Photovoltaics | 23.984 | 0.10783 | Mean of "electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted, DE"[39], "electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted, DE"[40] and "electricity production, photovoltaic, 570kWp open ground installation, multi-Si, DE"[41] |
| Total | | 0.04239 | |

[33] Treyer, K., electricity production, hydro, reservoir, non-alpine region, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[34] Treyer, K., electricity production, hydro, run-of-river, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[35] Treyer, K., electricity production, wind, <1MW turbine, onshore, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[36] Bauer, C., electricity production, wind, 1-3MW turbine, onshore, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[37] Treyer, K., electricity production, wind, >3MW turbine, onshore, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[38] Bauer, C., electricity production, wind, 1-3MW turbine, offshore, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[39] Treyer, K., electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[40] Treyer, K., electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[41] Treyer, K., electricity production, photovoltaic, 570kWp open ground installation, multi-Si, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

### A.3.1 LCI *PtH_PEM*

Table 38: Literature values for *PtH_PEM* - conversion

| *Electrolysis characteristics* | *Conversion factors* | *Input electricity* *[$kWh_{el}/m^3$ $regH_2$]* | *Input $H_2O$* *[kg $H_2O/m^3$ $regH_2$]* | *Reference* |
|---|---|---|---|---|
| 18 to 22 kg $H_2$ output/MWh electricity | - | 4.497 | - | [27, p. 392] |
| 4.5 to 7.5 kWh electricity input/$m^3$ H2 | - | 6.000 | - | [26, p. 1373] |
| PEM, 1 MW:<br>4.8 kWh electricity input/$Nm^3$ $H_2$ | - | 4.800 | - | [64, L. 40] |
| 300 kW facility:<br>• kWh electricity input/$Nm^3$ $H_2$<br>• 1.1 kg water input/$Nm^3$ $H_2$ | - | 4.900 | 1.100 | [20, p. 330] |
| PEM, 100 kW, compression to 350 - 700 bar:<br>• 5.19 kWh electricity input/$Nm^3$ $H_2$<br>• 1.1 kg water input/$Nm^3$ $H_2$ | - | 5.190 | 1.100 | [64, L. 122] |
| PEM, 100 kW, subsequent methanation:<br>• 1kWh electricity input<br>• 0.224 kg $H_2O$ input/kWh electricity<br>• 0.204 $Nm^3$ $H_2$ output/kWh electricity | - | 4.902 | 1.098 | [64, L. 51] |
| 50 – 70% efficiency | - | - | - | [23, p. 4570] |

### A.3.2 LCI *PtH_SR*

Table 39: Literature values for *PtH_SR* - conversion

| *Steam reforming characteristics* | *Conversion factors* | *Input electricity [$MJ_{el}$/ $m^3$ $regH_2$]* | *Input heat [$MJ_{th}$ / $m^3$ $regH_2$]* | *Input $H_2O$ [kg $H_2O$ / $m^3$ $regH_2$]* | *Input $CH_4$ [kg $CH_4$ /$m^3$ $regH_2$]* | *Output $H_2O$ [kg $H_2O$ /$m^3$ $regH_2$]* | *Reference* |
|---|---|---|---|---|---|---|---|
| Input<br>• 0.26 kg natural gas/$Nm^3$ $H_2$<br>• 1.15 $MJ_{th}$ from natural gas/$Nm^3$ $H_2$<br>• 1.24 $MJ_{el}$/$Nm^3$ $H_2$<br>• 1.24 kg steam/$Nm^3$ $H_2$<br>Output<br>• 0.86 kg steam/$Nm^3$ $H_2$ | - | 1.240 | 1.150 | 1.240 | 0.260 | 0.860 | [59, p. 1177] |
| Input<br>• 153.311 $MJ_{el}$/d<br>• 392 t natural gas/d<br>• 1293 t steam/d<br>Output<br>• 1.5E06 $Nm^3$ $H_2$/d<br>• 1.112E05 kg $H_2$/d<br>• 1858 t steam/d | - | 1.022E-04 | - | 0.862 | 0.261 | 1.239 | [58, p. 2074 f., f.2078] |
| • 62 to 70% efficiency<br>Input<br>• 4.2 to 4.8 $kWh_{el}$/$Nm^3$ $H_2$ | - | 16.200 | - | - | - | - | [43, p. 74] |

### A.3.3 LCI *PtM_cat*

Table 40: *PtM_cat* - separation between electrolysis and methanation

| *Characteristic parameter* | *PtM_cat* | *PEM electrolysis* | *Catalytic methanation* |
|---|---|---|---|
| Input electricity [$MJ_{el}/m^3$ $regCH_4$] | 78.043 | 77.467 | 0.576 |
| Input $CO_2$ [kg $CO_2/m^3$ $regCH_4$] | 2.194 | - | 2.194 |
| Input $H_2O$ [kg $H_2O/m^3$ $regCH_4$] | 3.400 | 3.400 | - |
| Interim output $regH_2$[42] [kg $regH_2/m^3$ $regCH_4$] | 0.190 | 0.190 | - |
| Output $regCH_4$ [$m^3$ $regCH_4$] | 1.000 | - | 1.000 |
| Output $H_2O$ [kg $H_2O/m^3$ $regCH_4$] | 1.698 | - | 1.698 |
| Output $CO_2$ [kg $CO_2/m^3$ $regCH_4$] | 0.219 | - | 0.219 |

[42] The determined output of the electrolysis is used as input for the methanation process.

Table 41: Literature values for *PtM_cat* – conversion and upgrading

| *Methanation characteristics* | *Conversion factors* | *Input electricity* *[$MJ_{el}/m^3$ $regCH_4$]* | *Input $H_2$* *[kg $H_2$ /$m^3$ $regCH_4$]* | *Input $CO_2$* *[kg $CO_2$ /$m^3$ r $regCH_4$]* | *Output $H_2$* *[kg $H_2$ /$m^3$ $regCH_4$]* | *Output $CO_2$* *[kg $CO_2$ /$m^3$ $regCH_4$]* | *Output $H_2O$* *[kg $H_2O$ /$m^3$ $regCH_4$]* | *Reference* |
|---|---|---|---|---|---|---|---|---|
| Input<br>• 0.506 kg $H_2$/kg $CH_4$<br>• 2.939 kg $CO_2$/kg $CH_4$<br>• 0.33 $kWh_{el}$/kg $CH_4$<br>Output<br>• 0.194 kg $CO_2$/kg $CH_4$<br>• 0.009 kg $H_2$/kg $CH_4$<br>• 1 kg $CH_4$ | - | 0.066 | 0.362 | 2.104 | 0.006 | 0.139 | - | [65, p. 2] |
| Input<br>• 80 $m^3$ $CO_2$/h<br>• 27.2 $MJ_{el}$/h<br>• 310.2 $m^3$ $H_2$/h<br>Output<br>• 80 $m^3$ $regCH_4$/h<br>• 615.9 $MJ_{th}/m^3$ $CO_2$ | - | 0.340 | 0.349 | 1.964 | - | - | - | [47, p. 287] |
| 80% efficiency | - | - | | | - | - | - | [20, p. 332] |
| Input<br>• 1.84 kg $CO_2$<br>• 4 $Nm^3$ $H_2$<br>Output<br>• 1 $Nm^3$ $CH_4$<br>• 10.56 MJ waste heat<br>• 1.5 kg $H_2O$ | - | - | 0.360 | 1.840 | - | - | 1.500 | [64, L. 125] |
| 70 – 85% efficiency | - | - | - | - | - | - | - | [66, p. 1192] |

### A.3.4 LCI *PtM_bio*

Table 42: *PtM_bio* - separation between electrolysis and methanation

| *Characteristic parameter* | *PtM_bio* | *PEM electrolysis* | *Biological methanation* |
|---|---|---|---|
| Input electricity [$MJ_{el}/m^3$ $regCH_4$] | 79.075 | 76.072 | 3.003 |
| Input $CO_2$ [kg $CO_2/m^3$ $regCH_4$] | 2.034 | - | 2.034 |
| Input $H_2O$ [kg $H_2O/m^3$ $regCH_4$] | 3.339 | 3.339 | - |
| Interim output $regH_2$[43] [kg $regH_2/m^3$ $regCH_4$] | 0.186 | 0.186 | - |
| Output reg $CH_4$ [$m^3$ $regCH_4$] | 1.000 | - | 1.000 |
| Output $H_2O$ [kg $H_2O/m^3$ $regCH_4$] | 1.669 | - | 1.669 |
| Output $CO_2$ [kg $CO_2/m^3$ $regCH_4$] | 0.061 | - | 0.061 |

[43] The determined output of the electrolysis is used as input for the methanation process.

# Annex B: Evaluation

## B.1 Biomethane

### B.1.1 Monte Carlo Simulation

Table 43: Relevant parameters for Monte Carlo simulation of *bioCH₄_manure*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Credits for avoiding manure storage [kg $CO_{2,\,eq}$/kg wet manure] | 0.053 | 0.038 (-27.97%) Calculated from [9, p. 8] | 0.066 (+25.65%) Calculated from [13, p. 39 f.] |
| Input of manure into the digestion process [kg manure/$Nm^3$ raw biogas] | 41.463 | 29.07 (-29.89%) Calculated from [48, p. 87] | 73.684 (+77.71%) Calculated from [9, p. 8] |
| Input of heat into the digestion process [$MJ_{th}$/$Nm^3$ raw biogas] | 3.869 | 1.83 (-52.7%) Calculated from [10, p. 56] | 5.804 (+50%) Stated variation |
| Input of raw biogas into the upgrading process [$Nm^3$ raw biogas/$Nm^3$ $bioCH_4$] | 1.818 | 1.667 (-8.33%) Calculated from [41, p. 161] | 1.961 (+7.84%) Calculated from [10, p. 180] |
| Total methane slip [%] | 0.200 | - | 1.58 (+690%) Calculated from [34, p. 315] |

Table 44: Relevant parameters for Monte Carlo simulation of *bioCH₄_maize*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from maize silage production [kg $CO_{2,\,eq}$/kg maize silage] | 0.049 | 0.041 (-16.28%) Calculated from [5, p. 111] | 0.0707 (+44.7%) Calculated from [10, p. 136] |
| Transport distance of raw material [tkm/kg maize silage] | 0.093 | - | 0.4995 (+434.65%) Calculated from [40, p. 55] |
| Input of maize silage into the digestion process [kg maize silage/$Nm^3$ raw biogas] | 4.6 | 4.59 (-0.21%) Calculated from [10, pp. 49, 180] | 9.722 (+111.37%) Calculated from [9, p. 8] |
| Input of electricity into the digestion process [$MJ_{el}$/$Nm^3$ raw biogas] | 0.476 | 0.043 (-91.03%) Calculated from [41, p. 165] | 1.286 (+170.12%) Calculated from [9, p. 8] |
| Input of heat into the digestion process [$MJ_{th}$/$Nm^3$ raw biogas] | 1.904 | 0.104 (-94.54%) Calculated from [41, p. 165] | 5.429 (+185.12%) Calculated from [9, p. 8] |
| Input of raw biogas into the upgrading process [$Nm^3$ raw biogas/$Nm^3$ $bioCH_4$] | 1.923 | 1.67 (-13.33%) Stated variation | 1.976 (+1.18%) Calculated from [10, pp. 54, 180] |
| Total methane slip [%] | 0.2 | - | 1 (+400%) Stated variation |

Table 45: Relevant parameters for Monte Carlo simulation of *bioCH$_4$_waste*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from biowaste provision [kg $CO_{2,\,eq}$/kg biowaste]] | 0.107 | - | 0.319 (+197.12%) Calculated from [47, p. 13] |
| Input of biowaste into the digestion process [kg biowaste/$Nm^3$ raw biogas] | 7.133 | 6.227 (-12.7%) Calculated from [10, p. 64] | 10 (+40.2%) Calculated from ecoinvent dataset "treatment of biowaste by anaerobic digestion, CH"[44] |
| Input of electricity into the digestion process [$MJ_{el}$/$Nm^3$ raw biogas] | 0.793 | 0.077 (-90.29%) Calculated from ecoinvent dataset "treatment of biowaste by anaerobic digestion, CH" | 1.869 (+135.57%) Calculated from [41, p. 166] |
| Input of heat into the digestion process [$MJ_{th}$/$Nm^3$ raw biogas] | 1.882 | 1.719 (-8.67%) Calculated from [41, p. 166] | 2.416 (+28.4%) Calculated from ecoinvent dataset "treatment of biowaste by anaerobic digestion, CH" |
| Input of raw biogas into the upgrading process [$Nm^3$ raw biogas/$Nm^3$ $bioCH_4$] | 2.711 | 1.667 (-38.53%) Calculated from [41, p. 161] | - |
| Total methane slip [%] | 0.2 | - | 1 (+400%) Stated variation |

Table 46: Results Monte Carlo simulation biomethane

| | *bioCH$_4$_manure* | *bioCH$_4$_maize* | *bioCH$_4$_waste* |
|---|---|---|---|
| Mean [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -366.000 | 196.790 | 502.508 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-3.649* | *1.962* | *5.010* |
| Standard deviation [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | 146.439 | 32.598 | 138.114 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ b $bioCH_4$]* | *1.460* | *0.325* | *1.377* |
| 5% percentile [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -631.394 | 146.540 | 303.511 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-6.295* | *1.461* | *3.026* |
| 95% percentile [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -151.153 | 253.460 | 752.558 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-1.507* | *2.527* | *7.503* |
| Median [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -351.354 | 194.885 | 487.563 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-3.503* | *1.943* | *4.861* |
| Minimum [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -829.990 | 104.814 | 213.842 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-8.275* | *1.045* | *2.132* |
| Maximum [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -55.266 | 323.470 | 1,002.909 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-0.551* | *3.225* | *9.999* |
| LCA, total emissions w/o carbon uptake [kg $CO_{2,\,eq}$/MWh $bioCH_4$] | -287.389 | 125.038 | 325.993 |
| *[kg $CO_{2,\,eq}$/$Nm^3$ $bioCH_4$]* | *-2.887* | *1.247* | *3.250* |

[44] Zschokke-Gohl, M., treatment of biowaste by anaerobic digestion, CH, Allocation, cut-off by classification, ecoinvent database version 3.4

### B.1.2 Comparison with Literature

Table 47: Total results *bioCH4_manure* from literature

| *Total emissions bioCH4_manure* | *Conversion factors* | *Result [kg $CO_{2,eq}$/MWh $bioCH_4$]* | *Reference* |
|---|---|---|---|
| -106.3 g $CO_{2,eq}$/MJ $bioCH_4$ | - | -382.680 | Giuntoli 2017 [10, p. 136] |
| -395 kg $CO_{2,eq}$/$MWh_{el}$ | • 0.00350877 $MWh_{el}$/$Nm^3$ raw biogas<br>• 56% $CH_4$ in raw biogas | -248.240 | Fusi 2016 [9, p. 6, 8 ] |
| 64 to 146 g $CO_{2,eq}$/kWh | | 64 to 146 | Müller-Langer 2009 [5, p. 82] |
| -0.115 kg $CO_{2,eq}$/MJ raw biogas | Assumption: 55% $CH_4$ in raw biogas | -383.790 | Lansche 2012 [34, p. 317] |

Table 48: Total results *bioCH4_maize* from literature

| *Total emissions bioCH4_maize* | *Conversion factors* | *Result [kg $CO_{2,eq}$/MWh $bioCH_4$]* | *Reference* |
|---|---|---|---|
| 26.4 g $CO_{2,eq}$/MJ $bioCH_4$ | - | 95.040 | Giuntoli 2017 [10, p. 136] |
| 408 kg $CO_{2,eq}$/$MWh_{el}$ | • 252 $Nm^3$ raw biogas output/$MWh_{el}$<br>• Assumption: 52% $CH_4$ in raw biogas | 312.292 | Fusi 2016 [9, p. 8 f.] |
| • 1.64E-02 kg $CO_2$, biogenic/$Nm^3$ raw biogas<br>• 1.13E-02 kg $CH_4$, biogenic/$Nm^3$ raw biogas<br>• 3.38E-04 kg $N_2O$/$Nm^3$ raw biogas | 52.5 to 53 vol% $CH_4$ in raw biogas | 75.986 | Stucki 2011 [40, p. 16 f., f.55] |
| 102.84 g $CO_{2,eq}$/kWh, including distribution | - | 102.840 | Müller-Langer 2009 [5, p. 111] |

Table 49: Total results *bioCH4_waste* from literature

| *Total emissions bioCH4_waste* | *Conversion factors* | *Result [kg $CO_{2,eq}$/MWh $bioCH_4$]* | *Reference* |
|---|---|---|---|
| 10.1 g $CO_{2,eq}$/MJ $bioCH_4$ | | 36.360 | Giuntoli 2017 [10, p. 136] |
| Fossil emissions<br>• 2.15 g $CH_4$/kg biowaste<br>• 5.2 g $CO_2$/kg biowaste<br>• 0.11 g $N_2O$/kg biowaste | • 0.052 $Nm^3$ $bioCH_4$/kg biowaste, according to characteristics<br>• Biogenic missions during digestion: 210 g $CO_2$, biogenic/kg biowaste | 177.924 (fossil)<br>585.251 (incl. biogenic) | Dinkel 2012 [47, p. 14] |

## B.2 BioSNG

### B.2.1 Monte Carlo Simulation

Table 50: Relevant parameters for Monte Carlo simulation of *SNG_RFW*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from RFW chips provision [kg $CO_{2,\,eq}$/kg RFW chips] | 0.033 | 0.020 (-39.28%) Calculated from [5, pp. 48, 111] | 0.125 (+279.78%) Calculated from [16, p. 156] |
| Input of RFW into the gasification process [kg RFW chips/$Nm^3$ bioSNG] | 2.809 | 2.576 (-8.29%) Calculated from [54, p. 73] | 5.693 (+102.68%) Calculated from [5, p. 48] |
| Input of electricity into the gasification process [$kWh_{el}/Nm^3$ bioSNG] | 0.635 | - | 1.070 (+68.42%) Calculated from [5, p. 48] |

Table 51: Relevant parameters for Monte Carlo simulation of *SNG_SRF*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from willow chips provision [kg $CO_{2,\,eq}$/kg willow chips] | 0.058 | - | 0.429 (+644.05%) Calculated from [54, pp. 109, 154, 159] |
| Input of willow chips into the gasification process [kg willow chips/$Nm^3$ bioSNG] | 3.052 | 2.442 (-20.00%) Stated variation | 4.075 (+33.52%) Calculated from [54, pp. 154, 159] |
| Input of electricity into the gasification process [$kWh_{el}/Nm^3$ bioSNG] | 0.690 | - | 1.055 (+52.88%) Calculated from [54, pp. 154, 159] |

Table 52: Relevant parameters for Monte Carlo simulation of *SNG_straw*

| *Parameter* | *Value in LCA* | *Minimum value, (deviation [%])* | *Maximum value, (deviation [%])* |
|---|---|---|---|
| Emissions from straw provision [kg $CO_{2,\,eq}$/kg straw] | 0.068 | - | 0.137 (+100.00%) Stated variation |
| Input of straw into the gasification process [kg straw/$Nm^3$ bioSNG] | 3.914 | 3.131 (-20.00%) Stated variation | 7.827 (+100.00%) Stated variation |
| Input of electricity into the gasification process [$kWh_{el}/Nm^3$ bioSNG] | 0.885 | - | 1.416 (+60.00%) Stated variation |

Table 53: Relevant parameters for Monte Carlo simulation of *SNG_IP I*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from pellet provision [kg $CO_{2,\ eq}$/kg pellet] | 0.035 | - | 0.232 (+565.24%) Calculated from [16, p. 156] |
| Input of pellets into the gasification process [kg pellets/$Nm^3$ bioSNG] | 3.305 | 2.949 (-10.78%) Calculated from [15, p. 449] | 3.966 (+20.00%) Stated variation |
| Input of electricity into the gasification process [$kWh_{el}$/$Nm^3$ bioSNG] | 0.747 | 0.738 (-1.29%) Calculated from [15, p. 449] | 0.0897 (+20.00%) Stated variation |

Table 54: Relevant parameters for Monte Carlo simulation of *SNG_IP II*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from pellet provision [kg $CO_{2,\ eq}$/kg pellet] | 0.035 | - | 0.232 (+565.24%) Calculated from [16, p. 156] |
| Input of pellets into the gasification process [kg pellets/$Nm^3$ bioSNG] | 2.644 | 2.380 (-10.00%) Stated variation, based on SNG_ IP I | 2.949 (+11.52%) Calculated from [15, p. 449] |
| Input of electricity into the gasification process [$kWh_{el}$/$Nm^3$ bioSNG] | 0.598 | - | 0.738 (+23.39%) Calculated from [15, p. 449] |

Table 55: Results Monte Carlo simulation bioSNG

| | SNG_RFW | SNG_SRF | SNG_straw | SNG_IP I | SNG_IP II |
|---|---|---|---|---|---|
| Mean [kg $CO_{2,eq}$/MWh $bioCH_4$] | 79.840 | 130.491 | 124.975 | 138.516 | 83.551 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *0.796* | *1.301* | *1.246* | *1.381* | *0.833* |
| Standard deviation [kg $CO_{2,eq}$/MWh $bioCH_4$] | 15.948 | 37.813 | 19.860 | 21.264 | 15.747 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *0.159* | *0.377* | *0.198* | *0.212* | *0.157* |
| 5% percentile [kg $CO_{2,eq}$/MWh $bioCH_4$] | 55.767 | 74.624 | 94.985 | 106.018 | 59.378 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *0.556* | *0.744* | *0.947* | *1.057* | *0.592* |
| 95% percentile [kg $CO_{2,eq}$/MWh $bioCH_4$] | 108.325 | 195.787 | 160.481 | 174.323 | 109.127 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *1.080* | *1.952* | *1.600* | *1.738* | *1.088* |
| Median [kg $CO_{2,eq}$/MWh $bioCH_4$] | 78.335 | 128.987 | 13.370 | 137.914 | 83.149 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *0.781* | *1.286* | *1.230* | *1.375* | *0.829* |
| Minimum [kg $CO_{2,eq}$/MWh $bioCH_4$] | 44.032 | 57.272 | 77.232 | 93.480 | 51.856 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *0.439* | *0.571* | *0.770* | *0.932* | *0.517* |
| Maximum [kg $CO_{2,eq}$/MWh $bioCH_4$] | 132.197 | 234.303 | 189.268 | 193.079 | 120.160 |
| *[kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$]* | *1.318* | *2.336* | *1.887* | *1.925* | *1.198* |
| LCA, total emissions w/o carbon uptake [kg $CO_{2,eq}$/MWh $bioCH_4$] | 47.596 | 59.294 | 81.185 | 98.280 | 55.796 |
| [kg $CO_{2,eq}$/$Nm^3$ $bioCH_4$] | 0.475 | 0.591 | 0.809 | 0.980 | 0.556 |

### B.2.2 Comparison with Literature

Table 56: Total results *SNG_RFW* from literature

| *Total emissions SNG_RFW* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$/MWh bioSNG]* | *Reference* |
|---|---|---|---|
| 23.8 kg $CO_{2, eq}$/MWh wood chips | 2.809 kg RFW chips input/$Nm^3$ bioSNG, according to characteristics | 35.389 | Holmgren 2015 [16, p. 154] |
| 103.495 g $CO_{2, eq}$/kWh bioSNG | - | 103.495 | Müller-Langer 2009 [5, p. 111], mean |

Table 57: Total results *SNG_SRF* from literature

| *Total emissions SNG_SRF* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$/MWh bioSNG]* | *Reference* |
|---|---|---|---|
| • Substrate provision: 7.57 kg $CO_{2, eq}$/GJ bioSNG<br>• Substrate production: 0.67 kg $CO_{2, eq}$/GJ bioSNG<br>• Conversion to bioSNG: 18.03 kg $CO_{2, eq}$/GJ bioSNG | - | 94.572 | Müller-Langer 2011 [54, p. 189] |
| 1.7 kg C/GJ wood | • 3.052 kg SRF input/$Nm^3$ bioSNG, according to characteristics<br>• Energy content wood: 18.6 GJ/ODT<br>• 3.67 kg C/kg $CO_{2, eq}$ | 2.638 | Dubuisson 1998 [49, pp. 379, 387] [67, p. 1] |

Table 58: Total results *SNG_IP I* from literature

| *Total emissions SNG_IP I* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$/MWh bioSNG]* | *Reference* |
|---|---|---|---|
| 14.9 g $CO_{2, eq}$/MJ bioSNG | - | 53.640 | Alamia 2016 [15, p. 541] |

## B.3 Power to X

### B.3.1 Monte Carlo Simulation

Table 59: Relevant parameters for Monte Carlo simulation of *PtH_PEM*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from electricity provision [kg $CO_{2,eq}$/$kWh_{el}$] | 0.042 | 0.015 (-64.31%)<br>Calculated from ecoinvent dataset *"electricity production, wind, 1-3MW turbine, offshore, DE"*[45] | 0.108 (+153.6%)<br>Calculated from ecoinvent datasets *"electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted, DE"*[46], *"electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted, DE"*[47] *and "electricity production, photovoltaic, 570kWp open ground installation, multi-Si, DE"*[48] |
| Input of electricity into electrolysis [$kWh_{el}$/$m^3$ $regH_2$] | 5.102 | 4.286 (-16%)<br>Calculated according to range of efficiency from [23, p. 4570] | 6 (+17.6%)<br>Calculated from [26, p. 1373] |

Table 60: Relevant parameters for Monte Carlo simulation of *PtH_SOEC*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from electricity provision [kg $CO_{2,eq}$/$kWh_{el}$] | 0.042 | 0.015 (-64.31%)<br>See PtH_PEM. | 0.108 (+153.6%)<br>See PtH_PEM. |
| Input of electricity into electrolysis [$kWh_{el}$/$m^3$ $regH_2$] | 3.421 | - | 5.556 (+62.41%)<br>Calculated according to range of efficiency from [23, p. 4570] |
| Input of heat into electrolysis [$MJ_{th}$/$m^3$ $regH_2$] | 1.413 | 1.13 (-20%)<br>Stated variation | 1.695 (+20%)<br>Stated variation |

[45] Bauer, C., electricity production, wind, 1-3MW turbine, offshore, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[46] Treyer, K., electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[47] Treyer, K., electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

[48] Treyer, K., electricity production, photovoltaic, 570kWp open ground installation, multi-Si, DE, Allocation, cut-off by classification, ecoinvent database version 3.4

Table 61: Relevant parameters for Monte Carlo simulation of *PtH_SR*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from electricity provision [kg $CO_{2,\,eq}$/$kWh_{el}$] | 0.042 | 0.015 (-64.31%) See PtH_PEM. | 0.108 (+153.6%) See PtH_PEM. |
| Input of electricity into steam reforming [$kWh_{el}$/$m^3$ $regH_2$] | 2.055 | 2.839E-05 (-99.99%) Calculated from [58, p. 2074] | 4.839 (+135.48%) Calculated according to range of efficiency from [43, p. 74] |
| Output of $CO_2$ from steam reforming [$MJ_{th}$/$m^3$ $regH_2$] | 0.457 | 0.228 (-50%) Stated variation | 0.8 (+75.18%) Calculated from [59, p. 1177] |

Table 62: Relevant parameters for Monte Carlo simulation of *PtM_cat*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from electricity provision [kg $CO_{2,\,eq}$/$kWh_{el}$] | 0.042 | 0.015 (-64.31%) See PtH_PEM. | 0.108 (+153.6%) See PtH_PEM. |
| Input of electricity into electrolysis [$MJ_{el}$/$m^3$ $regCH_4$] | 77.467 | 45.706 (-41%) Calculated from [19, p. 287] | 114.31 (+47.56%) Calculated from [65, p. 2] |
| Input of electricity into methanation [$MJ_{el}$/$m^3$ $regCH_4$] | 0.576 | 0.34 (-41%) Calculated from [19, p. 287] | 0.85 (+47.56%) Calculated from [65, p. 2] |
| Input of $CO_2$ into methanation [kg $CO_2$/$m^3$ $regCH_4$] | 2.194 | 1.84 (-16.12%) Calculated from [64, L. 125] | - |
| Output of $CO_2$ from methanation [kg $CO_2$/$m^3$ $regCH_4$] | 0.219 | 0.139 (-36.67%) Calculated from [65, p. 2] | 0.263 (+20%) Stated variation |
| Methane slip [%] | 0.200 | - | 1 (+400%) Stated variation |

Table 63: Relevant parameters for Monte Carlo simulation of *PtM_bio*

| *Parameter* | *Value in LCA* | *Minimum value (deviation [%])* | *Maximum value (deviation [%])* |
|---|---|---|---|
| Emissions from electricity provision [kg $CO_{2,\,eq}$/$kWh_{el}$] | 0.042 | 0.015 (-64.31%) See PtH_PEM. | 0.108 (+153.6%) See PtH_PEM. |
| Input of electricity into electrolysis [$MJ_{el}$/$m^3$ $regCH_4$] | 76.072 | 45.643 (-40%) Stated variation | 106.501 (+40%) Stated variation |
| Input of electricity into methanation [$MJ_{el}$/$m^3$ $regCH_4$] | 3.003 | 1.802 (-40%) Stated variation | 4.204 (+40%) Stated variation |
| Input of $CO_2$ into methanation [kg $CO_2$/$m^3$ $regCH_4$] | 2.034 | 1.729 (-15%) Stated variation | - |
| Output of $CO_2$ from methanation [kg $CO_2$/$m^3$ $regCH_4$] | 0.061 | 0.04 (-35%) Stated variation | 0.073 (+20%) Stated variation |
| Methane slip [%] | 0.200 | - | 1 (+400%) Stated variation |

Table 64: Results Monte Carlo simulation PtX

| | PtH_PEM | PtH_SOEC | PTH_SR | PtM_cat | PtM_bio |
|---|---|---|---|---|---|
| Mean [kg $CO_{2,eq}$/MWh regX] | 106.000 | 128.000 | 223.333 | -161.667 | -170.333 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.318 | 0.384 | 0.670 | -0.485 | -0.511 |
| Standard deviation [kg $CO_{2,eq}$/MWh regX] | 47.333 | 42.667 | 67.000 | 234.333 | 225.000 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.142 | 0.128 | 0.201 | 0.703 | 0.675 |
| 5% percentile [kg $CO_{2,eq}$/MWh regX] | 34.000 | 65.000 | 117.000 | -486.000 | -485.667 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.102 | 0.195 | 0.351 | -1.458 | -1.457 |
| 95% percentile [kg $CO_{2,eq}$/MWh regX] | 183.000 | 200.333 | 336.333 | 275.000 | 240.667 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.549 | 0.601 | 1.009 | 0.825 | 0.722 |
| Median [kg $CO_{2,eq}$/MWh regX] | 104.667 | 126.000 | 223.000 | -190.000 | -194.667 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.314 | 0.378 | 0.669 | -0.57 | -0.584 |
| Minimum [kg $CO_{2,eq}$/MWh regX] | 22.000 | 47.000 | 78.667 | -573.000 | -569.000 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.066 | 0.141 | 0.236 | -1.719 | -1.707 |
| Maximum [kg $CO_{2,eq}$/MWh regX] | 214.667 | 240.667 | 434.333 | 527.000 | 489.000 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.644 | 0.722 | 1.303 | 1.581 | 1.467 |
| LCA, total emissions [kg $CO_{2,eq}$/MWh regX] | 72.453 | 84.67 | 183.597 | 337.903 | -333.407 |
| *[kg $CO_{2,eq}$/$Nm^3$ regX]* | 0.217 | 0.254 | 0.551 | -1.014 | -1.000 |

### B.3.2 Comparison with Literature

Table 65: Total results *PtH_PEM* from literature

| *Total emissions PtH_PEM* | *Conversion factors* | *Result* *[kg $CO_{2,\,eq}$/MWh reg$H_2$]* | *Reference* |
|---|---|---|---|
| Savings by feed-in of $H_2$ into natural gas grid: 0.1 - 0.2 t $CO_{2,\,eq}$/MWh surplus energy | 18 - 22 kg $H_2$/MWh electricity | -224.859 | Sternberg 2015 [17, pp. 392, 397] |
| Electricity supply from wind power: 5.04E-03 - 3.07E-02 kg $CO_{2,\,eq}$/MJ $H_2$ | - | 64.332 | Zhang 2017, wind [64, L. 63] |
| Electricity supply from solar power: 2.52E-02 – 6.48E-02 kg $CO_{2,\,eq}$/MJ $H_2$ | - | 162.000 | Zhang 2017, PV [64, L. 63] |
| Electricity supply from ENTSO-E: 0.248 kg $CO_{2,\,eq}$/MJ $H_2$ | - | 892.800 | Zhang 2017, EU [64, L. 63] |
| Electricity supply from wind power: 970 g $CO_{2,\,eq}$/kg $H_2$ | - | 29.082 | Cetinkaya 2012, wind [58, p. 2078] |
| Electricity supply from solar power: 2412 g $CO_{2,\,eq}$/kg $H_2$ | - | 72.315 | Cetinkaya 2012, PV [58, p. 2078] |
| Electricity from EU mix: 209 g $CO_{2,\,eq}$/MJ $H_2$ | - | 754.289 | Edwards 2013, EU [43, p. 134] |

Table 66: Total results *PtH_SR* from literature

| *Total emissions PtH_SR* | *Conversion factors* | *Result* *[kg $CO_{2,\,eq}$/MWh reg$H_2$]* | *Reference* |
|---|---|---|---|
| 0.133 kg $CO_{2,\,eq}$/MJ $H_2$ | - | 478.800 | Zhang 2017 [64, L. 63] |
| 0.3 kg $CO_{2,\,eq}$/$Nm^3$ $H_2$ | - | 100.000 | Dufour 2012 [59, p. 1179] |
| 11893 g $CO_{2,\,eq}$/kg $H_2$ | - | 356.566 | Cetinkaya 2012 [58, p. 2078] |
| Steam methane reforming without carbon capture: 11.5 kg $CO_{2,\,eq}$/kg $H_2$ | - | 344.784 | Salkuyeh 2017 [60, p. 18906] |
| 73 - 86 g $CO_{2,\,eq}$/MJ $H_2$ | - | 286.200 | Edwards 2013 [43, p. 129] |

Table 67: Total results *PtM_cat* from literature

| *Total emissions PtM_cat* | *Conversion factors* | *Result* *[kg $CO_{2, eq}$/MWh $regCH_4$]* | *Reference* |
|---|---|---|---|
| Savings by feed-in of $H_2$ into natural gas grid: 0.03 - 0.15 t $CO_{2, eq}$/MWh surplus energy | 0.33 $kWh_{el}$/kg $CH_4$ | -2.138 | Sternberg 2015 [17, p. 397], [65, p. 2] |
| Electricity supply from wind power: 33 g $CO_{2, eq}$/kWh fuel | - | 33.000 | Sterner 2017 [27, p. 466] |