D5.1 Assessment of integrated concepts and identification of key factors and drivers

Deliverable:	*D5.1 Assessment of integrated concepts and identification of key factors and drivers*
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Executive Summary

The development of a sustainable European energy system that is in line with ambitious targets for climate protection and contributes to the UN Sustainable Development Goals is a challenge, which requires manifold actions from policymakers, science and Industry. The REGATRACE Project aims to support the international trade of sustainable renewable gases which can be considered one important element towards long-term strategies for a sustainable energy system. Within REGATRACE, WP5 analyses potential promising technologies for the production of renewable gases and identifies sensitive issues and open questions related to the assessment and sustainability certification of renewable gases. This report is the first of three deliverables from this work package. It includes a discussion of the GHG calculation methodology for renewable energy carriers under the RED II framework, as well as an analysis of existing results regarding the costs and GHG emissions of different renewable gas technologies.

The assessment of the cost and GHG emission intensities based on generic data and literature revealed rather large result ranges. Furthermore, the analysis shows a significant influence of regional or spatial aspects on the assessment results. As for Biomethane from Biogas upgrading, the type of feedstock used is of high importance regarding the GHG emission and costs. Since local or regional feedstock availabilities, as well as costs can vary significantly across the EU, ideal or optimise technology and feedstock combinations, as well as the resulting costs and GHG emission intensities of Biomethane concepts can also be very different across EU member states.

In general, the production of Biomethane from wastes and residues can be relatively advantageous with regards to the GHG emission intensity compared to the use of energy crops. In particular, the use of manure and or slurry can be a very promising option, since the GHG calculation approach under the RED II framework allows for a consideration of a GHG credit for these substrates. This credit, which can largely affect the result of the GHG balance of the Biomethane produced from manure acknowledges GHG emissions that might be avoided due to the substitution of the conventional storage of manure in agricultural systems. Furthermore, regarding the cultivation of biomass feedstock for Biomethane production, regional characteristics such as biomass yields or soil conditions, influencing for example N_2O emissions can be important parameters influencing the overall GHG emission intensity. Additionally, various approaches and starting points do exist for further optimisation of the GHG emission performance along the Biomethane supply chain. These include amongst other parameters such as the choice of fertilisers, the concept for the supply of process energy for the Biogas and Biomethane processing units, methane emissions from Biogas production, non-CO_2 emissions from CHP units as well as the storage systems for the Biogas digestate.

As for the production of hydrogen, the specific characteristics and upstream emissions of the feedstock used (currently) lead to significant differences regarding the GHG emissions of hydrogen from electrolysis (e.g., from sourced from the public grid) compared to a production based on steam reforming (e.g., from natural gas). However, depending on the future development of the energy sector and the decarbonisation of electricity and gas production, these differences might decrease over time, resulting in low or almost net-zero emissions. Similarly, as for PtG production, especially the price (and the upstream emissions) for the electricity used as well as the CAPEX for the PtG plants are the most relevant factors influencing costs and the GHG emission intensity.

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The assessment revealed substantial differences regarding the short-term availability, as well as the market-readiness and the current competitiveness of the technologies analysed. While the production of Biogas and Biomethane from Biogas upgrading is a well-established technology, which is widely implemented in different EU member states, concepts for the production of (Bio-) synthetic natural gas (i.e., from biomass gasification), Power-to-Gas or Hydrogen from renewable electricity or biomethane are currently not (widely) available in the market, mostly due to comparably higher production costs. However, several publications argue that production costs of especially Hydrogen from renewable sources, as well as PtG production, might decrease significantly in the future, depending on the development of factors such as electricity prices and CAPEX of Hydrogen and PtG production plants.

Consequently, for the development of short-term strategies for the production of renewable gases existing capacities of Biogas and biomethane production in the EU can be a starting point, both for the production of Biomethane as well as sustainable biogenic CO_2 which can be sourced from Biogas upgrading. Depending on the local availability of biomass feedstock as well as the political frame conditions, these installed capacities might increase in the future in different member states. Secondly, existing and potential future capacities for the production of renewable electricity can be another important element to identify regions with potentially high availability of both, biogenic CO2 from Biomethane production as well as renewable electricity production. Depending on the future development of CAPEX for Hydrogen from electrolysis, as well as PtG production and the development of electricity and CO_2 prices, these identified regions could become potential hot spots for an additional production of renewable gas, based on the coupling of existing electricity and CO_2 potentials.

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Table of Content

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Abbreviations

CSP	Concentrated Solar Power
GHG	Greenhouse gas
GO	Guarantee of Origin
ISCC	International Sustainability and Carbon Certification
ISO	International Standard Organisation
LCA	Life Cycle Assessment
MJ	Megajoule
PoS	Proof(s) of Sustainability
PPA	Power Purchase Agreement
PtG	Power-to-Gas
PtX	Power-to-X
PV	Photovoltaic
RE	Renewable Energy
RED	Renewable Energy Directive 2009/28/EC
RED II	Renewable Energy Directive 2018/2001/EC
RES-E	Renewable energy sources for electricity
SDGs	Sustainable Development Goals
SNG	Synthetic Natural Gas

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REGATRACE in a Nutshell

REGATRACE (REnewable GAs TRAde Centre in Europe) aims to create an efficient trade system based on issuing and trading biomethane/renewable gases certificates/Guarantees of Origin (GO) with exclusion of double sale.

This objective will be achieved through the following founding pillars:

- European biomethane/renewable gases GO system
- Set-up of national GO issuing bodies
- Integration of GO from different renewable gas technologies with electric and hydrogen GO systems
- Integrated assessment and sustainable feedstock mobilisation strategies and technology synergies
- Support for biomethane market uptake
- Transferability of results beyond the project's countries

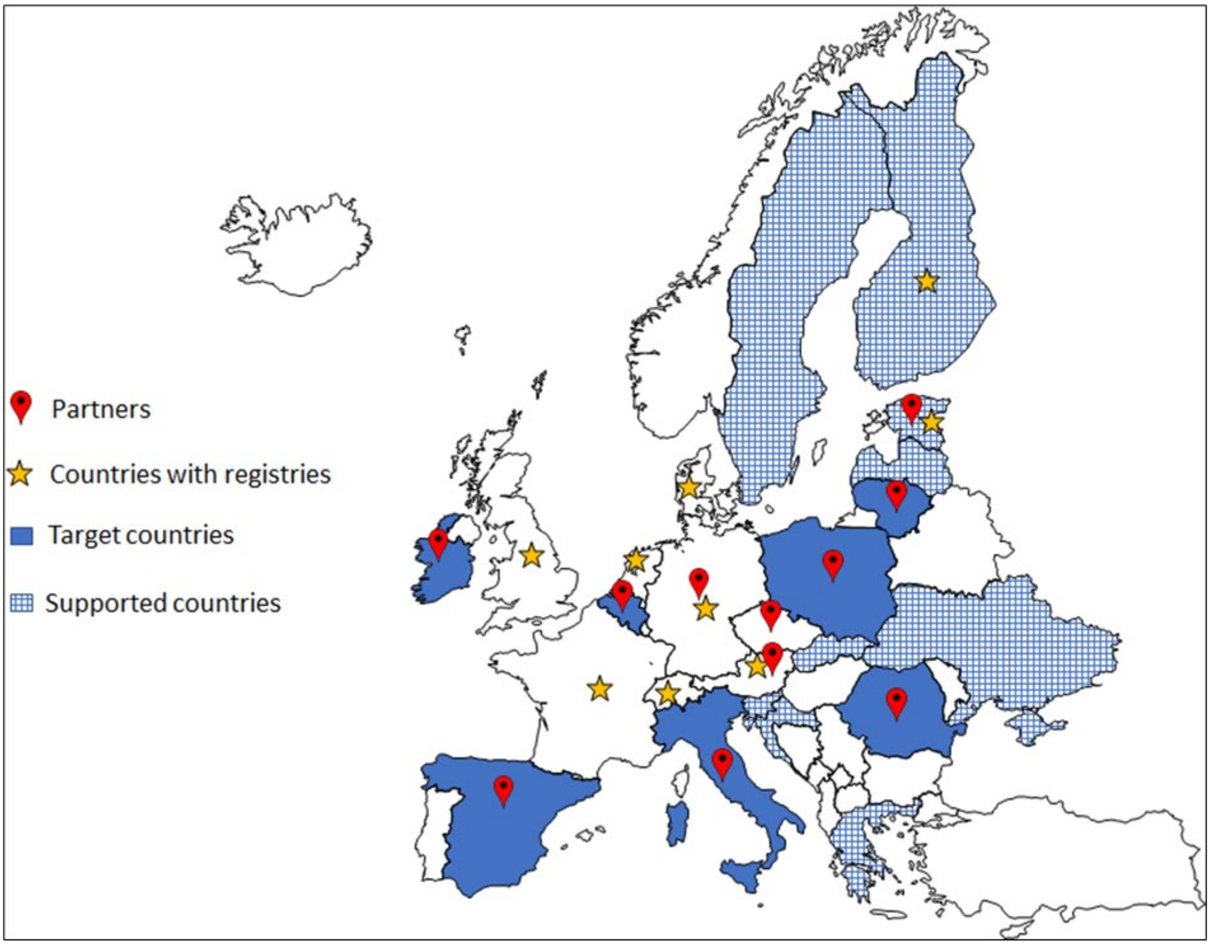

Figure 1: REGATRACE countries and partners

The network of issuing bodies will be established by including existing national biomethane registries (Austria, Denmark, Estonia, Finland, France, Germany, The Netherlands, Switzerland, and UK) and by creating issuing bodies in the Target countries of the project (Belgium, Ireland, Italy, Lithuania, Poland, Romania, and Spain).

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Moreover, REGATRACE will prepare the ground for setting-up national biomethane registries in other 7 Supported countries (Croatia, Czech Republic, Greece, Latvia, Slovakia, Slovenia, Sweden, and Ukraine).

Using a participatory process involving several stakeholders, REGATRACE will develop strategic visions and national roadmaps to boost the biomethane market.

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1 Introduction

Supporting the transformation and conversion of the EU energy system towards to use a sustainable feedstock and technology base, which is in line with international targets for the reduction of GHG emissions and objectives such as the Sustainable Development Goals (SDGs) requires manifold actions from science, policymakers and stakeholders from the industry.

The REGATRACE project is supporting this development by contributing elements to foster trade of renewable gases amongst EU member states and thus, enabling a more efficient coupling of energy and industry sectors in the EU. However, as recognised by the EU Commission with the introduction of the Renewable Energy Directive, renewable energy technologies are not per se sustainable.

To develop a political framework for the sustainable transformation of the EU Energy system, it is of high importance to understand potential risk and impacts related to the development of renewable gas technologies as well as to develop associated strategies for risk and impact mitigation.

1.1 The objectives of WP5 within the REGATRACE project

While REGATRACE in general deals with several topics to support the trade of Renewable Gases in the EU, **REGATRACE WP 5 will address selected aspects related to the sustainability of Renewable Gases.**

These aspects will include:

- **The identification of promising technologies and concepts** for the production of biomethane (both from anaerobic digestion and gasification) and Power-to-Methane. This identification will be based on the potential **GHG intensity** as well as the **costs of renewable gas production**. The assessment of both indicators will be based on a twofold approach. The first step, which is subject to this report **D5.1, will focus on general trends and lessons learned from literature data and published information.** Also, **key drivers and influencing factors will be discussed**. The second step will **include a number of regional case examples** for single technologies which can be used to produce renewable gas, or which could potentially be coupled to create synergies in the future. **Main focus of D5.2**.
- The **identification of potential hotspots for physical links between technologies** for renewable gas production in the EU. **Main focus of D5.2.**
- Finally, **open questions and potential barriers for the sustainability assessment and certification** of Power-to-Methane concepts shall be analysed and appropriate solutions will be developed. **Main focus of D5.3.**

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1.2 Main objectives of Deliverable 5.1

This Deliverable aims to build a foundation for achieving the above mentioned WP5 targets.

In that sense, **Deliverable 5.1 focusses on GHG emissions and costs of generic pathways for the production of renewable gas** via, i) the bio-chemical conversion to Biogas and the subsequent upgrading to biomethane, ii) the production of methane from the gasification of biomass, iii) the production of hydrogen from electricity (electrolysis) and gaseous energy carriers (natural gas and biomethane via steam reforming) as well as iv) the production of synthetic natural gas from CO_2 (different CO_2 sources) and hydrogen produced from electricity.

Since **all of these technologies include complex supply chains with different regional or spatial characteristics** (e.g., regional feedstock preferences and yields, soil-climatic conditions, conversion efficiencies, regional supply and demand patterns, etc.), statements on GHG intensities and costs cannot be given as absolute ratings. Rather contrarily, they do in general reflect all regional specifics of the assessed technological pathway, which is reflected by assumptions on feedstock yields, conversion efficiencies, etc. Thus, results from the assessment of the same technologies, implemented in different regions can be substantially different. **For this reason, the discussion of GHG and cost indications of renewable gas technologies included in this deliverable 5.1 aims to analyse general trends and drivers influencing both indicators.**

Since **the recast of the renewable energy directive (RED II) is about to be implemented in EU member states, the framework for the assessment of GHG emissions** from renewable gases which need to prove compliance with the RED II **will become more and more relevant for producers and stakeholders of markets for renewable gases.** The RED II aims for a harmonisation of the respective GHG emission calculations in order to allow for comparability with default values, comparator values as well as a direct comparison between direct market competitors (e.g., producers of Biomethane as a transportation fuel in a GHG quota system). Since **only very few experiences do exist with the implementation of the RED II GHG emission calculation methodology**, we have decided to dedicate **one chapter of this report to discuss a potential way of applying the abstract methodologies included in the RED ii Annexes.**

Finally, **Deliverable 5.1 prepares the discussion of potential issues and difficulties which can or could occur during the sustainability certification and GHG emission calculation** of renewable gas technologies under the RED II framework. This discussion is the main subject to the final Deliverable 5.3 of WP5.

1.3 Technologies and concepts to be considered in WP5

To identify potentially competitive technologies for the production of renewable gases in the short, medium and long turn (e.g., in the 2030 and 2050 timeframe) in the EU and specifically in the REGATRACE we are considering both, already existing technologies (e.g., Biogas and Biomethane) as well as technologies which are not yet implemented in the market at a large scale (e.g., Bio-SNG), as well as combinations of different technological components (e.g., Power-to-Gas).

Throughout REGATRACE WP5, we are aiming to describe technologies and technology combinations that are feasible for specific countries and regions, based on aspects such as GHG mitigation

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potentials, costs as well as regional availabilities (e.g., already installed, or anticipated production capacities of Biogas/Biomethane or renewable electricity).

Our starting point for this identification is the analysis of the main drivers or decisive factors which drive costs or the GHG intensity of these technologies. This discussion, which is based mostly on generic data is the main focus of this deliverable. The general concept for the production of Power-to-Gas, illustrated in Figure 2 shows our basic framework for the derivation of technologies and technology combinations to be considered. This framework includes the production of electricity based on renewable sources such as wind or solar power, the production of hydrogen from this renewable electricity, the production of biomethane from either Biogas upgrading or the gasification of biomass (Bio-SNG) as well as the combination of hydrogen and carbon dioxide (e.g., from the Biogas process) to produce Power-to-Gas (i.e., methane).

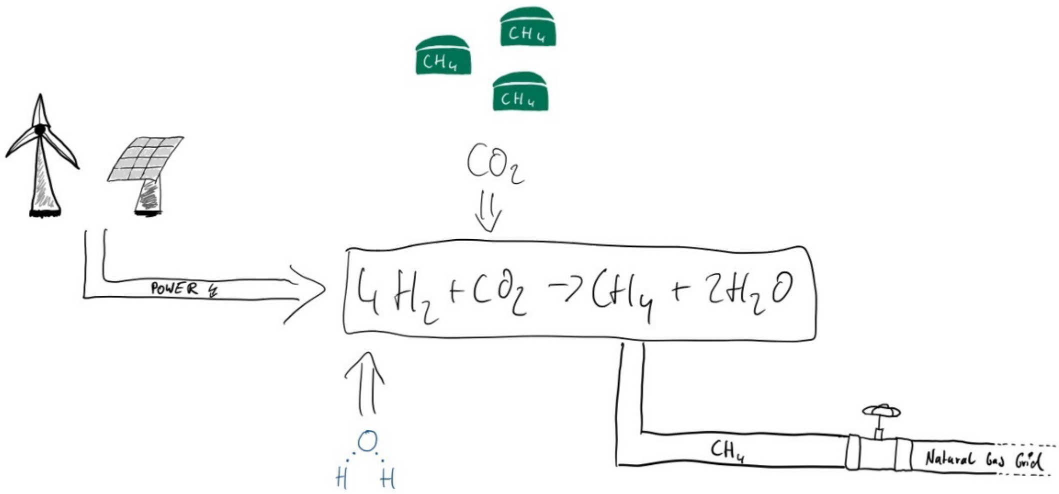

Figure 2 General concept of technology combinations for Power-to-Gas production

Thus, in general the assessment in WP 5 will include three broader groups of technologies as well as their combinations. These groups include:

- Biogas and Biomethane from biogenic feedstocks
- Biomethane from the gasification of biomass
- Hydrogen produced from electricity (via Electrolysis) or gaseous energy carriers (natural gas and Biomethane)
- Power-to-gas from Hydrogen and CO_2.

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2 GHG emission calculations in sustainability certification

This chapter discusses the methodology for the calculation of GHG emissions under the RED II framework. It includes a proposal for the application of the RED II methodology as well as an exemplary calculation, aiming to illustrate the methodological proposal.

2.1 Introduction to the assessment of GHG emissions from bioenergy systems

In general, a wide range of methodologies, tools and standards is available to calculate the climate effects of bioenergy. Existing approaches include scientific standards such as the ISO 14040 and ISO 14067:2018 as well as a vast number of tools with different scopes such as for example the GHG protocol tools or calculators such as BioGrace I & II, Greet, GaBi and others. Existing methodologies and tools do differ, mostly regarding their scope and consequently regarding aspects such as system boundaries, emission factors, characterisation factors, impact assessment methodologies and general assumptions on efficiencies, yields and several others. The differences between some of these tools are subject to a number of research activities such as for example the work conducted by (Pereira et al. 2019).

The REGATRACE project focusses on the policy framework in the EU and EU member states and aims to support the market development for and trade of renewable gases. Thus, the renewable energy directive II (RED II) is an important regulatory instrument for the development of the respective regulatory framework, ensuring a sustainable basis for the production and trade of renewable gases. The RED II sets a framework for the calculation of GHG emissions of bioenergy pathways that need to proof compliance with the GHG mitigation criteria of the RED II. While the actual implementation of the RED II is not completed in most EU member states (as of April 2021), experience from certification and auditing practices under the renewable energy directive is still lacking. Due to the importance of the RED II, the theoretical methodological basis for GHG assessment of Bioenergy carriers included in RED directive is our main focus and guideline for the GHG assessment in WP5 of REGATRACE. Thus, we will focus mainly on the discussion of the RED methodology. However, since the implementation of the RED II and their respective GHG assessment methodology is still outstanding, we are also using results from publications based on other methodological approaches such as life cycle assessment (LCA) for the results presented in chapter 3.

2.2 Methodology for the assessment of GHG emissions in the RED framework

In 2009, the European Union (EU) introduced the Renewable Energy Directive (RED) with the main purpose to promote the use of energy from renewable sources. The directive is particularly important for bioenergy, as it defines uniform sustainability criteria for biofuels and bioliquids. Fulfilment of the criteria is not obligatory. However, it is a prerequisite to count the contribution of a bioenergy carrier towards the targets of the directive. For biofuels in the EU transport sector, this regulation has led to the creation of a market for sustainable transport fuels, in compliance with the RED, where compliance is in most cases demonstrated by independent certification schemes.

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Responsibility for implementing the directive lies with the EU Member States, which transposed the RED into national law. The RED uses a co-regulation approach, which allows the control of compliance with the sustainability criteria of the directive by private certification schemes. These schemes must be recognised by competent national authorities and by the EU Commission (COM). In order for a biofuel that is to be placed on the market to be classified as "sustainable", all interfaces of the value chain along the life cycle of the fuel must be certified. This concerns biomass producers, traders, processors and mineral oil companies. Auditing and certification are usually being organised by certification bodies that are approved and controlled by the competent national authorities and the respective certification schemes (please see also REGATRACE D4.1; Chapter 3.2.; Proof of Sustainability) (Sailer et al. 2021).

In 2018, the revised Renewable Energy Directive (RED II) was adopted (European Commission European Commission: Brussels, Belgium, 2018). This recast of the RED covers the time period from 2021 to 2030. In principle, the RED II continues the basic rationale of the sustainability criteria but introduces additional criteria and expands the scope. As a result, electricity, heating and cooling from solid and gaseous biomass fuels must also meet the sustainability criteria according to RED II if they shall be counted towards the RED II targets. However, the scope of application seems to be limited to plants above 2MW for gaseous biomass fuels and 20MW for solid biomass fuels (but member states might change this threshold in the national implementation). As a result, national legislation, certification systems and methods for operationalising the requirements must be adapted or created and developed.

This chapter discusses the methodological basis for the assessment of GHG emissions and the proof of compliance with the GHG reduction criteria under the RED II framework with a special focus on the application for Biogas and Biomethane.

2.2.1 General approach to GHG accounting in the context of RED II

The approach to GHG accounting in RED II is based on the general rationale of the life cycle assessment (LCA) methodology. However, LCAs can be extensive and complex and require in-depth knowledge and experience depending on the specific scope and field of application. The aim of the RED II GHG calculation approach is to provide a basis and framework to produce robust and comparable results in the context of the practice of certification schemes and bodies. This includes a number of simplifications, which result in a strong focus on the material and energy flows of the analysed supply chains. On the other hand, materials as for example cement and steel which can be needed to produce the processing plants for bioenergy production are not included in the GHG emission calculations under the RED II framework.

The basic approach can be described in three steps (compare Figure 3).

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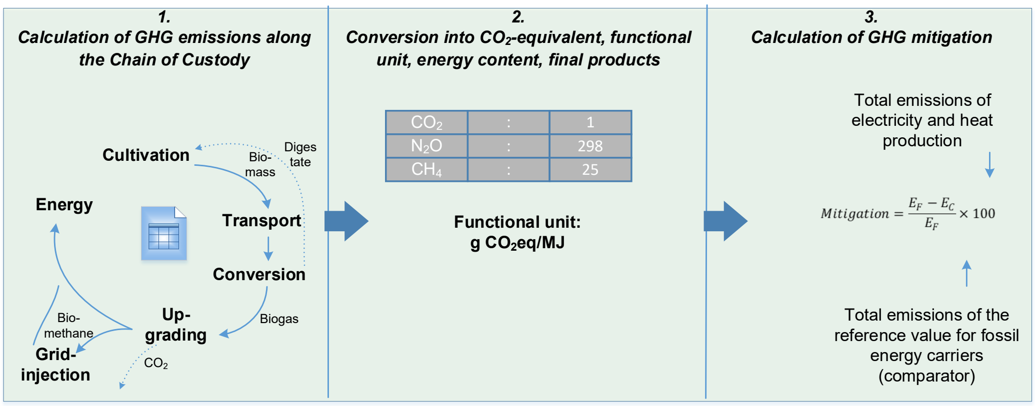

Figure 3 general procedure of GHG calculations according to RED II in three superordinate steps.

- In the first step, the greenhouse gas emissions are being calculated based on the relevant inputs and outputs of all processes in the chain of custody of a bioenergy carrier.
- The second step involves harmonising the partial results to a uniform reference value, the so-called functional unit: g CO_2eq/MJ. If the results of the sub-processes are added up, the value for the GHG emissions potentially caused in the life cycle of the product (electricity, heating or cooling) is obtained.
- In the last step, the GHG emissions are compared to those of a fossil reference value (comparator) and thus the GHG emission saving is calculated. The saving is the subject of the criterion from RED II. For the different products of the Biogas and Biomethane value chains, RED II defines emission savings that must be achieved so that energy can be RED II-compliant and thus classified as "sustainable".

According to the requirements of RED II, a distinction can be made between three different procedures for calculating GHG savings.

1. Default values can be used to demonstrate compliance with the required GHG emission savings. A number of default values for various bioenergy carriers is included in Annex VI A of the Directive. A distinction is made between default values and disaggregated default values. Default values specify the GHG emissions and emission savings for a defined value chain. Their use can be convenient and efficient, since no calculation has to be carried out by market actors.
2. Alternatively, emissions can be calculated individually, based on actual information of the market actors.
3. Thirdly, a combination of disaggregated default values for single processes (e.g. Transport or Processing) can be combined with the calculations based on actual information. The disaggregated standard values provide the GHG emissions of individual interfaces in the value chain. Thus, this combination can allow to understand the GHG emission saving of the entire value chain.

Especially in the first few years after the introduction of the RED I, market actors in the transport sector mainly used the existing standard values. A main reason for this was that the dominant biofuel options in the transport sector (i.e., bioethanol and biodiesel) are mostly based on a limited amount of feedstock options which are mostly covered by the existing default values. Furthermore, the GHG emission saving thresholds to be demonstrated have been comparatively low. However, due to the rather conservative assumptions behind the default values, individual calculations can often yield higher savings.

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As it was in most cases possible for market actors to prove compliance with the required GHG emission savings in the RED I just based on the use of default values, the motivation to calculate GHG emissions individually was often low. However, there are examples such as the change of the biofuel quota regime in Germany, which introduced a strong inventive for market actors to use individual calculations in order to demonstrate the highest possible GHG reduction.

Biogas and Biomethane production across Europe is based on a wide range of different feedstocks, however, the RED II does only provide a small number of default values for Biogas and Biomethane substrates. Depending on the actual implementation of the RED 2 in the different member states, it can be assumed that individual calculation will increase in the context of the future certification of Biogas and biomethane plants and batches.

Default values are available for Biogas used for electricity generation and for biomethane used as a fuel in the transport sector. The input data for the existing Biogas and Biomethane default values are published in (European Commission. Joint Research Centre. 2017), (European Commission. Joint Research Centre. Institute for Energy and Transport. 2014).

Where digestate from Biogas production is dried on the site of the biodigester, the default values differ for Biogas used for electricity generation, depending on the energy provision towards and the type of digestate storage (open or covered) and with regard to the following three cases:

- Process electricity and heat for the Biogas facility provided internally by the own CHP plant.
- Process electricity for the Biogas facility sourced from the grid, process heat supply provided internally.
- Process electricity for the Biogas facility sourced from the grid, process heat supply provided by a Biogas boiler.

Furthermore, the existing standard values for biomethane distinguish four cases:

- Open digestate storage, no flue gas combustion
- Open digestate storage, flue gas combustion
- Closed digestate storage, no flue gas combustion
- Closed digestate store, flue gas combustion

In addition, all default values for both Biogas and Biomethane represent only three feedstocks and feedstock combinations, differentiated by the sectors of bioenergy provision and use:

- Biogas for electricity generation (manure, maize, bio-waste; manure/manure-maize (80%/20%), manure/manure-maize (70%/30%), manure/manure-maize (60%/40%)).
- Biomethane for transport (manure, maize, bio-waste; manure/manure-maize (80%/20%), manure/manure-maize (70%/30%), manure/manure-maize (60%/40%))

Reviewing the standard GHG emission values in existence, it becomes clear that two major drivers influence the magnitude of emission savings. On the one hand, the effect of the digestate storage cover is clearly visible. Secondly, the type of substrate plays a major role. Higher proportions of manure/slurry have a strong effect on the result.

2.2.1.1 Calculating GHG emissions along the Biogas and Biomethane process chain

The methodological basis of the RED II for calculating greenhouse gas emissions from the production of biofuels is provided by Equation 1 (RED II, Annex VI B,1). The equation represents the basic elements

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of the supply chain to be considered. The individual terms represent potential sources of emissions that occur in the respective life cycle phases and contribute to the total emissions. In addition, measures which can lead to additional emission savings are being included. Greenhouse gas emissions from the production and use of biomass fuels (before conversion into electricity, heating and cooling), are calculated according to the following formula:

Eq. 1 $$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$$

Where:

E	total emissions from the use of the fuel;
e_{ec}	emissions from the extraction or cultivation of raw materials;
e_l	annualised emissions from carbon stock changes caused by land-use change;
e_p	emissions from processing;
e_{td}	emissions from transport and distribution (including emissions from the transport of Biomethane in the grid);
e_u	emissions from the fuel in use;
e_{sca}	emission savings from soil carbon accumulation via improved agricultural management;
e_{ccs}	emission savings from CO_2 capture and geological storage; and
e_{ccr}	emission savings from CO_2 capture and replacement.

In order to calculate the emissions for the different process steps (emissions for cultivation, transport, processing, etc.), all relevant inputs and outputs of the respective sub-process need to be described and considered. The inputs include material flows (e.g. seeds, fermenter additives, etc.) and energy (e.g. diesel, electricity) and are multiplied by a corresponding emission factor:

Eq. 2 $$e_x = Input_{material,energy} \times EF$$

In the methodological framework of RED II, emissions associated with the production of processing facilities and the equipment used are not considered (RED II; Annex VI B. 1. a)) and are therefore outside the defined system boundaries (cf. Figure 4).

Furthermore, it is possible to define "cut-off criteria" which define a certain threshold under which specific inputs will not be considered in the calculations. This can be particularly useful if inputs have a very small influence on the result and their inclusion unnecessarily increases the effort of data collection and the complexity of the calculations. The RED II does not specifically define cut-off criteria. With regards to the RED I, the COM Communication 2010/C 160/02 ((European Commission 2010), states the following, rather vague guidance: "It does not seem necessary to include inputs that have little or no impact on the outcome, such as chemicals used in small quantities during processing."

More precise guidance is found in the Biograce calculation rules: "If the contribution of the input or process to the total biofuel life cycle emissions is less than 0.1g CO_2eq/MJ biofuel, it can be truncated." (Biograce Consortium)

It should be noted that these are not binding rules and the assessment of the completeness of the inputs and processes included in the balance in the certification process ultimately lies with the auditors and certification bodies.

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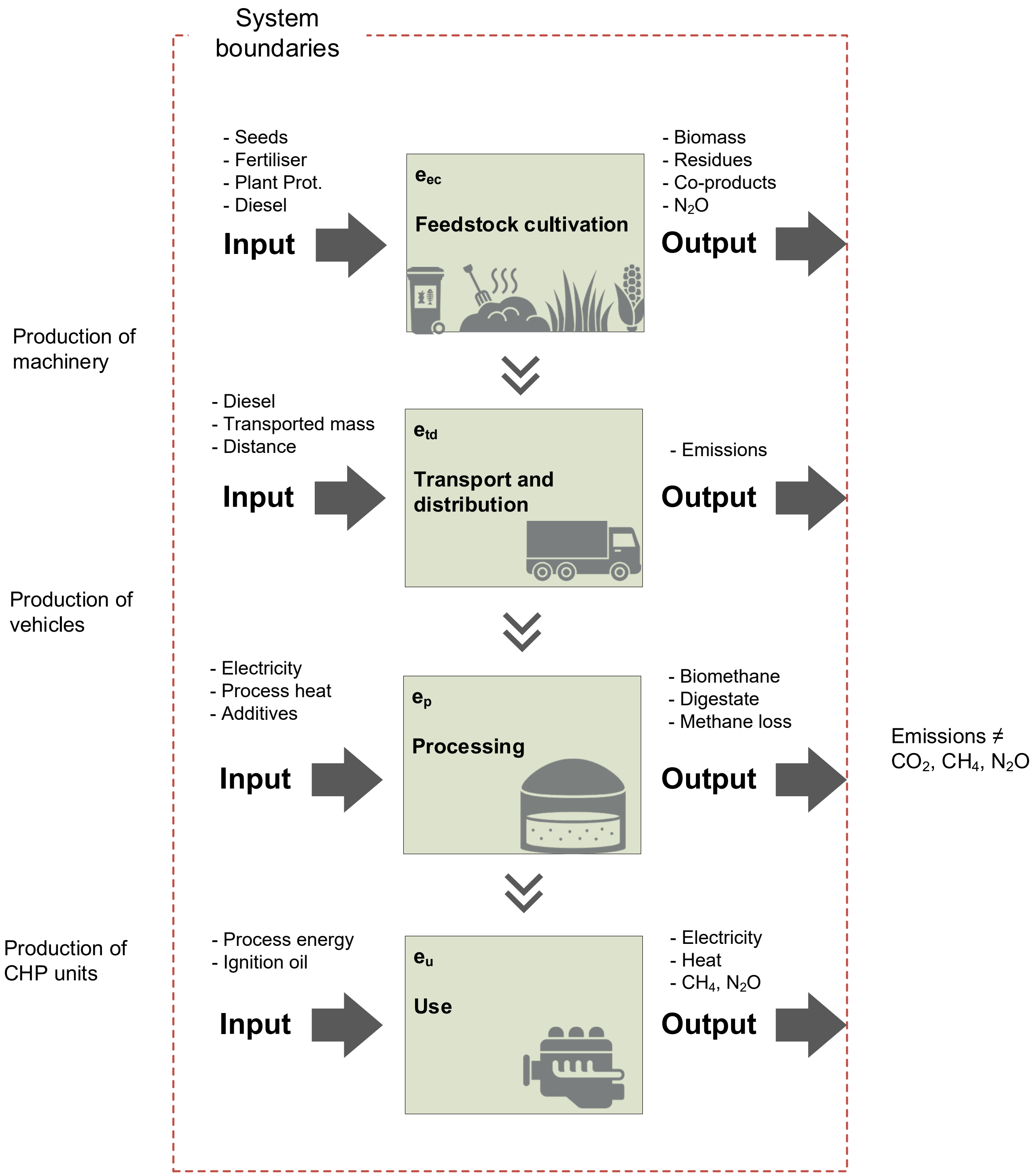

Figure 4 Illustration of a process chain for energy production from biogas and biomethane with the most important input and output flows and the system boundary.

2.2.1.2 Calculation based on actual values (individual calculations)

Emissions from cultivation of biomass (e_{ec})

In the first step of balancing, the feedstock used (for, in our case, biomethane production) has to be characterised in order to differentiate between wastes and residual materials as well as cultivated biomass. The first interface of the supply chain, in the case of the use of cultivated biomass as a substrate, is biomass cultivation. If, on the other hand, it is a value chain based on waste and residues, this has an influence on the balancing. In some cases, it may not be clear at first whether a given raw material is to be assigned to the category "waste and residues". In order to address this issue, the European Commission (COM) has published a decision guidance document which, although it refers to the first version of the RED that is currently still valid, continues to provide guidance for this purpose.

The classification is of significance since residues and waste materials can be used for biofuel production without any accounting for upstream emissions.

In case energy crops are being used for bioenergy production, all processes during crop production processes must be considered.

In general, a uniform reference value should be used within the GHG balance, the so-called functional unit (FU). In the context of RED II, it is specified as MJ final energy product (electricity, heat or fuel). The result of the GHG balance (step 2; Figure 3) is to be stated accordingly in g CO_2eq/MJ.

When considering biomass cultivation, however, it can be advisable to first present the results for this process step in a mass-related reference value (e.g., per tonne of biomass). A conversion of the reference quantity from mass (t) to energy (MJ) is then carried out in a subsequent step, based on the physical characteristics (i.e., lower heating value) of the biofuel.

Main sub-processes of the biomass cultivation process can for example include soil cultivation, sowing, fertilisation, plant protection measures and harvesting. Often, literature values for their upstream chains and emission factors are used for the fertiliser, pesticide (e_{PPM})and seed production (i.e., the emission factors for these inputs). However, the consumption of input materials must be calculated individually and depends, for example, on the actual distances, the tillage and plant protection measures carried out and their frequency, the type of machinery used as well as the use of fertiliser, etc.

The greenhouse gas emissions generated for raw material extraction (or biomass cultivation) can be calculated by the ratio of the sum of the emissions from the sub-processes and the yield per unit area according to equation 3:

Eq. 3: $$e_{ec} = \frac{e_{fertiliser} + e_{PPM} + e_{Fuel} + e_{Seeds} + e_{Soil\ emissions}}{Yield_{Biomass}}$$

This way, the emissions from the sub-processes (or the use of different materials and energy carriers) are related to an area unit and year and are expressed in the unit kg CO_2eq/ha*a. Based on the yield of the respective area, results can be easily converted to kg CO_2eq/kg biomass.

If GHG emission values have to be calculated for cultivation, this usually has to be done on a plot-by-plot basis. If necessary, plots with the same cultivation system and the same yield can be aggregated. It should be noted that the GHG intensity must be reported for substrate separately.

The emissions from the sub-processes (i.e., the use of the different materials and energy carriers) result from the input flow into the sub-process (substance or energy) and the respective emission factor, which is taken from the literature.

The use of so-called emission factors allows the inclusion of emissions from the upstream processes (i.e., the production of e.g., a fertiliser) in the GHG balance of a process step in addition to the GHG emissions from the actual use of these materials (e.g., the application of a fertiliser or the combustion of an energy carrier). This means that emissions from the production of fertilisers, pesticides, seeds

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and energy sources (e.g., diesel) are usually considered by the use of emission factors. The greenhouse gas emissions caused by the production of machinery (agricultural tractors, harvesters, etc.) are not included in the balance (cf. Figure 2).

The use of digestate as fertiliser

The use of digestate as a fertiliser is a typical use case, especially for Biogas and Biomethane facilities that are integrated in agricultural production processes. If a digestate is applied on land in order to produce biomass for Biogas and biomethane production, this can have a positive effect on the fertiliser management scheme on the respective agricultural land. More precisely, the use of digestate might reduce the demand for synthetic fertiliser inputs and can thus reduce emissions from mineral fertiliser production at the same time. However, nitrous oxide emissions from the application of digestate have to be considered, as shown in the following section.

Calculation of nitrous oxide emissions from fertiliser application

Due to the impact of nitrous oxide on global warming, the consideration of nitrous oxide from nitrogen application in agricultural processes is of great importance. They contribute significantly to the total emissions from biomass production. Different approaches do exist for their quantification, whereby in the context of RED II, the GNOC model and the IPCC Tier 1 approach are the most relevant and recognised methods (Joint Research Centre; IPCC 2006, 2019). With GNOC ("Global Nitrous Oxide Calculator"), the EU Commission has provided a tool that can be used to calculate N_2O emissions for a selection of feedstocks on a site-specific basis. However, since the selection of feedstocks in GNOC is limited, for some Biogas and Biomethane pathways, a consideration of the IPCC methodology can be meaningful.

The general approach of a calculation according to the IPCC Tier 1 method for mineral soils, differentiated between direct and indirect emissions, is presented below. The method was adjusted according to the specific requirements of the Biogas and Biomethane production (in particular, emissions from nutrient inputs from grazing animals were not considered here). (IPCC 2006, 2019)

Direct N_2O emissions

Direct N_2O emissions are calculated using the following equation:

Eq. 4 $$N_2O_{Direct} - N = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_1 \text{ x } 44/12$$

Where:

N_2O_{Direct}-N	annual direct N_2O-N-emissions from agricultural soils, kg N_2O-N/a
F_{SN}	annual amount of applied synthetic fertiliser, kg N/a
F_{ON}	annual amount of organic fertiliser (e.g., compost, sewage sludge, etc., kg N/a)
F_{CR}	annual amount of nitrogen from crops (above and below ground), kg N/a
F_{SOM}	annual amount of mineralised nitrogen as a consequence of carbon stock losses due to land use change of soil management, kg N/a
EF_1	emission factor for N_2O emissions from nitrogen inputs kg N_2O-N/kg N input
44/12	Conversion factor from N_2O–N to N_2O

The term F_{ON} is based on the annually applied quantities of farm manure (with the exception of manure from grazing animals), compost, sewage sludge and other organic residues and waste used as fertiliser.

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The term F_{SOM} is only considered if there is a change in land use or a change in farming practices affecting soil carbon stocks and is calculated according to the following equation:

Eq. 5 $$F_{SOM} = \left(\Delta C_{Mineral,LU} \times \frac{1}{R}\right) \times 1000$$

In accordance with the procedure under RED II for carbon stock changes due to land use changes, the amount of mineralised nitrogen caused by a land use change is annualised over 20 years:

Eq. 6 $$F_{SOM} = \left(\Delta C_{Mineral,LU} \times \frac{1}{R}\right) \times \frac{1}{20} \times 1000$$

Where:

F_{SOM}	annual amount of mineralised nitrogen as a consequence of carbon stock losses due to land use change of soil management, kg N/a
$\Delta_{CMineral,\ LU}$	average annual loss of soil organic carbon, tonne C; equals (CS_R-CS_A)
R	C:N Ratio of the organic soil content.

Indirect N_2O emissions

A distinction is made between two pathways regarding indirect emissions:

- The volatilisation of nitrogen as ammonia (NH_3) and nitrogen oxides (NO_x) with subsequent deposition of these gases and their products NH_4^+ (ammonium) and NO_3^- (nitrate) in soils and waters.
- The leaching and surface runoff of nitrogen from soils with potential accumulation of ammonium and nitrate in groundwater or water bodies. Biological processes can convert ammonium and nitrate to nitrous oxide and release them into the atmosphere.

Indirect emissions from atmospheric deposition of fugitive nitrogen from managed land are calculated using the following equation:

Eq. 7 $$N_2O_{(ATD)} - N = [(F_{SN} \times Frac_{GASF}) + (F_{ON} \times Frac_{GASM})] \times EF_4 \text{ x } 44/12$$

Where:

$N_2O_{(ATD)}$-N	annual amount of N2O-N emissions from the atmospheric deposition of volatile nitrogen from farmed land, kg N_2O-N/a
F_{SN}	annual amount of synthetic nitrogen fertiliser applied, kg N/a
F_{ON}	annual amount of applied organic fertiliser, compost, sewage sludge, etc., kg N/a
$Frac_{GASF}$	proportion of nitrogen from synthetic fertiliser, volatilising to NH_3 and NOx, kg N volatile/kg N applied
$Frac_{GASM}$	share of nitrogen from organic fertiliser that volatilises to NH_3 and NOx, kg N volatile/kg N applied
EF_4	emission factor for N_2O emissions from atmospheric deposition to soils and waters, kg N_2O-N/kg NH_3-N+NOx-N volatilised
44/12	Conversion factor from N_2O–N to N_2O

Indirect N_2O emissions from leaching and surface runoff in regions where these processes occur are calculated according to the following equation:

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Eq. 8 $$N_2O_{(L)} - N = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times Frac_{LEACH-(H)} \times EF_5$$

Where:

$N_2O_{(L)}$-N	annual amount of N_2O-N emission due to leaching, runoff of nitrogen inputs on cultivated land in regions where leaching, runoff occurs, kg N_2O-N/a
F_{SN}	annual amount of applied synthetic fertiliser, kg N/a
F_{ON}	annual amount of applied organic fertiliser, compost, sewage sludge, etc., kg N/a
F_{CR}	annual amount of nitrogen from crops (above and below ground), kg N/a
F_{SOM}	annual amount of mineralised nitrogen as a consequence of carbon stock losses due to land use change of soil management, kg N/a
$Frac_{LEACH(H)}$	proportion of total nitrogen (applied & mineralised) in cultivated soils infiltrated by leaching/surface runoff, kg N/kg N applied
EF_5	emission factor for N_2O emissions from N by leaching/surface runoff, kg N_2O-N/kg N by leaching/surface runoff

The results from the three described sources of N2O-N are added in a next step:

Eq. 9 $$N_2O - N_{Total} = N_2O_{Direct} + N_2O_{(ATD)} + N_2O_{(L)}$$

The conversion of N2O-N into N2O emissions is done according to the following equation:

Eq. 10 $$N_2O = N_2O - N_{Total} \times \frac{44}{12}$$

Carbon stock changes due to land use change (el)

Depending on the type of land use, the carbon stock on a specific area can differ substantially. With regard to land use changes, 01.01.2008 was set as the cut-off date under the RED. In practice, this means that any land use change after this date must be taken into account for the calculation of GHG emissions and the proof of compliance with the GHG mitigation criteria. (Europäische Kommission 2010; IPCC 2006)

The approach for the calculation of emissions from carbon stock changes compares the carbon stock of the specific area for biomass production to the reference land use, annualised over a time span of 20 years. Furthermore, it is in general possible to account for a potential bonus in case the biomass comes from land that was formerly degraded and where the cultivation of this land resulted in an increase in the carbon stock.

The general definition of land use change is based on the IPCC land use classification, which distinguishes between the following six land categories:

- Forest land
- Grassland
- Cultivated land (arable land)
- Wetlands
- Settlement areas
- Other areas

Accordingly, a change in land use corresponds to a change between these categories. A change between different crops on an existing agricultural area is not considered as land use change. However, a change in the crop rotation system or the crops cultivated on an area might lead to a change in the carbon stock of the specific type of land. The impacts of these changes on the GHG mitigation potential of a biofuel which is produced from crops from the respective area can be included under the term „emission savings from the accumulation of soil organic carbon due to improved agricultural management practices "

The emissions caused by land use changes are calculated according to the following equation 11:

Eq. 11 $$e_l = (CS_R - CS_A) \times 3{,}664 \times \frac{1}{20} \times \frac{1}{P} - e_B$$

Where:

- CS_R the carbon stock of the reference land use (in t C/ha incl. soil and vegetation). The type of land use corresponds to the land use in 2008 or 20 years before the extraction of the raw material
- CS_A the carbon stock of the actual land use (in t C/ha incl. soil and vegetation)
- P crop productivity (in energy of biomass fuel/ha*a)
- e_B bonus of 29 gCO_2/MJ for cultivation on formerly degraded land

If no land use change (according to the above-mentioned categories) has occurred after the defined cut-off date, a calculation of e_l is not necessary. In this case, the value for e_l can be set to zero. Emissions from land use change are not included in the default values. Therefore, in the case of a land use change, an individual calculation is always necessary.

In principle, a calculation of carbon stock changes (CSR-CSA) can be based on actual (measured) values. In addition to the definitions in RED II Annex VI point 7, a calculation can also be carried out using tabular data in accordance with Decision 2010/335/EU. To select the data, the soil type and the climate region must first be determined.

To determine the carbon stock, the following rules apply first:

1. the entire area for which the carbon stock in the soil is calculated must:

    - have similar biophysical conditions (climate, soil type),
    - have a similar management history in terms of tillage,
    - have a similar history in terms of carbon input into the soil.

2. the carbon stock associated with the actual land use (CSA) corresponds to

    - carbon loss: the estimated stabilised carbon stock of the soil in the new land use;
    - carbon accumulation: the estimated carbon stock after 20 years or at the time of crop maturity, whichever is the earlier.

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The carbon stock is made up of the organic carbon in the soil and the carbon content of above- and below-ground vegetation and is calculated using the following equation:

Eq. 12 $$CS_i = (SOC + C_{VEG}) \times A$$

Where:

CS_i	the carbon stock per unit area associated with land use i (mass of carbon per unit area)
SOC	soil organic carbon (mass of carbon per hectare)
C_{VEG}	above- and below-ground carbon content of vegetation (mass of carbon per hectare)
A	factor for scaling to the respective area (hectares per unit area)

Factor A refers to the converted area. In case that 100% of the area has been converted, A is set to 1.

Organic carbon stock in soils:

For organic soils, 2010/335/EU does not specify a calculation method for determining the soil carbon content. For mineral soils, the following equation can be applied:

Eq. 13 $$SOC = SOC_{ST} \times F_{LU} \times F_{MG} \times F_I$$

Where:

SOC	soil organic carbon (mass of carbon per hectare)
SOC_{ST}	standard value for organic carbon in the topsoil layer (0-30 cm) (mass of carbon per hectare)
F_{LU}	Land use factor for the deviation of the value for soil organic carbon at the respective land use type from the standard value for soil organic carbon
F_{MG}	Management factor for the deviation of the soil organic carbon value for the respective main management practice from the standard value for soil organic carbon
F_I	Input factor for the deviation of the value for organic carbon in the soil from the standard value at different levels of carbon input

Furthermore, it is in general possible to use alternative methods for the determination of SOC. For suitable values for FLU, FMG and FI, see (Europäische Kommission 2010).

Above and below ground carbon stock of vegetation:

A suitable value from point 8 can be used for the carbon stock of vegetation (CVEG). Alternatively, or for applications where no value is given, CVEG can be calculated as shown below:

Eq. 14 $$C_{VEG} = C_{BM} + C_{DOM}$$

Where:

C_{VEG}	above- and below-ground carbon stock of vegetation (in mass C per ha)
C_{BM}	above- and below-ground carbon content in living biomass (in mass C per ha)
C_{DOM}	above- and below-ground carbon content in dead organic matter (in mass C per ha)

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CBM can be calculated with the following equation:

Eq. 15 $$C_{BM} = C_{AGB} + C_{BGB}$$

Where:

C_{BM}	above- and below-ground carbon content in living biomass (in mass C per ha)
C_{AGB}	aboveground carbon content in living biomass (in mass C per ha)
C_{BGB}	below-ground carbon content in dead organic matter (in mass C per ha)

Aboveground carbon content in living biomass:

Eq. 16 $$C_{AGB} = B_{ABG} \times CF_B$$

Where:

C_{AGB}	aboveground carbon content in living biomass (in mass C per ha)
B_{AGB}	weight of above-ground living biomass (DM per ha)
CF_B	C content of the DM of the living biomass (C per DM)

For cultivated land, permanent crops and forest plantations, the value for B_{AGB} corresponds to the average weight of above-ground living biomass during the production cycle. For C_{FB}, the value 0.47 can be used.

Belowground carbon content in living biomass (a choice can be made between the following alternative formulas):

Eq. 17 $$C_{BGB} = B_{BGB} \times CF_B$$

Where:

C_{BGB}	belowground carbon content in living biomass (in mass C per ha)
B_{BGB}	Weight of below-ground living biomass (DM per ha)
CF_B	C content of the DM of the living biomass (C per DM)

In analogy to the procedure for aboveground biomass, for cultivated land, permanent crops and forest plantations the value for B_{AGB} corresponds to the average weight of aboveground living biomass during the production cycle. For C_{FB}, the value 0.47 can be used.

Eq. 18 $$C_{BGB} = C_{AGB} \times R$$

Where:

C_{BGB}	belowground carbon content in living biomass (in mass C per ha)
C_{AGB}	aboveground carbon content in living biomass (in mass C per ha)
R	ratio between above-ground and below-ground carbon content in living biomass

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Emissions from processing (ep)

The emissions assigned to the process step "processing" refer to all processes, inputs and energy carriers that serve to convert biomass fuels into energy. Transport processes are excluded from this, as these are accounted for under a separate term (td). Emissions from processing include the processing itself, wastes and leakages (e.g., methane slip) as well as the use of chemicals and other production inputs.

To capture the emissions associated with electricity production, the RED II framework allows the use of default values of the applicable regional electricity mix (e.g., a national electricity mix or EU electricity mix). In addition, average values can be used if the electricity comes from a single generation facility that is not connected to the electricity grid.

For the process of Biogas and Biomethane production, the calculation for the processing step includes all relevant inputs and outputs for the Biogas production, gas processing/upgrading as well as electricity and heat generation. One output from this process module is the by-product digestate. Under certain conditions, it is possible to allocate a part of the process emissions to this by-product.

Emissions from processing are calculated as the sum of the products of the input streams (substances, energy) and the respective emission factors divided with the amount of energy produced (MJ) according to equation 19:

Eq. 19
$$e_p = \frac{Input_1 \times EF_1 + Input_2 \times EF_2 + \cdots}{MJ/a}$$

Emissions from transport and distribution (etd)

All emissions that occur during the transport of raw materials and intermediate products as well as the storage and distribution of final products are considered under this term. In principle, a distinction can be made between transport by land (road, rail), water (ship), air (air freight) and, in case of biomethane by the natural gas grid.

The following elaboration is focussing on road transportation. If the GHG emissions of a transport process are to be calculated, ideally the following information need to be collected (or respective assumptions have to be made):

- data on the transport distance (D, km) for
- loaded (D_l, km) and
- unloaded (D_e, km) runs of the transport vehicle, as well as on the
- fuel consumption (C) for
- the loaded (C_l, l/km) and
- unloaded (C_e, l/km) transport vehicle.

Using the emission factor for the fuel (EF_F, kg CO2eq/l), the value is calculated according to the following equation:

Eq. 20
$$e_{td} = \frac{(D_l \times C_l + D_e \times C_e) \times EF_F}{m_{Biomass}}$$

For Biogas plant concepts with satellite CHP units, another type of transportation process can be relevant. In this case, Biogas or Biomethane is usually fed into the gas grid or a pipeline at the point of production and fed out at the point of conversion, where it is consequently burned in a CHP unit. In the context of gas transport, energy is used primarily at the injection point and at compression points. These aspects shall also be accounted for under the term e_{td}.

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Emissions from the use of the fuel (eu)

Typically, when biomass is being cultivated and grown, a specific amount of carbon dioxide is being sequestered and fixated in the plant biomass. This effect has not been accounted for so far in the GHG balance. The reason is, that there is the general, simplified assumption, that the CO_2 emissions released during combustion of the biomass or the bioenergy carrier produced equal the amount that the biomass fixes during growth. Therefore, biogenic CO_2 emissions are not included in term e_u.

It is important to notice here, that the effect of captured biogenic CO2 emissions (e.g. from biogas production and/or upgrading) can be accounted for under the term 'emission savings from carbon capture …'.

However, this only applies to CO_2 emissions. Other GHGs such as CH_4 and N_2O emissions, which do occur within the scope of the RED II, must be included in the balance under the term e_u. These emissions can be caused for example by incomplete combustion during the conversion of biogas into electricity and can be released to the environment with the flue gas flow of a CHP unit.

In order to quantify these emissions, the flue gas composition must be known. Alternatively, literature values and assumptions might be used.

Emission savings from the accumulation of soil organic carbon due to improved agricultural management practices (e_{sca})

Management practices that lead to an increase in soil carbon stocks are usually accompanied by less intensive tillage and/or an addition of carbon, e.g., through the application of humus. In the context of GHG accounting, effects from carbon accumulations can be accounted for, in case robust and verifiable evidence is available. RED II does not provide a positive list of allowable measures, but gives the following examples:

- Shift in agricultural management practices to reduced or zero tillage
- Improved crop rotations
- Use of cover crops
- Use of soil improvers such as compost or residues from manure/slurry fermentation.

The use of natural soil improvers, as a measure to increase soil organic carbon is of particular importance for the biogas sector. The question of how reliable and verifiable evidence of the increase in soil carbon stocks can be provided in practice (methods, analyses, etc.) cannot be conclusively clarified within the scope of this work. Regarding this point, the RED II does state that robust proof has to be provided and checked during the process of sustainability certification.

Emission savings from carbon capture and geological storage or carbon capture and replacement (eccs and eccr)

In process chains that include upgrading to biomethane, additional greenhouse gas savings can be achieved in case carbon dioxide is being captured and further utilised. A distinction is made between CO_2 capture and replacement (CCR) and CO_2 capture and storage (CCS).

In the case of CO_2 capture with geological storage, potential emission savings (e_{ccs}) are limited to the emissions avoided by capturing and storing emitted CO_2. In addition, these emissions must be directly associated with the extraction, transport, processing and distribution of biomass fuel and must not have already been accounted for in e_p. Furthermore, the carbon storage must be carried out in accordance with the requirements defined in the Directive 2009/31/EC.

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The emission saving from carbon capture and replacement (e_{ccr}) must be directly linked to the production of the biomass fuel to which it is attributed. It is also limited to the emissions avoided through CO_2 capture. In this context, the carbon must further originate from biomass and replace CO_2 of fossil origin in the production of commercial products and services.

In general, the basic approach for the calculation of emissions and emission savings does not differ between the two variants. The result is given in terms of the energy content of the end product (electricity, heat) in g CO_2eq/MJ, calculated according to the following equation. The savings are to be calculated by the operator of the facility providing the CO_2 for CCR or CCU purposes.

Eq. 21

$$e_{ccr}/e_{ccs}\left[\frac{gCO_2eq}{MJ}\right] = \frac{Mass\ CO_2[g] - Process\ energy[kWh] \times EF\left(\frac{gCO_2eq}{kWh}\right) - Input\ materials\ [kg] \times EF\left[\frac{g\ CO_2eq}{kg}\right]}{Energy\ content\ final\ product\ [MJ]}$$

Credits/Boni

The RED II framework allows to include potential emission savings, due to specific agricultural practices or the use of specific feedstocks into the GHG emission calculation of a biofuel. The following sections describe the calculation of two potential bonuses in the GHG emission calculation in case manure/slurry is being used for biogas production or in case the biogas feedstock has been grown on land which has been degraded land. It could be argued, that in some cases also the use of organic biowaste or residues could lead to emission savings due the avoidance of emissions in other sectors (e.g., the decomposition of some straw fractions on agricultural land or the deposition of biowaste). However, it is not directly possible to include these effects under the current RED II methodology in the same manner as the two examples below.

a) Credit for the use of manure/slurry as biogas substrate

The conventional storage of manure can lead to significant emissions of methane. These emissions can be reduced in case manure/slurry is used as a substrate for biogas production. This benefit is recognised by the RED II by a credit of 45 gCO_2eq per MJ manure/slurry used (i.e., 54 kg CO_2eq/t FM). The bonus is applied in the e_{sca} term for emission savings as a result of improved agricultural management practices.

b) Degraded Land

If feedstocks for bioenergy production are being grown/cultivated on previously degraded land, a credit of 29 gCO_2eq/MJ can be given. This credit can be granted in case the following conditions are met:

The area must demonstrably

- not having been used for agriculture or any other purpose in January 2008, and
- consist of highly[1] degraded land, including former agricultural land.

Starting from the date of conversion to agricultural land, the bonus may apply for a period of up to 20 years, provided that:

[1] According to RED II, severely degraded land is land that has either been heavily salinated over a long period of time or that has a particularly low organic matter content and is severely eroded.

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- a continuous increase in carbon stock and
- a significant reduction in erosion can be ensured on the land concerned.

Emissions of the energy carrier produced

In case biomethane is used as a fuel (e.g. in the transport sector), the calculated total emissions (E) can be used to calculate the respective GHG saving. If the objective is to calculate the GHG emission savings of electricity and/or heat production from bioenergy, the total emissions after conversion (EC) have to be calculated first.

Emissions from electricity and heat producing processes

For processes producing only heat, GHG emissions are calculated by the quotient of the total emissions before conversion (E) into heat and the heat efficiency (η_h):

Eq. 22 $$EC_h = \frac{E}{\eta_h}$$

For processes producing only generate electricity, the quotient of total emissions before conversion (E) and the electrical efficiency (η_e) is formed accordingly:

Eq. 23 $$EC_e = \frac{E}{\eta_e}$$

Emissions from installations with combined heat and power generation

In plants with cogeneration, the emissions of the final energy product (E_h or E_{el}) are calculated via the exergy share (C_{el} or C_h) (share of energy that can perform mechanical work). The calculation for emissions from the production of heat and electricity is as follows:

Eq. 24 $$EC_{el} = \frac{E}{\eta_{el}}\left(\frac{C_{el}\times\eta_{el}}{C_{el}\times\eta_{el}+C_h\times\eta_h}\right)$$

Eq. 25 $$EC_h = \frac{E}{\eta_h}\left(\frac{C_h\times\eta_h}{C_{el}\times\eta_{el}+C_h\times\eta_h}\right)$$

Here, the exergy share of the electricity is set to 100% and thus C_{el} is set T 1.

The exergy share of the useful heat ("Carnot's efficiency") is calculated from the measured, absolute temperature (in Kelvin) of the useful heat at the delivery point (Th) and the ambient temperature (T0) fixed at 273.15 Kelvin (corresponds to 0°C):

Eq. 26 $$C_h = \frac{T_h - T_0}{T_h}$$

Allocation of emissions between main and co-products

Industrial production processes can yield in multiple product outputs. Allocation can be used to divide the emissions that occurred among different process outputs. In general, different rationales can be used, leading to an allocation of emissions based on e.g. mass ratios, energy content, economic value, etc. RED II allocates emissions of different production outputs based on the lower heating value of the products produced. During the biogas process, the co-product digestate is produced in addition to the product biogas. To allocate emissions between the main product and the co-product, the allocation factor first calculated according to the following formula:

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Eq. 27 $$Allocation\ factor\ fuel = \frac{Energy\ content\ fuel}{Energy\ content\ fuel + Energy\ content\ co\text{-}product}$$

Within the scope of the RED II, allocation between products is only possible according to the energy content (determined based on the lower heating value of the respective fresh mass). If the energy content is negative, it is set at zero. The allocation is carried out by multiplying the calculated relevant emissions by the allocation factor. All emissions up to and including the process step in which the co-product is produced are considered (Table 1).

Table 1 General approach for the derivation of allocation factors

Biomass cultivation	→	Transport	→	Processing	→	Transport & Distribution	→	Use		Total emissions
e_{ec}	+	e_{td}	+	e_p	+	e_{td}	+	e_u	=	E (w/o allocation)
e_{ec} **x AF**	+	e_{td} **x AF**	+	e_p **x AF**	+	e_{td}	+	e_u	=	E (w allocation)

$$Mitigation = \frac{E_F - E_C}{E_F} \times 100$$

Calculation of total GHG mitigation

The GHG mitigation potential of the biofuel is calculated based on a comparison of the total GHG emissions from the production and use of the alternative fuel to the fossil fuel reference values (e.g. 94 gCO2eq for fossil fuel in the transport sector), the so-called comparators. Depending on the type of energy use, different comparators are specified (compare RED II Annex VI, B (19). The savings are calculated according to equation 28:

Eq. 28 $$Mitigation = \frac{E_F - E_C}{E_F} \times 100$$

E_F = total emissions of the biofuel or the electricity and heat production from the fuel

E_C = total emissions of the comparator

Procedure for substrate or feedstock mixtures

The methodical procedure described so far is suitable to conduct assessments for plants with mono-digestion of single feedstocks. However, most plants are operated with more than one feedstock type and use substrate mixtures instead. The emissions from the production of biogas or biomethane through the co-fermentation of any number of different substrates are calculated according to the following equation:

Eq. 29 $$E = \sum_1^n S_n \times \left(E_{ec,n} + E_{td,Feedstock\ f,n} + E_{l,n} - E_{sca,n}\right) + E_p + E_{td,Product} + E_u - E_{ccs} - E_{ccr}$$

Where:

E = greenhouse gas emissions per MJ biogas or biomethane produced from co-digestion of the defined mixture of substrates

S_n = Share of feedstock n in energy content

$E_{ec,n}$	=	emissions from extraction and cultivation of the feedstock n
$E_{td,Rohstoff,n}$	=	emissions from the transport of the feedstock n to the conversion plant
$E_{l,n}$	=	emissions from changes in the carbon stock due to land use changes for production of feedstock n annualised
E_{sca}	=	emission savings through better agricultural management practices of the raw material n or bonus in the use of slurry/muck
E_p	=	emissions from the processing of the biofuel
$E_{td,Product}$	=	emissions from transport and distribution of the product (Biogas, Biomethane)
E_u	=	emissions from the use of the fuel
E_{ccs}	=	reducing emissions through CO_2 capture and geological storage
E_{ccr}	=	emission savings through CO_2 capture and replacement

In contrast to the calculation of GHG emissions from process chains based on mono-digestion, the calculation differs, since the feedstock-relevant part of the calculation formula (e_{cn}, e_{td}, e_l and e_{sca}) is included individually for each feedstock that is part of the substrate mix for the co-digestion. This assumes that interactions between the individual substrates in the substrate mix do not lead to a significant change in the biogas yield. This simplification may not exactly reflect the real conditions in the fermenter, but it allows for a more simplified calculation, reducing the overall effort for market actors.

In order to account for different mass fractions of the individual substrates in the substrate mix, the emissions of the individual substrates are included in the calculation as a weighted average value.

Eq. 30
$$S_n = \frac{P_n \times W_n}{\sum_1^n (P_n \times W_n)}$$

The energy yield of a raw material is calculated as the product of the biogas yield, the proportion of volatile components (VS) in the fresh mass and the calorific value:

Eq. 31

$$P_n \left[\frac{MJ}{kg\ FM}\right] = Biogas\ yield_n \left[\frac{m^3}{kg\ VC}\right] \times volatile\ components\ _n \left[\frac{kg_{VC}}{kg_{FM}}\right] \times energy\ content_{Biogas} \left[\frac{MJ_{Biogas}}{m^3{}_{Biogas}}\right]$$

The weighting factor puts the annual input of the raw materials (FM) in relation to the annual input of the substrate mix. The quotient is multiplied by a correction factor to account for fluctuations in moisture content:

Eq. 32
$$W_n = \frac{I_n}{\sum_1^n I_n} \times \left(\frac{1 - AM_n}{1 - SM_n}\right)$$

I_n	=	annual input of the substrate n, t FM
AM_n	=	annual average moisture of the substrate n, kg Wasser/kg FM
SM_n	=	standard moisture substrate n

This rather abstract calculation framework has to be operationalised and more guidance is needed might be provided by certification schemes throughout the process of the RED II implementation into their system documents.

2.2.2 Exemplary calculations

In order to illustrate the rationale of the previously described methodology, the chapter includes two exemplary calculations for biomethane production systems.

2.2.2.1 Upgrading and grid injection of biogas from biowaste

Example: A waste management company operates a biogas plant using biowaste as substrate. The biogas is upgraded to biomethane and fed into the natural gas grid. The biowaste substrate material is collected within a radius of 30 km from the biogas facility. The biogas plant uses 50,000 t of biowaste per year plant. To provide the necessary process heat for the fermenter unit, a part of the biogas produced is used in a CHP unit. The electricity generated in this process is fed into the power grid. Surplus heat is used to supply heat to surrounding residential buildings. The characteristic values of the substrate used are shown in Table 2.

Table 2 Substrate characteristics Biowaste (KTBL 2020)

	Biogas yield		Methane content	Annual amount	
	ln/kg oDM	m_n^3/t FM	Vol.-%	t FM/a	Mass.-%
Biowaste, 40% DM	615	119.9	60	50,000	100

The schematics of the general plant concept are being shown in Figure 4. 37% of the biogas produced is used in the CHP unit, while 63% is upgraded and fed into the natural gas grid. Process heat is extracted via heat exchangers at different temperatures, depending on the temperature level of the

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respective process. The following calculation is based primarily on data from a plant model generated with a KTBL calculator (KTBL 2020). The main input data are listed in Table 2.

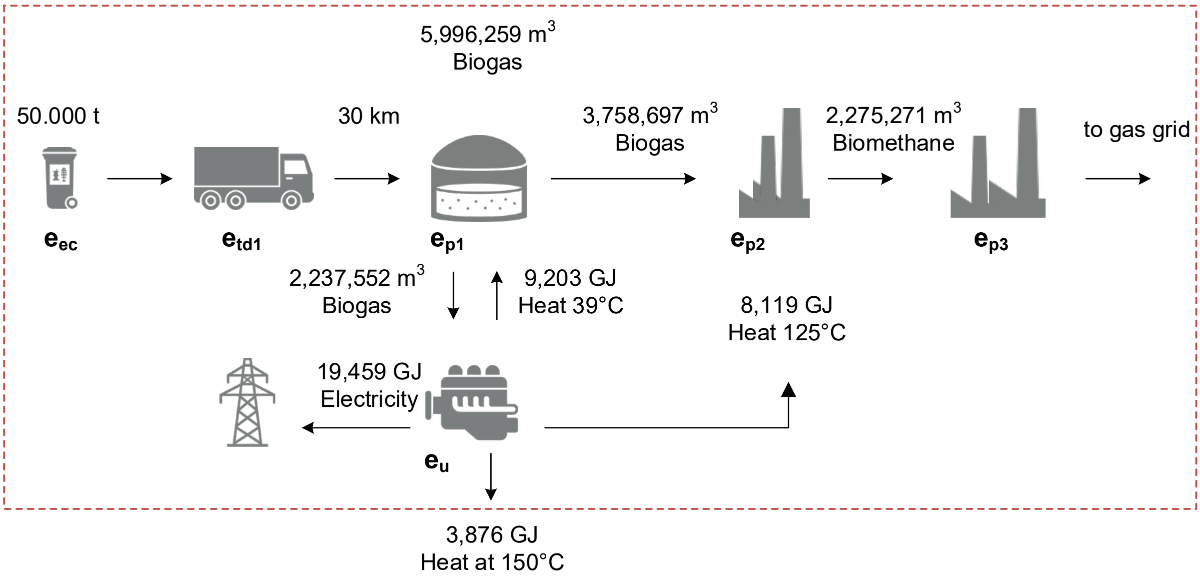

Figure 5: Flow diagram of the process steps for the production and injection of biomethane with connected biogas CHP for process heat and power generation.

Table 3 Main characteristics and assumptions for the example biogas facility

Fermentation and yields	
Annual substrate use	**50.000 t/a**
Dry Matter (DM) of Substrate	39.0 % of FM
Organic Matter (oDM)	50.0 % of DM
Average retention time in the fermenter	70 d
Heat demand fermenter	**2,556,409.0 kWh_{th}/a**
Raw biogas production	**5,996,250 m³/a**
Biomethane content	3,597,750 mn³/a
CHP	
CHP Engine	Gas-Otto-Engine
Raw gas	**2,237,552 mn³/a**
	255 mn³/h
Full use hours CHP	8,400 h/a
Electrical Power	650 kW_{el}

Electrical efficiency	**40.8 %**
CHP and transformer losses	1.0 %
Thermal Power	701 kW_{th}
Thermal efficiency	**42.5 %**
Produced electricity (fed in)	**5,405,400 kWh_{el}/a**
Produced heat (no external use)	**5,888,400 kWh_{th}/a**
Biogas upgrading	
Process of biogas upgrading	Amine wash
Raw gas input	3.758.697 mn^3/a
	429 mn^3/h
Full use hours upgrading unit	8,400 h/a
Capacity of the upgrading unit	500 mn^3/h
Capacity utilisation	89,5 %
Methane slippage	**0.1 %**
Methane content product gas	99 %
Electricity demand	**0.09 kWh/mn^3 Raw gas**
Heat demand	**0.60 kWh/mn^3 Raw gas**
Useable heat from the process	0.30 kWh/mn^3 Raw gas
Ammount of product gas	**2,275,721.0 mn^3/a**
	270.9 mn^3/h
Ammount of heat used	**2,505,798 kWhth/a**
Biomethane injected into the grid (Hs,n)	24,895,246.0 kWh/a

The calculation of the emissions from the individual process steps for this example is based on equation 1. The step-by-step calculation is shown below.

Emissions of raw material extraction and raw material cultivation e_{ec}:
Since the substrate is a waste material, no emissions for extraction are accounted for (eec=0).

Emissions from the transport of the raw material e_{td}

The substrates used have to be delivered to the plant. The calculation of transport emissions is based on the following assumptions:

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Table 4 Assumptions transport – example

Parameter	Value	Unit
Transport distance, loaded	30	km
Transport distance, unloaded	30	km
Fuel consumption, loaded	0.49	l/km
Fuel consumption, unloaded	0.25	l/km

A lorry with a loading capacity of 24t is used for the transport of the maize silage. The emission factor for diesel is assumed to be 2.1kg CO_2eq/litre. The calculation path for emissions from the transport of biowaste is as follows:

$$e_{td1} = \frac{\left((30\ km \times 0.49 \frac{l}{km}) + (30\ km \times 0.25 \frac{l}{km})\right) \times 2{,}1\ \frac{kgCO_2eq}{l}}{24\ t} = \mathbf{1.94}\ \frac{\boldsymbol{kgCO_2eq}}{\boldsymbol{t\ FM}}$$

The conversion to the desired reference value is done by dividing by the energy yield [2]:

$$e_{td1} = 1.94\ \frac{kgCO_2eq}{t\ FM} \times 2697.75 \frac{MJ}{t\ FM} \times 1000 = \mathbf{0.72} \frac{\boldsymbol{gCO_2eq}}{\boldsymbol{MJ\ Biogas}}$$

Emissions from processing - biogas production e_{p1}

The data from the following table were used to calculate the emissions from biogas production. The electricity demand was assumed to be 0.1 kWh/m³ raw gas. The process heat is provided by the biogas CHP unit. Emissions from the CHP unit, namely CH_4 and N_2O resulting from the biogas combustion in the CHP unit must be allocated to the useful heat consumed in the biogas production by means of energetic allocation.

Table 5 Assumptions biogas production – example

Parameter	Unit	Emission factor	Emissions in kg CO_2eq/ a
Electricity consumption	599,625 kWh/a[3]	0.47 kg CO_2eq/kWh	281,824
Process heat	9,203,072 MJ/a	0.00246 kg CO_2eq/MJ	22,640
Methane leakeage	25,904 kg/a	25 kg CO_2eq/kg	647,595
Sum			**952,058**

The conversion to the desired reference value is done by dividing by the biogas yield taken from the KTBL model:

$$e_{p1} = \frac{952058 \frac{kgCO_2eq}{a}}{5996250 \frac{m^3 Biogas}{a}} \times 1000 = \mathbf{158.8}\ \frac{gCO_2eq}{m^3 Biogas}$$

The conversion to the desired reference value is done by dividing by the calorific value of biogas:

[2] Energieausbeute=Spezifischer Biogasertrag x Heizwert=119,9 m³/t FM x 22,5 MJ/m³ = 2697,75 MJ/t FM
[3] Für den Strombedarf der Biogaserzeugung wurde der Richtwert 0,1 kWh/m³ Rohgas (FNR Leitfaden Biogas) verwendet, der sich auf die Biomethanbereitstellung bezieht

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$$e_{p1} = \frac{158.8\ \frac{gCO_2eq}{m^3Biogas}}{22.5\ \frac{MJ}{m^3}} = \mathbf{7.06}\frac{gCO_2eq}{MJ\ Biogas}$$

Derivation of emission factor for process heat from biogas CHP:

To derive the emission factor for process heat, the emission factor for the combustion of biogas in the CHP unit is first determined, taking into account data from (European Commission. Joint Research Centre. 2017; European Commission. Joint Research Centre. Institute for Energy and Transport. 2014)

Table 6 Assumptions emissions CHP unit – Example

Output CHP	Value	Unit	Emission factor	Emissions, g CO_2eq/ MJ
Methane	0,34	g CH_4/MJ Biogas	25 g CO_2eq/MJ	8.5
N_2O	0.00141	g N_2O/MJ Biogas	298 g CO_2eq/MJ	0.4
Summe (e_u)				**8.9**

Subsequently, the share of emissions attributable to the usable heat consumed in the digester is calculated using the following formula. For this, the electrical and thermal efficiency of the CHP can be taken from the KTBL model (η_{el}=40.8 %; η_h=42.5 %). The exergy share of electricity is set at 100 % (as defined by the RED II), therefore C_{el}=1. The exergy share of useful heat is calculated as follows, taking into account the ambient temperature t_0=273.15 K (0°C) and the temperature of the useful heat at the delivery point $t_{h=}$ 312.15 k (39°C):

$$C_{h(39°C)} = \frac{T_h - T_0}{T_h} = \frac{312.15 - 273.15}{312.15} = 0.125$$

The emissions for the process heat from the biogas CHP can now be calculated with the following equation:

$$EC_h = \frac{E}{\eta_h}\left(\frac{C_h \times \eta_h}{C_{el} \times \eta_{el} + C_h \times \eta_h}\right) = \frac{8.9}{42.5}\left(\frac{0.125 \times 42.5}{1 \times 40.8 + 0.125 \times 42.5}\right) = \mathbf{2.45}\ \frac{gCO_2eq}{MJ}$$

Emissions from Processing – Biogas upgrading e_{p2}

The biogas is upgraded by means of amine scrubbing. The electricity demand of 0.09 kWh/m³ biogas is taken from the electricity grid. The process heat requirement is 0.6 kWh/m³ biogas and is provided by the biogas CHP unit, whereby CH_4 and N_2O emissions from the CHP unit are assigned to the biogas upgrading in the same way as calculated for biogas production. The methane slip is assumed to be 0.1 %. (all assumptions were taken from the KTBL model). The emission factor for the process heat was carried out according to the calculation in step 3, with the temperature of the useful heat being adjusted accordingly. It is assumed that the amine wash is carried out at a temperature of 125 °C:

$$C_{h(125°C)} = \frac{T_h - T_0}{T_h} = \frac{398.15 - 273.15}{398.15} = 0.314$$

$$EC_h = \frac{E}{\eta_h}\left(\frac{C_h \times \eta_h}{C_{el} \times \eta_{el} + C_h \times \eta_h}\right) = \frac{8.9}{42.5}\left(\frac{0.314 \times 42.5}{1 \times 40.8 + 0.314 \times 42.5}\right) = \mathbf{5.56}\ \frac{gCO_2eq}{MJ}$$

Overview of total emissions:

Table 7 Total emissions – Example

Parameter	Value	Emission factor	Emissions, in kg CO_2eq/ a
Electricity demand	338,283 kWh/a	0.47 kg CO_2eq/kWh	158,993
Heat demand	8,118,768 MJ/a	0.0056 kg CO_2eq/MJ	45,178
Methane slippage	2706 kg/a	25 kg CO_2eq/kg	67,657
Sum			**271,827**

The calculation of emissions per functional unit of biomethane is conducted considering the specific biomethane yield:

$$e_{p2} = \frac{271.827\,\frac{kgCO_2eq}{a}}{2.275.721\,\frac{m^3 Biomethane}{a}} \times 1000 = \mathbf{119,45}\ \frac{g\ CO_2eq}{m^3 Biomethane}$$

Emissions from processing – Grid injection e_{p3}

The biomethane produced undergoes further processing before being fed into the natural gas grid. At the injection station, the gas is compressed to increase the pressure above the pressure of the gas grid and thus enable it to be fed into the grid. This is done with a compressor. Furthermore, the gas is odorised. In this example, it is assumed that due to the high product gas quality from the amine scrubbing, no calorific value adjustment by adding additional gases is necessary. Odourisation is also not included in our calculation. The emissions to be balanced consequently depend on the energy demand of the biomethane compression:

Table 8 Emissions electricity demand compression – Example

Parameter	Value	Emission factor	Emissions, in kg CO_2eq/ a
Electricity demand	0.0025 kWh/m³	0.47 kg CO_2eq/kWh	2673.97

$$e_{p3} = \frac{2.679,9\,\frac{kgCO_2eq}{a}}{2.275.721\,\frac{m^3 Biomethane}{a}} \times 1000 = \mathbf{1,18}\ \frac{g\ CO_2eq}{m^3 Biomethane}$$

Emissions from transport of biomethane in the gas grid e_{td2}

Emissions from gas losses during transportation in a gas grid have been assumed based on IFEU (2010). According to this publication, 0.08% of the gas which was fed into the grid is assumed to be emittet:

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Table 9 Emissions biomethane transport – Example

Parameter	Value	Emission factor	Emissions, in kg CO_2eq/ a
(Bio-)methane emissions	1310.8 kg CH_4/a	25 kg CO_2eq/kg CH_4	33770.4

$$e_{td2} = \frac{33{,}770\,\frac{kgCO_2eq}{a}}{2{,}275{,}721\,\frac{m^3 Biomethane}{a}} \times 1000 = \mathbf{14.4}\ \frac{g\ CO_2eq}{m^3 Biomethane}$$

Calculation of total emissions of biomethane

For our example the emissions for the complete supply chain are calculated as follows:

$$E_{Biomethane} = e_{td1} + e_{p1} + e_{p2} + e_{p3} + e_{td2}$$

$$E_{Biomethan} = 0.72 + 7.06 + 3.32 + 0.033 + 0.4 = \mathbf{11.53}\ \frac{gCO_2eq}{MJ}$$

Calculation of emissions and emission savings for electricity and heat production from the biogas CHP unit

$$E_{Biogas} = e_{td1} + e_{p1} + e_u$$

$$E_{Biogas} = 0.72 + 7.06 + 8.9 = \mathbf{16.68}\ \frac{gCO_2eq}{MJ}$$

The allocation of emissions for the electricity (fed into the grid) and the surplus heat is based on the exergy according to the calculation below. It is assumed that the surplus heat is used to supply surrounding residential buildings. According to RED II, or at an assumed temperature of 150 °C for the useful heat, the exergy share of the heat is ch=0.3546. According to RED II, the exergy share for electricity is 100 % (cel=1). The efficiencies of the CHP are assumed to be: η_{el}=40.8 %; η_h=42.5 %.

$$EC_{el} = \frac{E}{\eta_{el}}\left(\frac{C_{el} \times \eta_{el}}{C_{el} \times \eta_{el} + C_h \times \eta_h}\right) = \frac{16.68}{0.408}\left(\frac{1 \times 0.408}{1 \times 0.408 + 0.3546 \times 0.425}\right) = \mathbf{29.85}\ \frac{g\ CO_2eq}{MJ}$$

$$EC_h = \frac{E}{\eta_h}\left(\frac{C_h \times \eta_h}{C_{el} \times \eta_{el} + C_h \times \eta_h}\right) = \frac{16.68}{0.425}\left(\frac{0{,}3546 \times 0{,}425}{1 \times 0.408 + 0.3546 \times 0.425}\right) = \mathbf{10.59}\ \frac{g\ CO_2eq}{MJ}$$

Using the comparators for electricity (183 g CO_2eq/MJ) and heat (80 g CO_2eq/MJ) from the RED II, the emission savings are calculated as follows:

$$GHG\ mitigation\ electricity = \frac{183 - 29.85}{183} \times 100 = \mathbf{83.7}\ \%$$

$$GHG\ mitigation\ heat = \frac{80 - 10.59}{80} \times 100 = \mathbf{86.7}\ \%$$

2.2.2.2 Calculation of emissions from carbon stock changes due to a land use change from grassland to maize cultivation

Scenario: An operator of a biogas production plant cooperates with a farmer who supplies manure, grass silage and maize silage to the biogas facility. The maize silage comes from an area that was used as a pasture until 2018. The land status has demonstrably changed from grassland to arable land, after the cut-off date for land use change in the RED II. The land conversion was assessed as permissible in terms of biodiversity, allowing the farmer to use the land for biomass production within the scope of the Renewable Energy Directive. However, in calculating the emission savings of the energy from biogas, the emissions associated with the land use change must be taken into account. This is done in the term e_l according to the following equation:

$$e_l = (CS_R - CS_A) \times 3.664 \times \frac{1}{20} \times \frac{1}{P} - e_B$$

The RED II allows for the possibility to impute a bonus in the GHG assessment for restored degraded areas. As this example is a converted pasture, the factor e_B is neglected. The farmer does not have access to measured values of carbon stock before and after land conversion and therefore calculates the factors CS_R and CS_A. In the following, the calculation of e_l is presented step by step.

Calculation of the carbon stock change from the reference land use CS_R (grassland) to the actual use CS_A (Maize production)

The carbon stock includes the terms carbon content of the soil (SOC) and the vegetation (C_{VEG}) and is calculated according to the following approach:

$$CS_i = (SOC + C_{VEG}) \times A$$

The soil organic carbon content in mineral soils is calculated as follows:

$$SOC = SOC_{ST} \times F_{LU} \times F_{MG} \times F_I$$

Carbon stock of grasslands

To calculate the carbon stock on the reference land use are, the following exemplary assumptions have been made:

- SOC_{ST} = 95 t C/ha (Soil type: " Clay soils, high soil activity"; Climatic region: "temperate, cool, humid".)
- F_{LU} = 1 (permanent cropping)
- F_{MG} = 1.1 (no tillage)
- F_I = 1 (Input medium)

Using these values in the formula gives the following result for the organic carbon content of the soil:

$SOC_{Grassland}$ = 95 x 1 x1.1 x 1 = 104.5 t C/ha

The carbon content of the vegetation is assumed to be:

$C_{VEG, Grassland}$ = 6.8 t C/ha

Thus, the carbon content of grassland is:

CS_R = (104.5+6.8) x 1 = 111.3 t C/ha

Carbon stock area for maize production

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Due to the intense tillage and the intensive fertilisation, it is assumed that the soil type will change in to "Clay soils, weak soil activity". The value for SOC_{ST} is assumed to be 85 t C/ha under these assumptions. Additionally, the following assumptions are made (Factors for cultivated areas):

- F_{LU} = 0.69 (land use: cultivation)
- F_{MG} = 1 (intense tillage)
- F_I = 1.44 (Input high, organic fertiliser)

This results in the following value for the soil carbon content:

$SOC_{Maize\ cultivation}$ = 85 x 0.96 x 1 x 1.44 = 84.5 t C/ha

For the carbon stock of the vegetation of cultivated areas, the value $C_{VEG,\ Maize\ cultivation}$ is set to 0 t C/ha.

The carbon content of the maize area is thus:

CS_A = (84.5+0) x 1 = 84.5 t C/ha

Plant productivity Maize

The RED II does not further specify how crop productivity shall be calculated. However, the RED II explains the parameter as "measured as biomass fuel energy per unit area and year“. In the present example, the crop productivity of maize was derived as follows:

Term	Explanation	Value	Unit
a	Biogas yield	216	m³ Biogas/t FM
b	LHV Biogas	22.5	MJ/m³
a *b	Energy yield	4860	MJ/t FM
c	Maize yield	50	t FM/ha*a
(a*b)*c	Plant productivity	243000	MJ/ha*a

Since emissions in connection with land use changes are in practice calculated by biomass producers or first gathering points in the supply chain, who may not be aware of the final use of the biomass or biomass fuel, it seems more appropriate to present the result in the reference quantity g CO_2eq/t DM.

Calculation of the term e_l:

$$e_l = \left(111.3\, t\frac{C}{ha} - 84.5t\frac{C}{ha}\right) \times 3.664 \times 10^6 \times \frac{1}{20} \times \frac{1}{243000\frac{MJ}{ha}*a} - 0 = \mathbf{20.2\ g\ CO_2eq/MJ}$$

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3 GHG emissions and cost indications for Renewable Gas technologies

The following chapter will briefly discuss aspects related to the GHG emission intensity as well as the production costs of different renewable gas pathways. It is important to mention that both, costs and GHG emission of the concepts discussed here are strongly affected by regional characteristics such as specific yields, conversion efficiency or the regional specific costs and upstream emissions of energy and material inputs. Furthermore, methodological choices and assumptions can affect the result of a cost or GHG assessment of a product. For this reason, the RED II framework has introduced specific rules for the assessment of GHG emission of bioenergy in order to allow for a more robust comparison amongst technologies and fossil reference products. Since there is not much experience with the assessment of GHG emissions from renewable gas technologies under the RED or RED II methodology, most of the literature sources and data discussed in this chapter use slightly different methodologies. Thus, a direct comparison or the deviation of absolute statements regarding the cost or GHG performance of the renewable gas technologies analysed is difficult. However, the analysed literature can be used to understand the importance of specific parameters which show a strong influence on the overall result.

3.1 GHG emissions and influencing factors of RG technologies

3.1.1 Biomethane from Biogas upgrading

The assessment of GHG emissions and environmental impacts from the production of Biogas and Biomethane via the fermentation of different biogenic materials has been the subject to several research projects and scientific publications in the past. However, due to relatively small relevance of biomethane as a transport fuel in the EU transport system, only a few of these studies are based on the methodological guidelines of the RED and RED II (as described under chapter 2). Thus, an extensive experience with results published in the context of sustainability certification under the RED framework is not yet available. Examples for GHG assessments of biomethane pathways under consideration of the RED methodology can be found in ((Majer and Oehmichen 2017), (Biograce Consortium)). Existing publications use different methodologies based for example on alterations of the Life Cycle Assessment Methodology and Carbon Footprinting Standards (e.g., the (ISO 14067:2018). One of the consequences of the use of different methodologies and approaches in existing literature is that results from existing studies are often not directly comparable. The reason is that specific methodological frame conditions as well as assumptions made by authors can directly influence the results of the assessment. Examples are the selection of the system boundaries, allocation approaches, the use of characterisation factors which are used to compare the impact of different GHGs to the reference unit of CO_2., as well as the consideration of spatial aspects (compare (Sinéad O'Keeffe et al. 2016), (O'Keeffe et al. 2016)) and characteristic.

Even though, the direct comparability of existing studies is limited, due to the above-mentioned aspects, existing publications can be used to describe a number of drivers and influencing factors with a specific impact on the result of the overall supply chain as well as the individual process steps in the supply chain.

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The following Figure 5 shows the results of different publications on the GHG emissions of biomethane production based on different substrates and substrate combinations. The figure includes results from (European Commission. Joint Research Centre. Institute for Energy and Transport. 2014; Daniel-Gromke et al. 2020; Meyer-Aurich et al.; Westerkamp et al. 2014; Oehmichen and Thrän 2017; Thrän et al. 2011; European Commission. Joint Research Centre. 2017; European Commission. Joint Research Centre. Institute for Energy and Transport. 2014; European Commission European Commission: Brussels, Belgium, 2018; Lyng and Brekke 2019; Lantz et al. 2018) The bandwidth of results for each category can be explained by two main aspects: i) methodological differences between the studies, leading to different results for comparable supply chains. ii) differences between the specific supply chains assessed (e.g., different biomass and biogas yields, different efficiencies, differences in energy demands, etc.) in the publications included in Figure 5. Both parameters prevent absolute statements on the GHG performance of biomethane concepts. However, the assessment of these publications allows to identify specific trends regarding major differences in the supply chain of biomethane supply chains and their impact on the overall results.

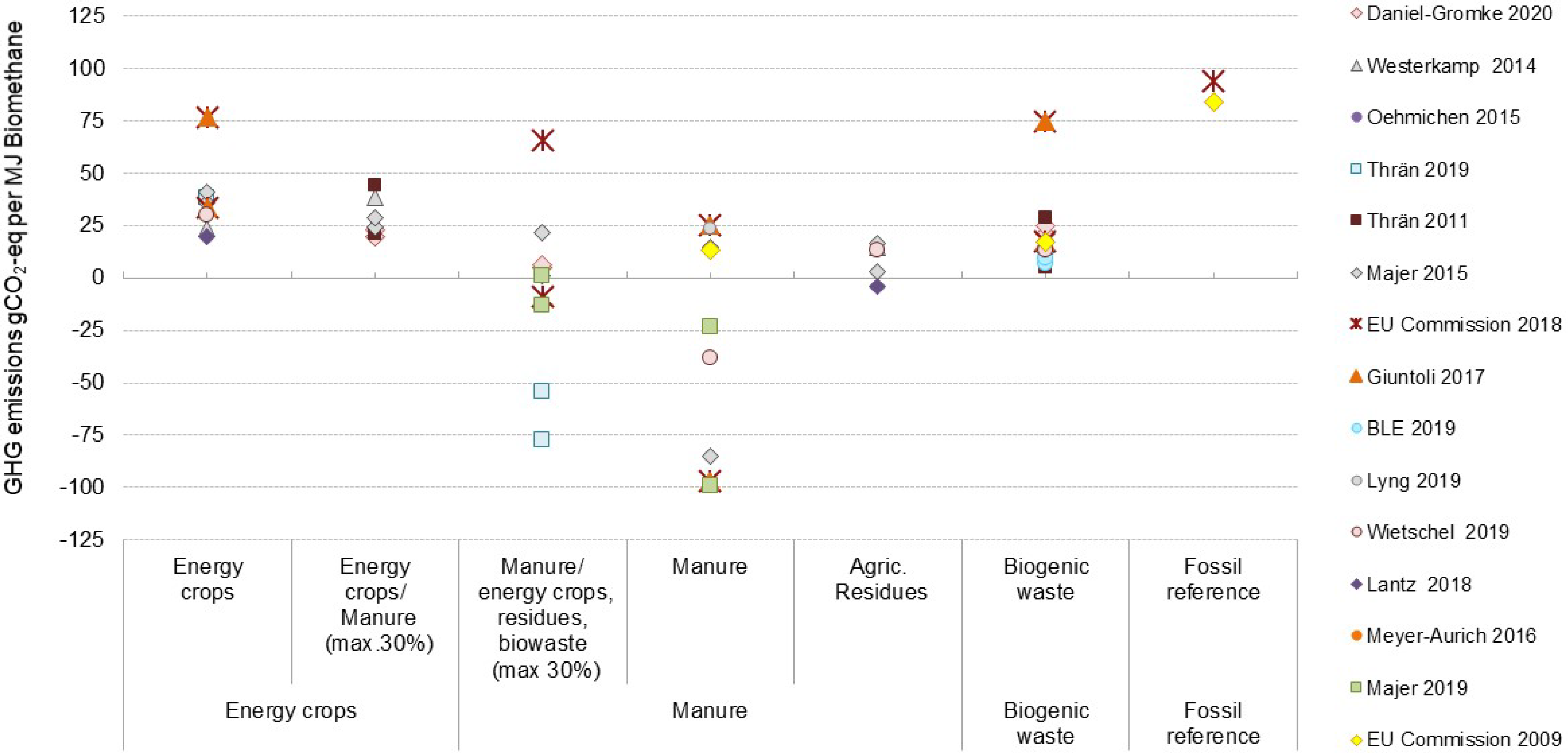

Figure 6 GHG emission results of Biomethane production from different publications

General parameters, leading to potentially significant impacts on the GHG performance of a biomethane pathway are for example:

- the use of the substrate for biogas production (e.g. the use of energy crops which are being produced with the help of external inputs such as fertilisers, plat protection agents, agricultural machinery, etc. vs. the use of waste and residues for which the calculation of GHG emissions often starts with the collection of the material) (e.g. (Majer and Oehmichen 2017)
- the demand as well as the source of energy for the biogas and biomethane production (i.e. depending on the upstream emission from the provision of the used energy, different scenarios for energy supply will lead to differences in the overall GHG emission performance of the pathway) (Majer et al. 2019), (Majer et al. 2016; Thrän et al. 2011)
- methane emissions from the biogas production and the digestate storage system, etc. (Oehmichen and Thrän 2017), (Majer et al. 2019)

The following Figure 6 illustrates the magnitude of the influence of different process parameters along the supply chain of a biomethane production based on energy crops. According to this example, the most significant parameters, include leakage of CH_4 at the processing unit, the supply of electricity for the processing unit(s), the supply and application of nitrogen fertiliser for agricultural production processes. It is important to mention, that regional aspects, such as for example the GHG intensity of electricity sourced from the public grid might to different results in the assessment for different regions and member states in Europe.

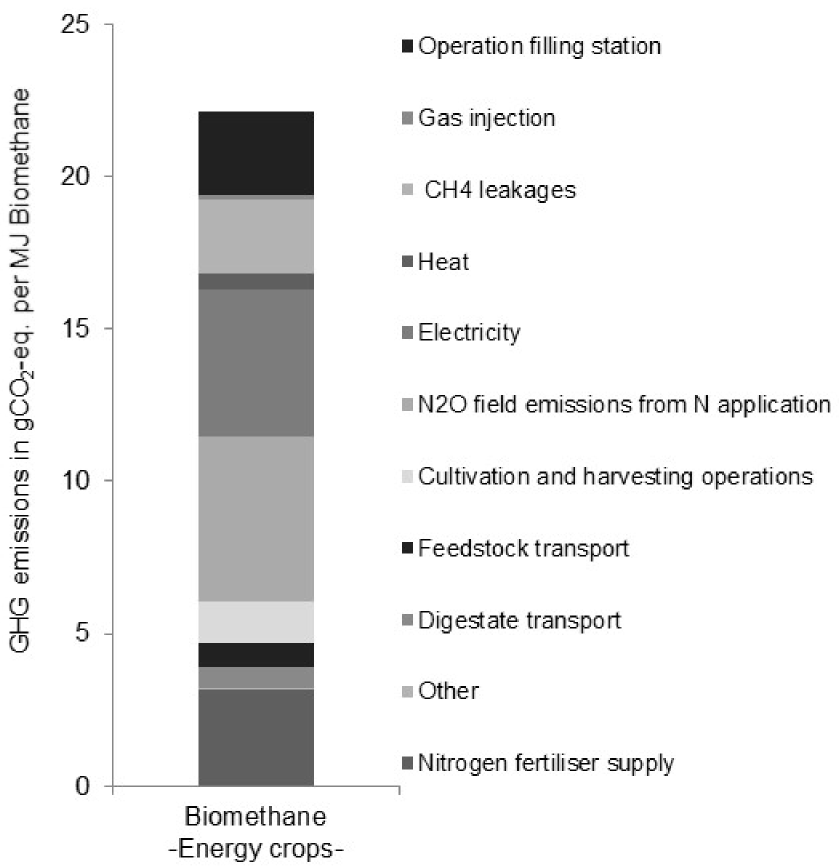

Figure 7 Relevant drivers and influencing factors in the GHG balance of Biomethane(own illustration based on[(Westerkamp et al. 2014), (Daniel-Gromke et al. 2020)]

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The RED II recognises the potential to reduce GHG emissions in agricultural processes due to the use of manure/slurry for biogas and biomethane production (compare section 2.2.1). The credit for this mitigation of emissions can have a significant impact on the overall result, depending on the amount of manure used per functional unit (e.g., MJ of biomethane or kWh of electricity produced from biogas). This effect is illustrated in the following Figure 8.

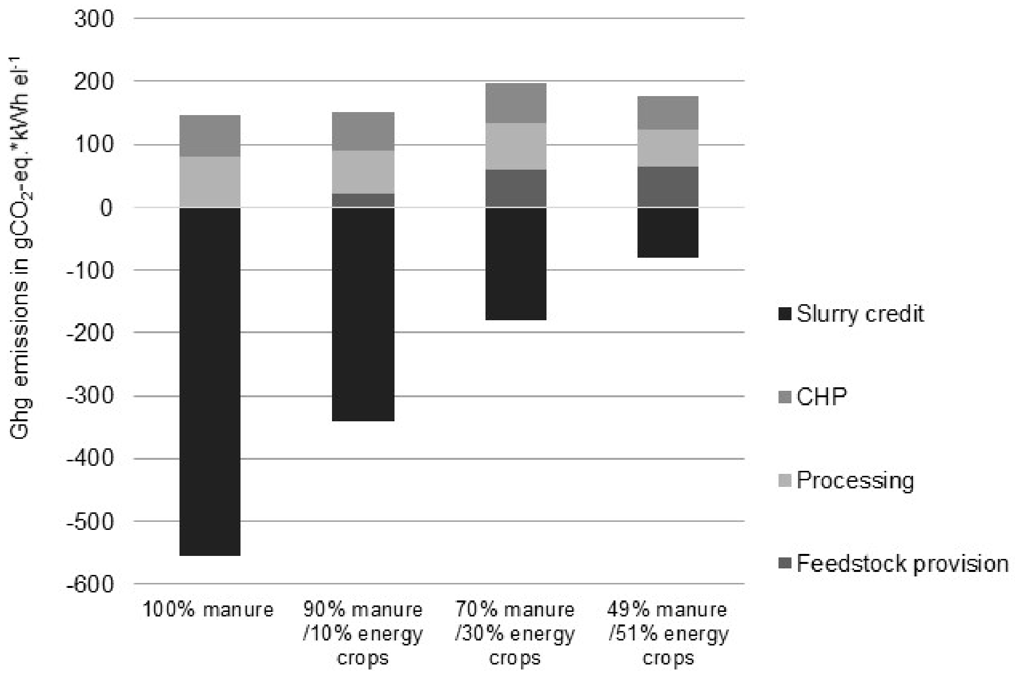

Figure 8 Influence of different feedstock compositions on the result (own illustration based on (Daniel-Gromke et al. 2020; Westerkamp et al. 2014)

Depending on the impacts related to the type of feedstock used for the production of biomethane on the overall GHG performance of the pathway, the following broad differentiation can be made:

i) wastes and residues: no emissions from the production of the biomass is accounted for;
ii) energy crops: emissions from the cultivation of the biomass have to be accounted for and included in the overall balance;
iii) credits for the use of degraded lands, improved agricultural practices leading to an increase in soil organic carbon stocks or the use of manure/slurry can significantly reduce the overall GHG emissions of the biomethane production pathway.

Figure 8 shows an exemplary GHG balance for the cultivation of energy crops for biomethane production. In this example, emissions from the application of nitrogen fertiliser (N_2O emissions) as well as the emissions from the production of the fertiliser are the most important and influential factors.

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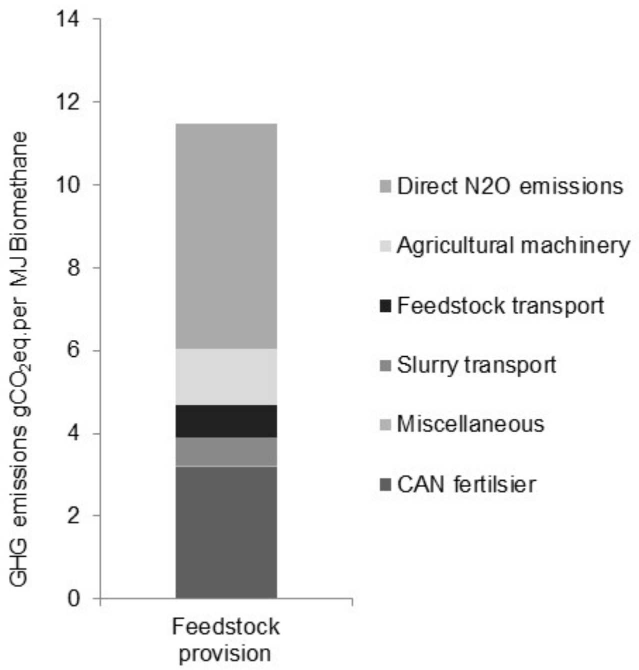

Figure 9 Factors influencing the GHG emissions of biogas feedstock production (Swiss centre for life cycle inventories 2019; Oehmichen and Thrän 2017; Westerkamp et al. 2014)

Upstream emissions of synthetic Nitrogen fertilizers are dependent on the specific production process and can for example be driven by the use of natural gas for the synthesis of ammonia. However, available publications (Swiss centre for life cycle inventories 2019; Oehmichen and Thrän 2017) show differences regarding the GHG performance of different Nitrogen fertilizers available, ranging for example between 2.6-15.9 $kgCO_2eq./kg$ N for the fertilizer included in Figure 9. Consequently, the choice of the Nitrogen fertiliser used can be one option to influence the GHG performance of the substrate cultivation process. Besides the option using synthetic fertilizer with comparably lower upstream emissions, the use of organic Nitrogen fertilisers (e.g., biogas digestate) can also be an interesting option.

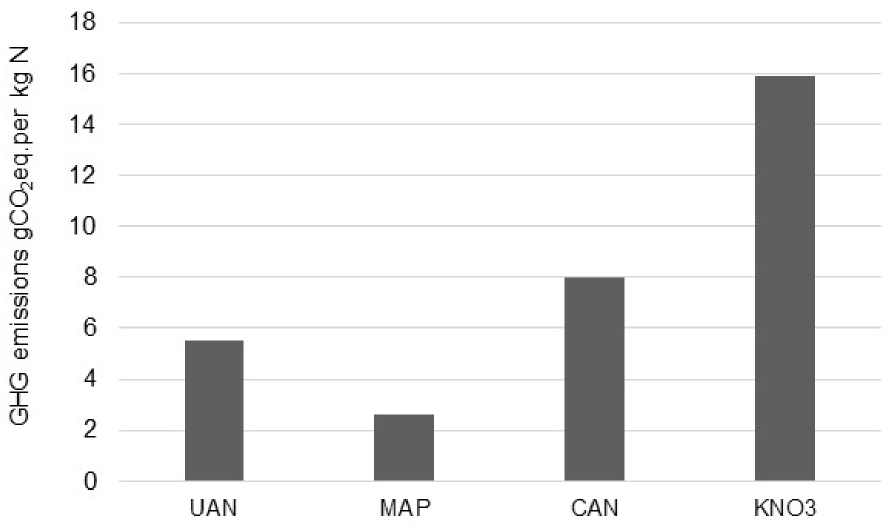

Figure 10 Upstream emissions of different Nitrogen fertilisers from (Swiss centre for life cycle inventories 2019; Oehmichen and Thrän 2017)

Furthermore, the application of Nitrogen fertiliser to agricultural production systems can result in losses of Nitrogen and thus, the formation of N_20, which can be emitted to the air. The magnitude of the respective N_2O emissions from Nitrogen application is dependent on a number of factors such as the application technology, the general soil-climatic conditions of the agricultural area as well as the cropping system. (Joint Research Centre)

The emissions can be in a range of approximately 0.3 to 3% of applied N leading to the formation of N_2O emissions, leading to substantial differences in the overall GHG performance of the Biomethane produced (compare Figure 10). The RED/RED II allows for the use of different approaches for the calculation of the respective N_2O emissions from biomass cultivation for energy production.

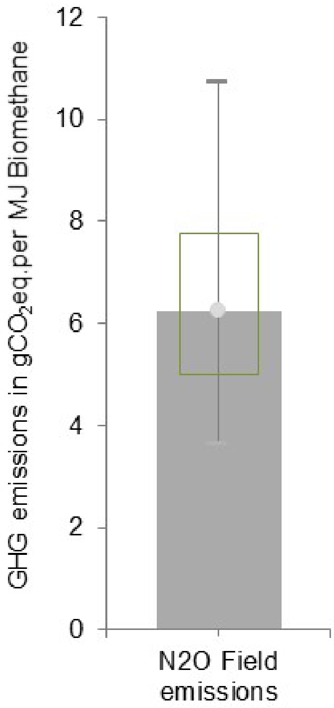

Figure 11 Exemplary magnitude of soil emissions from nitrogen application based on (Oehmichen and Thrän 2017; Westerkamp et al. 2014)

Furthermore, due to the high impact of methane as a greenhouse gas (25x compared to CO_2, as defined in the RED II) the consideration of direct methane emissions is particularly relevant, for example at the biogas plant. The operation of biogas fermenter, leakages and disturbances can lead to methane emissions during the process of biogas production. The RED II default values for the GHG emissions related to methane slip account for 1% of the methane produced during biogas production as being emitted throughout the overall process. Figure 11 shows the results from CH_4 measurements on different biomethane plants and the impact of these differences on the GHG performance of the biomethane. The shown median values correspond to 0.5% (plant1), 2% (plant 2) and 0,22% (plant 3) of CH_4 emissions per produced biogas. (Westerkamp et al. 2014). In addition, emissions from the upgrading of Biogas to Biomethane can be relevant as well, depending on the specific upgrading technology.

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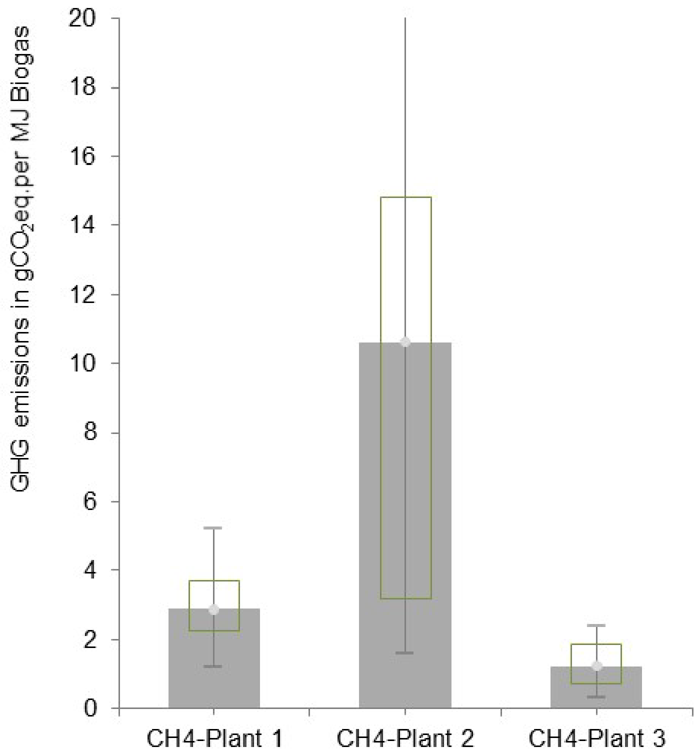

Figure 12 GHG emissions from methane losses at biogas plants Based on (Westerkamp et al. 2014; Vogt 2007)

The storage system for the biogas digestate can be another relevant source of CH_4 emissions from the biogas process. Figure 12 includes an exemplary calculation, based on (European Commission European Commission: Brussels, Belgium, 2018; Majer et al. 2019) showing the potential impact of CH_4 emissions from the digestate storage system. Especially, (too) low retention times can lead to a partly decomposition of the organic substrate. Consequently, residual CH_4 emissions can be generated in the digestate storage system. Exemplary calculations show emissions of 25gCO_2eq per MJ Biomethane in case of open digestate storage systems. (Majer et al. 2019)

The default values of the RED II do also highlight the relevance of this parameter, since default values for concepts with open digestate storage systems do not meet the mandatory GHG mitigation targets.

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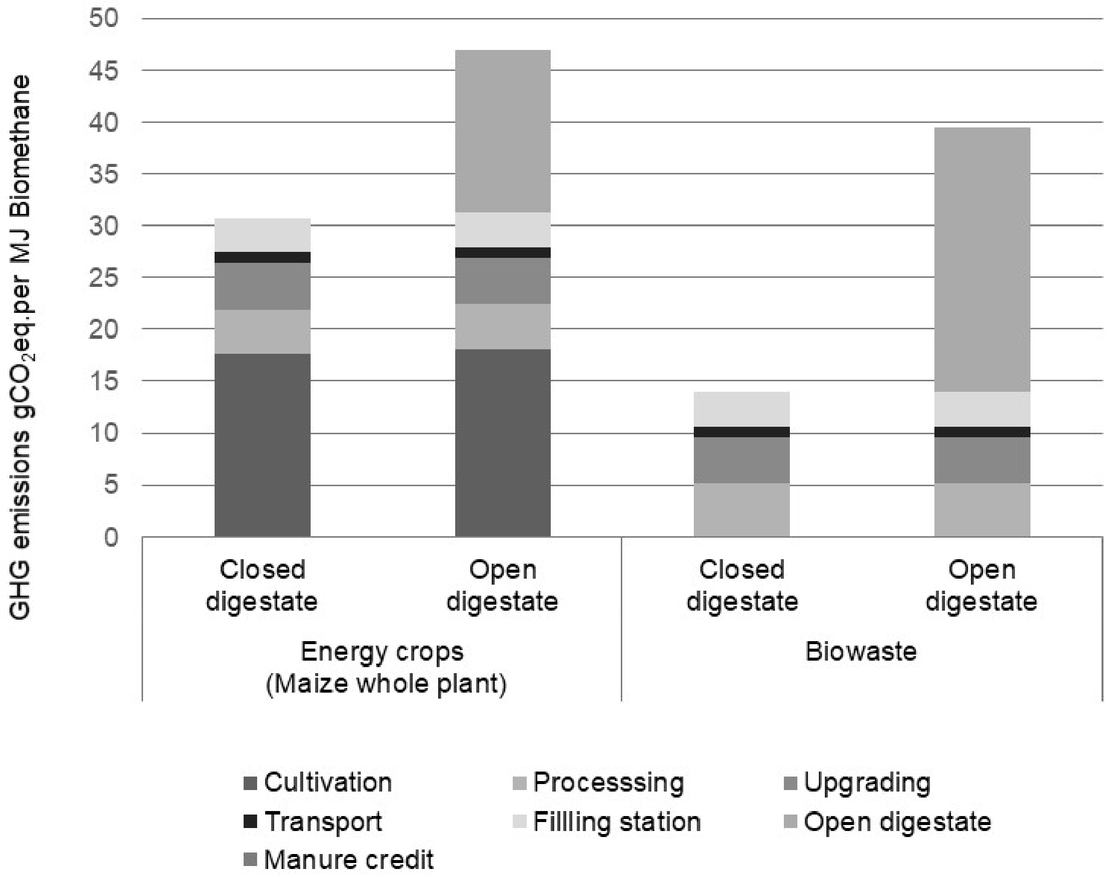

Figure 13 GHG emissions from different storage systems for biogas digestate based on (Majer et al. 2019; Biograce Consortium; European Commission European Commission: Brussels, Belgium, 2018)

Finally, GHG emission calculations for biomethane production processes usually identify the supply of process energy as one of the relevant parameters during the processing of biogas and biomethane. Amongst others, the operation of the biogas fermenter requires thermal and electrical energy. Depending on the actual configuration of the plant, both demands can be meet using internal solutions for energy provision (e.g., combustion of raw biogas in a boiler or CHP unit) or based on sourcing of energy from external sources (e.g., electricity from the public electricity grid). Depending on the specific emission factor for electricity supply from the public grid, the use of externally supplied electricity can cause significant higher emissions than the use of internal supplied energy or the use of other renewable energy. Figure 13 shows an exemplary calculation, using an emission factor for electricity from the German electricity grid, compared to an internal energy supply, based on the use of biogas in a CHP unit.

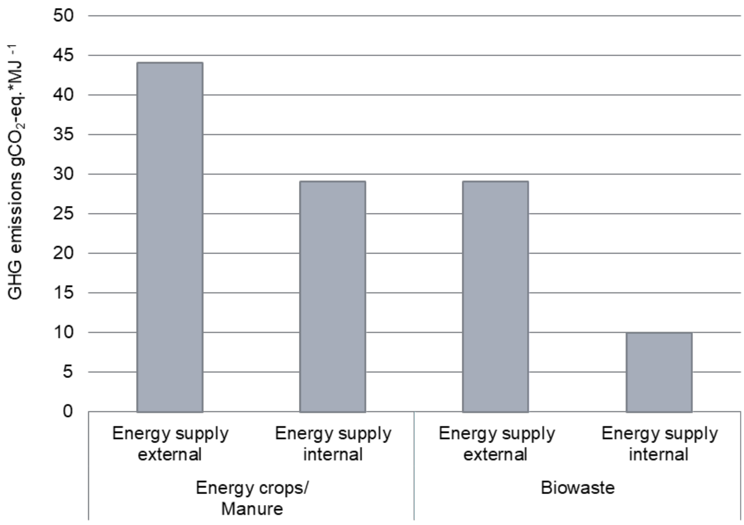

Figure 14 Influence of different scenarios for the supply of process energy at a biogas plant (Thrän et al. 2011; Majer et al. 2016)

3.1.2 Biomethane via gasification (Bio-SNG)

Another technological option for the production of biomethane is the gasification of biomass to produce methane. Respective concepts are typically based on solid biomass fuels from forestry or agriculture (e.g., Short Rotation Coppice (SCR)) as well as residues (e.g., from saw mills). In general, it has to be noted that the market relevance and penetration of BIO-SNG concepts is not comparable to the amount of existing Biogas and Biomethane production plants. Consequently, few publications on the assessment of the environmental and economic aspects of the Bio-SNG production exist.

Existing publications on the emissions of Bio-SNG concepts highlight a couple of differences in the GHG performance of this technological route for methane production compared to Biomethane production via fermentation. One of the major differences can be related to the process of the substrate or feedstock production and supply. In case for example waste wood or wood chips are being used for the production of Bio-SNG emissions from the supply of these feedstocks can be significantly lower compared to the cultivation process for energy crops for biogas/biomethane production (compare (Kraussler et al. 2018; Müller-Langer 2012).

Additionally, while it is in general feasible to omit CH_4 emissions from both technological routes for the production of Biomethane, (Kraussler et al. 2018) define state-of-the-art Bio-SNG concepts using components such as central waste gas treatment units and flares resulting in almost none CH_4 emissions from Biomethane processing. Figure 14 shows results from the calculation of GHG emissions from BIO-SNG production, ranging from approximately 26 gCO_2eq. per MJ Bio-SNG to ~35 gCO_2eq. per MJ Bio-SNG. Both authors identify the processing of the solid biomass to Bio-SNG as the most relevant source of emissions, with the supply of process energy being the most relevant parameter. Thus, further increases in conversion efficiencies, as anticipated by ((Kraussler et al. 2018; Müller-Langer 2012; Billig 2016) as well as alternative scenarios for the supply of process energy (with lower upstream emissions are potential measures for an optimisation of the GHG emission performance of these pathways.

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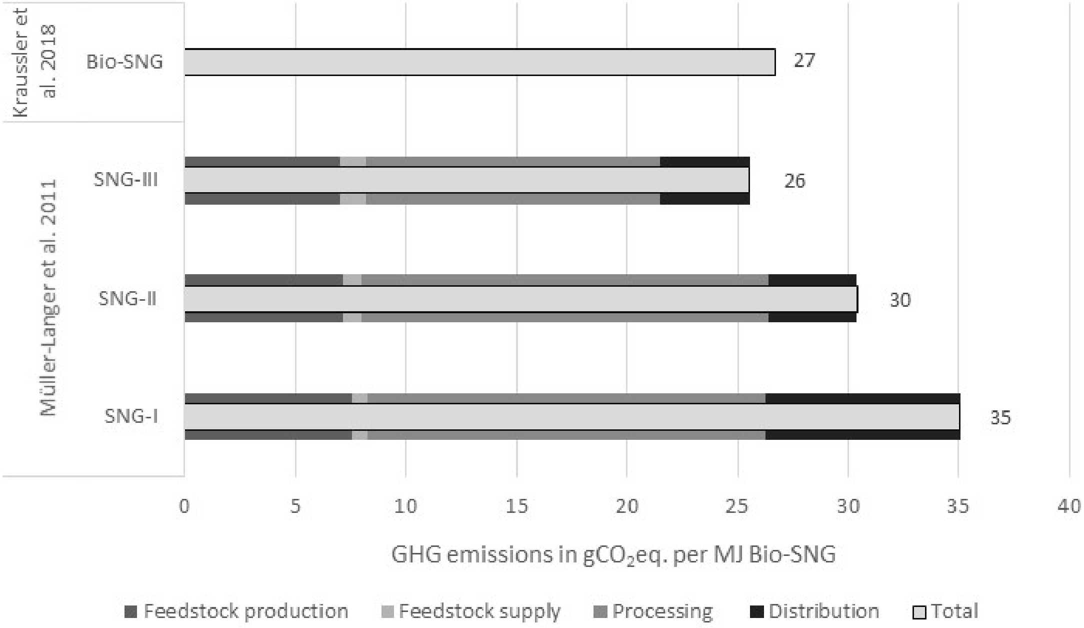

Figure 15 GHG emissions from Bio-SNG production based on (Müller-Langer 2012; Kraussler et al. 2018)

3.1.3 Hydrogen

This report focusses on the production of hydrogen via steam reforming and electrolysis. Both technological routes are considered to be amongst the currently most relevant pathways for the supply of hydrogen (Swiss centre for life cycle inventories 2019).

3.1.3.1 Hydrogen from electrolysis

Emissions from the production of hydrogen via electrolysis are comprised of the emissions from electricity production, and those from the electrolysis plant itself. A comparably wide range of data is available from different publications. However, direct comparison is (again) not possible in most cases because of differences in scope, e.g., building materials, electricity source, and electrolyser type, and general assumptions made (e.g., on lifetime and load factors). All of these factors can have a significant impact on the level of emissions.

The GHG emission performance of hydrogen produced by electrolysis depends significantly on how the electricity was generated. Consequently, potential future improvements on the GHG emission intensity of electricity production in EU member states will lead to hydrogen production with lower GHG intensity. The use of a low-carbon or waste heat source would furthermore decrease emissions.

While authors such as (Spath and Mann 2000) and (Mehmeti et al. 2018) indicate that emissions from the actual construction of the infrastructure (for both electricity and hydrogen production) can be significant, emissions from the construction of processing units are actually not to be accounted for under the RED II GHG calculation framework. (Dietrich et al. 2017)calculate the GHG emissions of hydrogen production under the RED framework, solely focussing on the upstream emissions from the electricity production. Consequently, a GHG emission intensity of ~149 gCO_2eq. per MJ of H_2 has been calculated based on hydrogen production via electrolyser using electricity from the German electricity grid. However, it has to be noted that due to the significant impact of the emissions factor for electricity, a further increase in the share of renewables in the public electricity grid would lead to an

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emission reduction for the hydrogen produced in this scenario. Alternative scenarios, using electricity based on renewable energy leads to zero emissions from hydrogen production (compare (Dietrich et al. 2017).

3.1.3.2 Hydrogen from steam reforming

There are a number of technologies for the production of hydrogen from natural gas, with steam methane reforming being the most widely applied method of hydrogen production today (compare (E4tech 2019)). Figure 15 shows results of different publications on the GHG emissions of hydrogen production via steam reforming (including those associated with the natural gas source fuel or the biomass feedstock used).

For hydrogen production from natural gas, the CO_2eq.emissions reported in Figure 16 vary between ~62 and ~100 gCO_2eq. per MJ H_2. The sources indicate that the majority of these CO_2 emissions are due to the carbon in the natural gas released at the hydrogen production plant. Consequently, the introduction of CCS components could contribute to a significant reduction in the overall GHG intensity of hydrogen production.

Additionally, (Dietrich et al. 2017) calculate GHG emissions of ~33 g CO_2eq. per MJ H_2 produced from Biomethane from energy crops (calculated based on (Biograce Consortium)).

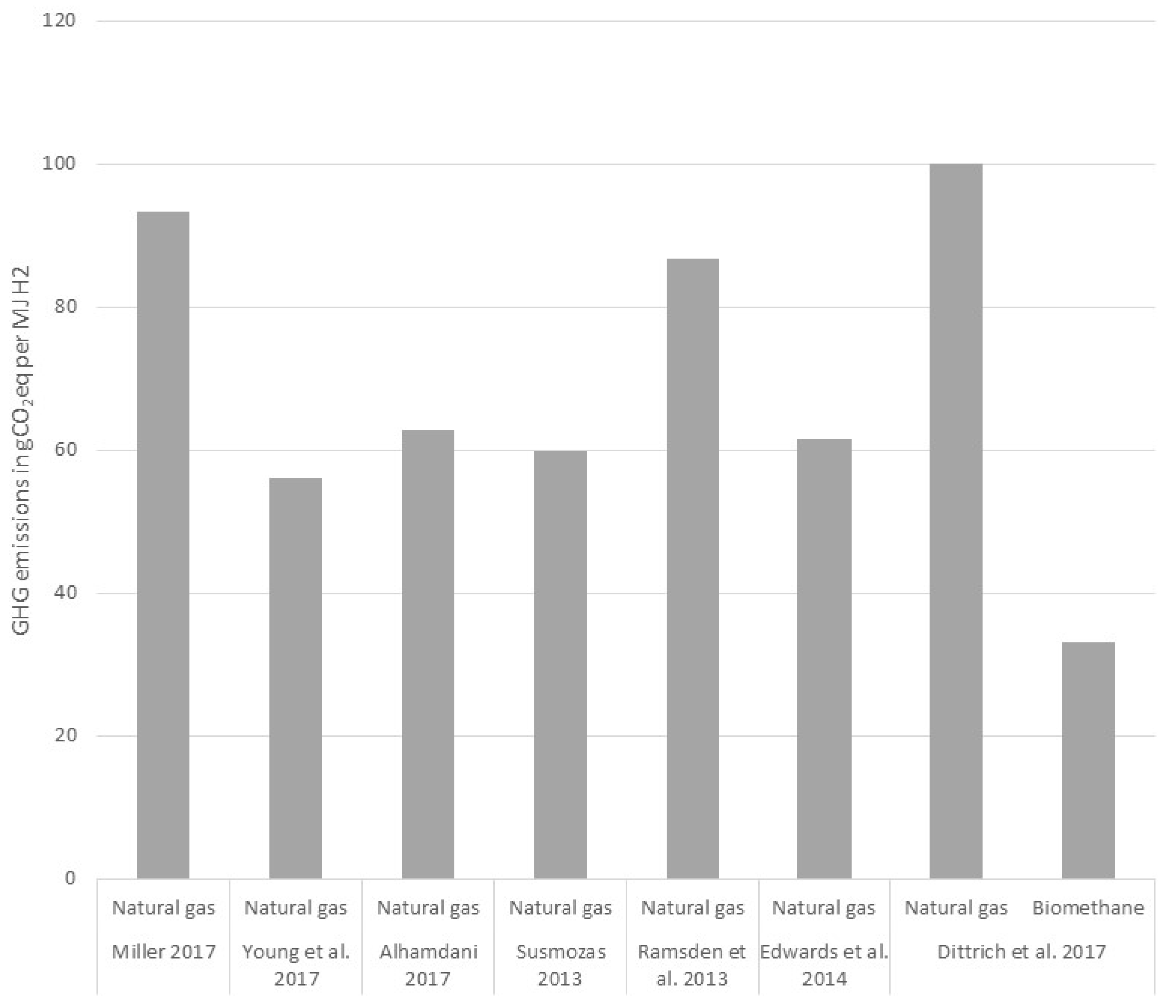

Figure 16 GHG emissions from hydrogen production based on (E4tech 2019)

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3.1.4 Power-to-Gas

The production of synthetic fuels, both gaseous and liquid based on concentrated CO_2 flows and electricity is gaining increasing attention from various stakeholder groups. One of the motivations behind this development is the potential need for additional options and concepts for the storage of energy, e.g., from fluctuating electricity technologies such as wind and solar power. The concept of Power-to-gas production allows for example the production of Methane which could be fed into the natural gas grid based on CO_2 and hydrogen produced with renewable electricity.

Consequently, the source and respective emission factor of the electricity used for hydrogen production (or the emission factor of the used hydrogen in general) as well as the carbon source for the CO2 used in the process are two main influencing parameters, which determine the GHG balance of PtG pathways.

Since a very wide range of potential combinations with electricity from different technologies and spatial locations as well as CO_2 sources can be used, it is almost impossible to develop a complete picture of existing possibilities. We will use the next deliverable (D5.2) of REGATRACE WP5 to discuss regional cases of technology combinations (e.g., renewable electricity and CO_2 from Biogas upgrading units in different EU member states) to expand the scope of this assessment of the GHG intensity of PtG production pathways.

Figure 15 includes results from the comprehensive study by (Meylan et al. 2017) who investigated the GHG intensity of different PtG pathways combining CO_2 sources from Natural Gas (NG), Coal, Cement production Biogas from energy crops an organic waste as well as from direct air capture with hydrogen production from electricity based on photovoltaics (PV), concentrated solar power (CSP), wind (on-shore), hydropower as well as surplus electricity (with an assumed emission factor of zero GHG emissions per kWh_{el}). Based on the above-mentioned impact of the carbon source and the electricity production, the authors found the highest emission intensity for concepts with fossil carbon sources (Cement, coal and natural gas) combined with hydrogen production based on PV electricity (which has the highest emission factor (~11 to 14 gCO2eq. per MJ) amongst the five electricity sources considered by (Meylan et al. 2017)). Conversely, concepts using biogenic carbon or carbon from direct air capture combined with hydrogen from surplus electricity show the lowest GHG intensity (~ 7 to 16 gCO_2eq. per MJ PtG).

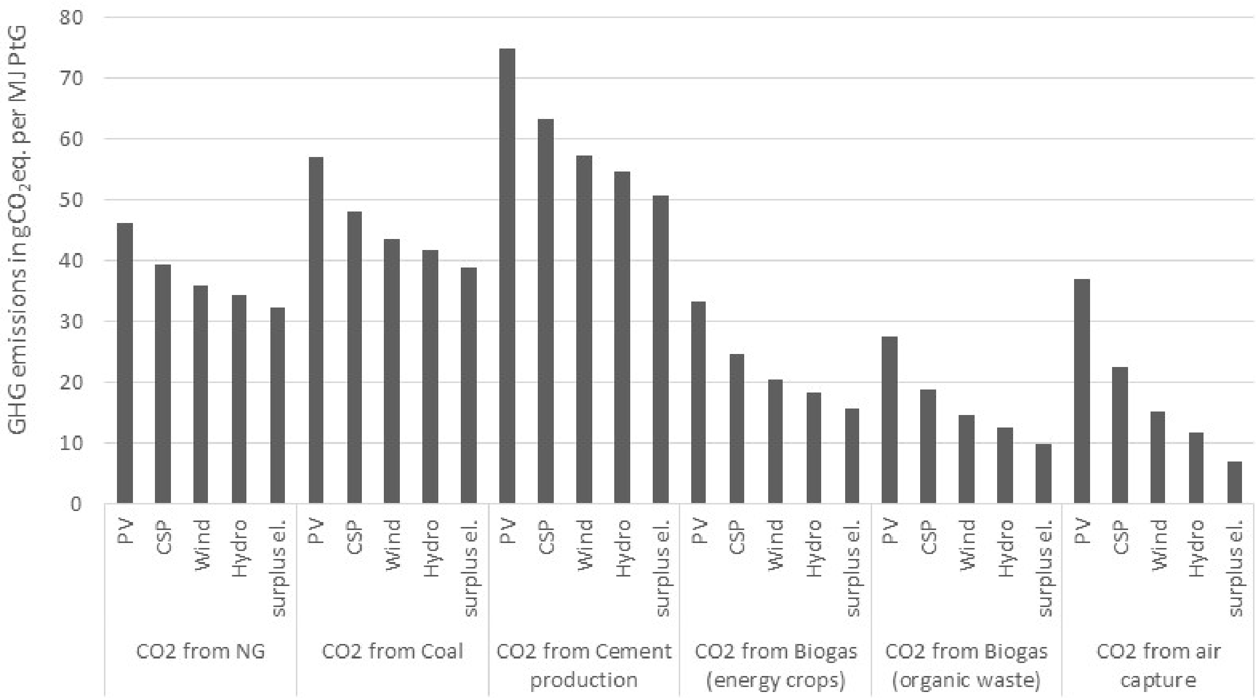

Figure 17 GHG emission intensity of PtG production from different scenarios, based on (Meylan et al. 2017)

3.2 Costs of Renewable Gas technologies

3.2.1 Biomethane from Biogas upgrading

Just as discussed under chapter 3.1.1, the GHG emissions of biomethane from biogas upgrading, also the costs of biomethane production can show a wide bandwidth, depending on a number of decisive factors, which can be completely different depending on the specific regional and technological set-up of a biomethane supply chains. These decisive factors do include, amongst others, the type of feedstock used and the related costs for feedstock production and supply (operating costs; OPEX), the costs for the operation of the biogas plant as well as costs for biogas upgrading and biomethane feed-in (capital costs). Furthermore, there are significant economy of scale effects, especially regarding the CAPEX costs, which can lead to higher costs in smaller production facilities. (Daniel-Gromke et al. 2020; Wietschel et al. 2019).

The costs for the production of biogas consist of the capital and operating costs for the plants, the energy costs and the costs for the provision of feedstock. In case of Biomethane production based on energy crops, feedstock costs can amount to up to 50% of the total production costs (Reinholz and Kühnel 2018) and thus have a significant influence. Given this strong influence on the total costs, potential variances in feedstock yields and costs can lead to volatile production costs for biomethane as well. (Völler and Reinholz 2019; Wietschel et al. 2019). The costs for biogas and biomethane production are clearly dependent on local conditions. Higher local availability of raw materials enables the operation of larger plants. With the size of the plant, the specific costs of the plant decrease and lower costs can be realised. (Wietschel et al. 2019)

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Figure 17 shows ranges for production costs of Biomethane from different feedstocks, based on publications by (IRENA 2013; Daniel-Gromke et al. 2020) and others. The cost figures differ significantly and range from 4.2 to 13.5 €ct/kWh.

In order to feed the produced Biomethane into the natural gas grid, the biogas has to be upgraded and cleaned. Costs for this production step depend on the capacity of the gas purification plant. (Klukas et al. 2018; Wietschel et al. 2019) assume costs in the range of 1.4 €Cent/kWh. Additionally, (Lischke A. et al. 2015) assume a further 0.3 €Cent/kWh for transport in the natural gas grid (Lischke A. et al. 2015).

Depending on the type of feedstock used, the results show ranges for biomethane production costs between 6.3 to 8.7 €Cent per kWh biomethane for the example of energy crops.

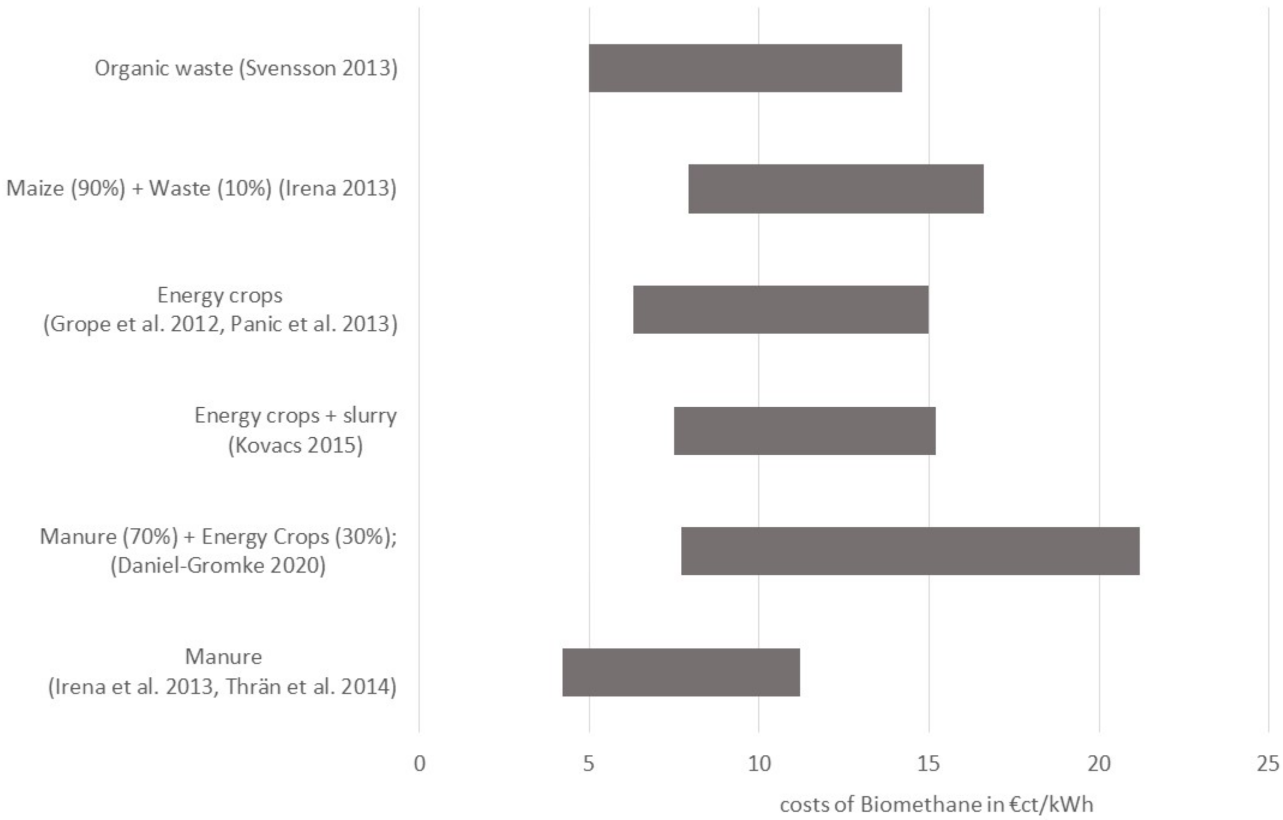

Figure 18 costs of Biomethane from Biogas upgrading based on different publications

Again, it has to be noted, that due to strong regional and local differences in feedstock costs, Biomethane production costs can in general vary across EU member states. Thus, we will continue the assessment of regional biomethane production concepts in the course of WP5 and the upcoming deliverable 5.2.

3.2.2 Biomethane via gasification (Bio-SNG)

Müller-Langer et al. 2011 calculates production costs of different alternative fuels. For biomethane from biomass gasification, a range of 19.7 to 26.4 EUR/GJ (i.e., 70.9 to 95 €cent per kWh Bio-SNG) are shown in the publication. These results are in the range for costs of Biomethane from biomass

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gasification calculated by (Kraussler et al. 2018), who calculated costs for a wide range of concepts. Results in this publication are in a range of 65.7 to 153.7 €cent per kWh Biomethane. Results from both publications are included in Figure 18.

In comparison to Biomethane from Biogas upgrading CAPEX costs are significantly higher for Bio-SNG production. In fact, they can add up to ~50% of the total costs (compare (Kraussler et al. 2018)). Consequently, positive scaling effects related to an increasing plant capacity can lead to a reduction in the capital-bound and thus the operation-bound costs. Regarding the operation of the plants, feedstock costs as well as consumption of electricity and feed-in costs are the most relevant parameters.

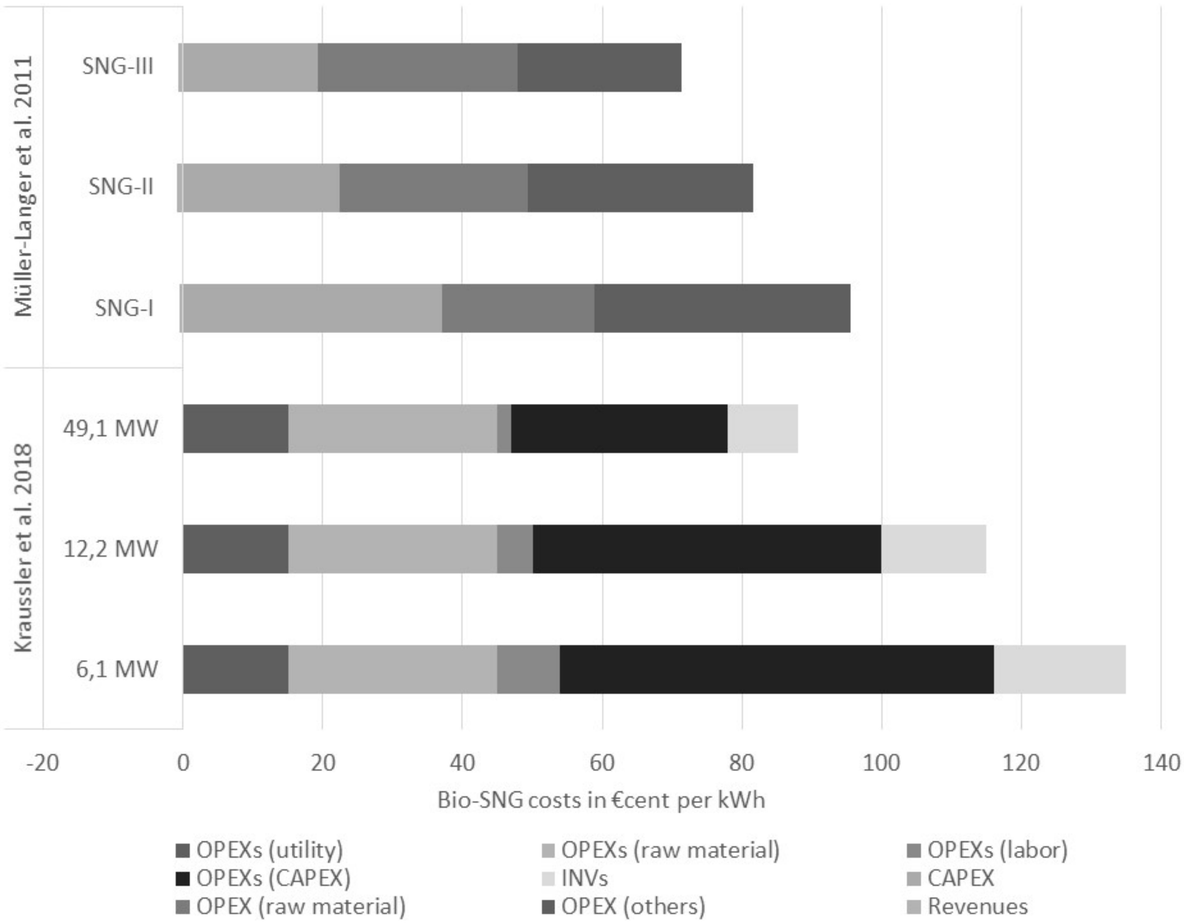

Figure 19 Costs of Bio-SNG production in €cent per kWh Bio-SNG

3.2.3 Hydrogen

(Dietrich et al. 2017) calculate the costs for hydrogen production and provision, based on different scenarios, including regions for the production of electricity, as well as technologies and feedstocks. For hydrogen production based on electrolysis, the production costs are dominated by the costs for the electricity to operate the electrolysers. However, the capital costs for the electrolysers and hydrogen storage are comparably high at low annual full load hours. The lower electricity costs can only compensate for this disadvantage to a limited extent. In contrast, conventional hydrogen production by means of steam reforming is associated with much lower costs. On the one hand, this can be attributed the specific investment costs of steam reformers, which are assumed to be (much)

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lower than electrolysers. Secondly, in general no large hydrogen storage facilities are needed, since the concept of hydrogen production from steam reforming allows for continuous production.

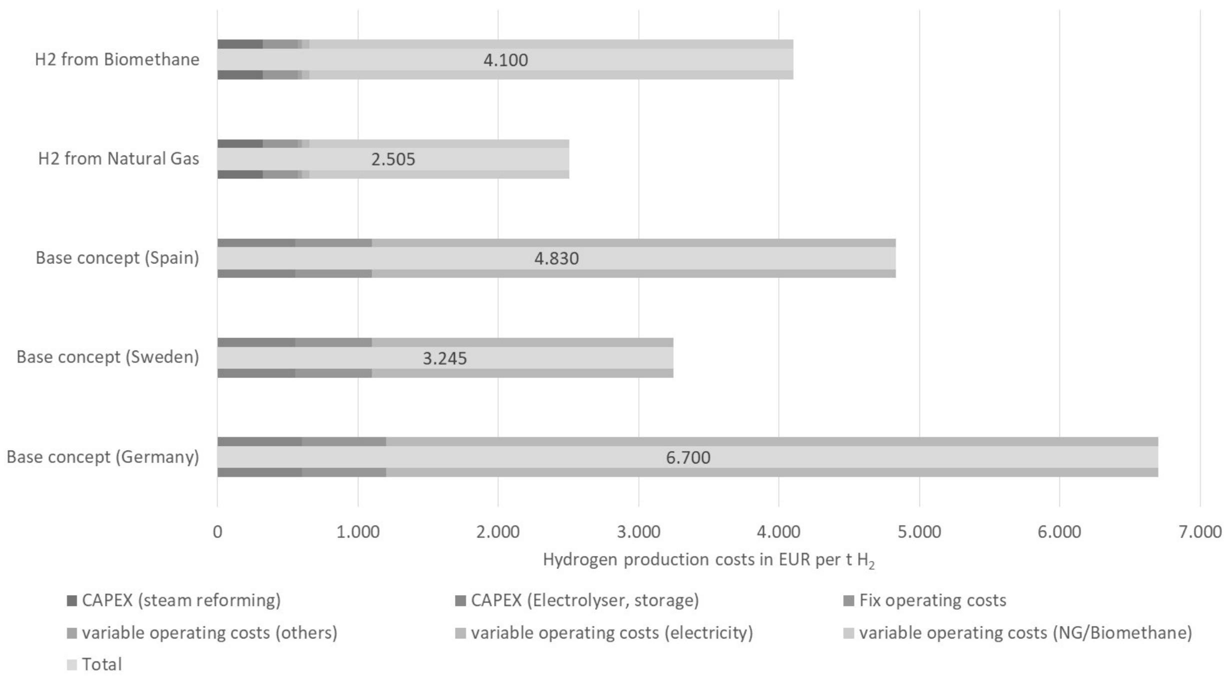

Figure 20 Production costs for hydrogen in EUR per tonne of H_2

3.2.4 Power-to-Gas

In general, costs for the production of Power-to-Gas are a function of capital expenditures (CAPEX) for the PtG plant as well as the costs for the electricity used. Since the CAPEX of PtG technologies is comparably high, PtG facilities require high full load hours and inexpensive renewable electricity in order to become economically competitive. (Gorre et al. 2019) Depending on the assumptions made for the costs of electricity and of sustainable CO_2 sources, a wide number of scenarios is possible, leading to a potentially wide range in the cost indications of PtG.

According to (Gorre et al. 2019), there are three decisive economic factors, which determine the operation strategy of a PtG production. Those are:

i) the (market) price of electricity and the maximum willingness-to-pay for electricity;
ii) ii) the market price of the respective PtG products, depending also on the potential willingness of customers to pay more compared to natural gas or other reference products; and
iii) the market price and the availability of the targeted CO_2 sources.

As of today, the CAPEX of today's PtG systems are comparably high, however, (Gorre et al. 2019) argues that CAPEX of PtG plants might decrease in the future due to potentially increasing experiences as well as economies of scale, leading in theory to lower costs for larger plants. (Deutsch October, 16th, 2018) argues that due to the high CAPEX, inexpensive electricity sources as well as high full load hours are necessary to produce PtG at competitive cost levels. This means, that there might be regional preferences for PtG production, especially in those regions that can produce inexpensive

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renewable electricity at high capacities for large parts of the year. Furthermore, Deutsch et al. argue that the general development and increase of global capacities in both renewable electricity production as well as electrolysis capacities are key components to develop PtG capacities.

Depending on the development of these volatile parameters Deutsch et al. estimates potential costs of PtG production in a range of 20-30 €cent/kWh. The authors argue that these costs could potentially decrease to around 10 €cent/kWh by 2050. (Gorre et al. 2019) show a wide range of cost estimates, for different scenarios and timelines.

Both publications underline the importance of the political framework which could influence aspects such as costs of renewable electricity, demand for electrolysers as well as CO_2 prices for the development of competitive PtG concepts.

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4 Sensitive issues in the assessment of renewable gas technologies under the RED II framework

Over the recent years, under the RED, significant effort has been made to create a framework for the production and use of biofuels under-recognition of different sustainability criteria. Furthermore, the instrument of co-regulation in the RED has led to the development of a large number of certification schemes and certification bodies that operate to control compliance with the RED sustainability criteria during all processes in a biofuel supply chain.

While it is in general admissible to discuss existing weaknesses and demand for further developments within this system of the RED framework and its approach to compliance and verification with the requirements defined in the RED and the RED II, it can be acknowledged, that this framework has created a market for sustainable bio-based products, based on comparably harmonised criteria, which can be considered unique within the EU Bioeconomy. (Majer et al. 5/14/2018)

While the RED framework has defined a coherent set of sustainability criteria and rules for their control, the future development of technologies which include process chains from different industrial sectors might lead to a number of potentially sensitive issues for the assessment of these supply chains. Some of the technologies and technology combinations discussed in REGATRACE can involve different processes, which might not always be included under the RED framework. However, a correct and coherent accounting of the GHG intensities of the different renewable gases as well as other products which might be produced within these supply chains is crucial and requires harmonised accounting rules as well as a transfer of information related to sustainability characteristics of the different products across sectors.

While discussing the decisive factors for the GHG intensity of the different technological concepts, a number of potentially sensitive points can be identified. These aspects will be briefly introduced in the next section. REGATRACE D5.3 will allow for a more comprehensive debate of these aspects as well as additional points, at a later stage of the project.

Credits from CCU vs. carbon accounting of PtG fuels. The GHG calculation methodology of the RED II allows for a consideration of emission savings from the use of carbon dioxide, captured from biofuels processes, in other product systems. In case, for example, carbon dioxide is captured from biogas upgrading and used to produce a PtG fuel, together with hydrogen from renewable electricity, the respective producer of the Biomethane might be able to claim a credit in the GHG emission calculation of the Biomethane. This credit can significantly affect the magnitude of the GHG emission intensity of the Biomethane fuel. However, the carbon dioxide which is produced in this manner is now input to another product system, which aims to produce a PtG fuel, containing the respective carbon from the biogas upgrading process.

The main question for the assessment of the GHG intensity of the PtG product which is now produced is, whether the actual combustion of the PtG fuel can be considered carbon neutral (at least for the part of the CO_2 emissions), even though the carbon stems from the cultivation of the biogas feedstocks. However, if for example, the biomethane producer has already claimed the “credit” from the benefit of the carbon dioxide use, it is important to avoid potential double counting in the GHG intensities of interlinked product systems. This can be even more relevant, in case not all parts of the products system are affected by the regulations of the RED framework. Furthermore, a correct accounting and even more importantly the robust control and supervision of such a cross-sectoral accounting of product GHG intensities might require an additional transfer of information across sectors and market actors. For the example illustrated here, this would mean that specific knowledge of the respective credit for CCU in the calculation of the GHG intensity of the biomethane would be crucial for the assessment of the PtG product and especially its use phase.

Furthermore, potential sectoral links for the production of renewable gases based on technology combinations might **require additional interfaces and coordination** between different approaches **for mass balancing.** Currently, track and trace mass balancing is the dominant approach to verify the compliance of biomass and biofuels with the RED sustainability criteria along the chain of custody. The result from this proof of compliance are typically proofs of sustainability (PoS) for the single processes in the supply chain and a sustainability certificate of the final biofuel. If for example biomethane sustainable biomethane is injected into the natural gas grid, a change regarding the underlying logic in the mass balancing will occur. While registries can be used to track the in- and output of different energy carriers into a system, they (at least in the gas sector) are mostly based on book and claim approaches for the general mass balancing. However, in case products from systems based on book and claim mass balancing approaches enter a supply chain in which the compliance with sustainability criteria is being organised according to a track and trace logic, it can be difficult to further distinguish between sustainable and unsustainable (i.e., without PoS or sustainability certificate) materials and products. In the case of PtG fuels, this can lead to additional questions about whether the PtG produced can be considered sustainable or “carbon neutral”.

Finally, and related to the previous aspect, the RED and RED II do refer to the concept of additionality regarding the use of electricity for the production of alternative fuels. Depending on the actual implementation of the RED (II) in the EU member states and the respective interpretation of this concept, this could result in an important aspect regarding the GHG intensity and costs of, amongst others, PtG fuels. As shown in chapter 3, the source of the electricity for the processing of biofuels or the production of PtG is a decisive factor for the GHG intensity of these products. In order to achieve for example a PtG product with low GHG intensity, the use of electricity from renewable sources is important (Meylan et al. 2017)). In the same way, the use of renewable electricity for the energy supply of a biofuel processing plant can lead to lower overall emissions compared to the use of electricity from fossil sources or the regional mix in the electricity grid (Majer and Oehmichen 2017; Majer et al. 2016). However, the interpretation and implementation of the additionality approach under the RED has, in some EU member states led to the situation, where the use of an alternative (compared to the emission factor for electricity from the public grid) emission factor for the electricity used was only possible in case an additional capacity for electricity production, without a direct connection to the public grid has been installed. As a consequence, such an installation of a dedicated renewable energy electricity production for the production of PtL, can lead to increasing overall production costs which can negatively affect the economic feasibility of the PtL fuels. Thus, the interpretation of the additionality concept during the implementation of the RED II can have a strong effect on the competitiveness of PtG fuels or PtX products under the RED II framework.

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5 Conclusions & Outlook

To support the identification of promising technologies for the production of renewable gas in WP5, this report focussed on aspects related to the assessment of the GHG emission intensity (methods and results), as well as production costs of different renewable gas technologies. This assessment, which was based on a review of existing literature revealed rather large ranges regarding costs and GHG emissions of the technological pathways considered. Furthermore, due to existing differences regarding general methodological assumptions between the different studies analysed, a direct comparison of the study results is often not possible.

However, regarding the envisaged identification of promising concepts, a number of conclusions can be drawn from the analysis included in this report.

The assessment revealed substantial differences regarding the short-term availability, as well as the market-readiness and the current competitiveness of the technologies analysed. While the production of Biogas and Biomethane from Biogas upgrading is a well-established technology, which is widely implemented in different EU member states, concepts for the production of (Bio-) synthetic natural gas (i.e., from biomass gasification), Power-to-Gas or Hydrogen from renewable electricity or biomethane are currently not (widely) available in the market, mostly due to comparably higher production costs. However, several publications argue that production costs of especially Hydrogen from renewable sources, as well as PtG production, might decrease significantly in the future, depending on the development of factors such as electricity prices and CAPEX of Hydrogen and PtG production plants.

Consequently, for the development of short-term strategies for the production of renewable gases existing capacities of biogas and biomethane production in the EU can be a starting point, both for the production of Biomethane, as well as sustainable biogenic CO_2, which can be sourced from Biogas upgrading. Depending on the local availability of biomass feedstock, as well as the political frame conditions, these installed capacities might increase in the future in different member states. Secondly, existing and potential future capacities for the production of renewable electricity can be another important element to identify regions with a potentially high availability of both, biogenic CO2 from Biomethane production, as well as renewable electricity production. Depending on the future development of CAPEX for Hydrogen from electrolysis, as well as PtG production and the development of electricity and CO_2 prices, these identified regions could become potential hot-spots for an additional production of renewable gas, based on the coupling of existing electricity and CO_2 potentials.

The analysis of driver and decisive factors, influencing the results of the GHG emissions and costs of the technologies showed a significant influence of regional or spatial aspects on the assessment results.

As for Biomethane from Biogas upgrading, the type of feedstock used is of high importance for the overall result. Since local or regional feedstock availabilities as well as costs can vary significantly across the EU, ideal or optimise technology and feedstock combinations as well as the resulting costs and GHG emission intensities of Biomethane concepts can also be very different across EU member states. In general, the production of Biomethane from wastes and residues can be relatively advantageous with regards to the GHG emission intensity compared to the use of energy crops. In particular, the use of manure and or slurry can be a very promising option since the GHG calculation approach under the RED II framework allows for a consideration of a GHG credit for these substrates.

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This credit, which can largely affect the result of the GHG balance of the Biomethane produced from manure, acknowledges GHG emissions that might be avoided due to the substitution of the conventional storage of manure in agricultural systems. Furthermore, regarding the cultivation of biomass feedstock for Biomethane production, regional characteristics such as biomass yields or soil conditions, influencing for example N_2O emissions, can be important parameters influencing the overall GHG emission intensity. Furthermore, various approaches and starting points do exist for a further optimisation of the GHG emission performance along the Biomethane supply chain. These include, amongst other, parameters such as the choice of fertilisers, the concept for the supply of process energy for the Biogas and Biomethane processing units, methane emissions from Biogas production, non-CO_2 emissions from CHP units, as well as the storage systems for the Biogas digestate.

As for the production of hydrogen, the specific characteristics and upstream emissions of the feedstock used do (currently) lead to significant differences regarding the GHG emissions of hydrogen from electrolysis (e.g., from sourced from the public grid) compared to a production based on steam reforming (e.g., from natural gas). However, depending on the future development of the energy sector and the decarbonisation of electricity and gas production, these differences might decrease over time, resulting in low or almost net-zero emissions. Similarly, as for PtG production, especially the price (and the upstream emissions) for the electricity used, as well as the CAPEX for the PtG plants, are the most relevant factors influencing costs and the GHG emission intensity.

Due to the wide range of influencing parameters, the further identification of promising renewable gas technologies in the different REGATRACE countries will be supported by a more detailed assessment of regional specific concepts. This assessment will be included in the next working steps in this work package.

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