



**Deliverable 2.1:
Potential of green CO₂ sources for
ethylene synthesis**

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**CO₂-based
Electrosynthesis of
Ethylene oXIDE**

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DELIVERABLE REPORT

ABSTRACT

This deliverable report covers the aspect of the potential and limitations of green carbon dioxide sources for the electrochemical ethylene synthesis addressed in the CO₂EXIDE project. In Europe around 437 Mt CO₂ /year are released from the combustion of solid biofuels. [1, 2, p. 17] Furthermore, in industrial bioethanol fermentation 4.3 Mt CO₂/year are produced taking into account the annual ethanol production [3, 4]. In the food and beverage industry, the wine and beer production account for approximately 1.5 Mt CO₂/year each. These numbers are projections according to production statistics [5, 6]. From biogas upgrading 3.44 Mt CO₂/year and combustion of remaining biogas 58 Mt CO₂/year are released. Summing up approximately 506 Mt biogenic CO₂ are produced annually in Europe via assessed process routes. The detailed theoretical quantification and characterisation show that only part of this CO₂ potential is available in reality for valorisation. Nevertheless, the amounts are vast related to the targeted utilization pathway in the CO₂EXIDE project.

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1 INTRODUCTION

This deliverable report covers the aspect of the potential and limitations of green carbon dioxide sources for the electrochemical ethylene synthesis. Ethylene oxide is a very important chemical in global industry [9, pp. 22-26], therefore the ethylene oxide production via CO₂-based electrochemical synthesis offers a promising pathway for Carbon Capture and Utilization. Up to now, the state-of-the-art production processes usually consist of direct oxidation where ethylene, oxygen and a recycle gas are mixed together in a catalytic reactor [9, p. 23], resulting in ethylene oxide, carbon dioxide and water [9, p. 36]. In recent years, research on replacing the oxygen by carbon dioxide is in the focus of actual research activities, e.g. by Mobley et al. [10]. CO₂EXIDE aims to produce ethylene by electrolysis from CO₂ and H₂O, followed by the chemical conversion of the intermediates to ethylene oxide.

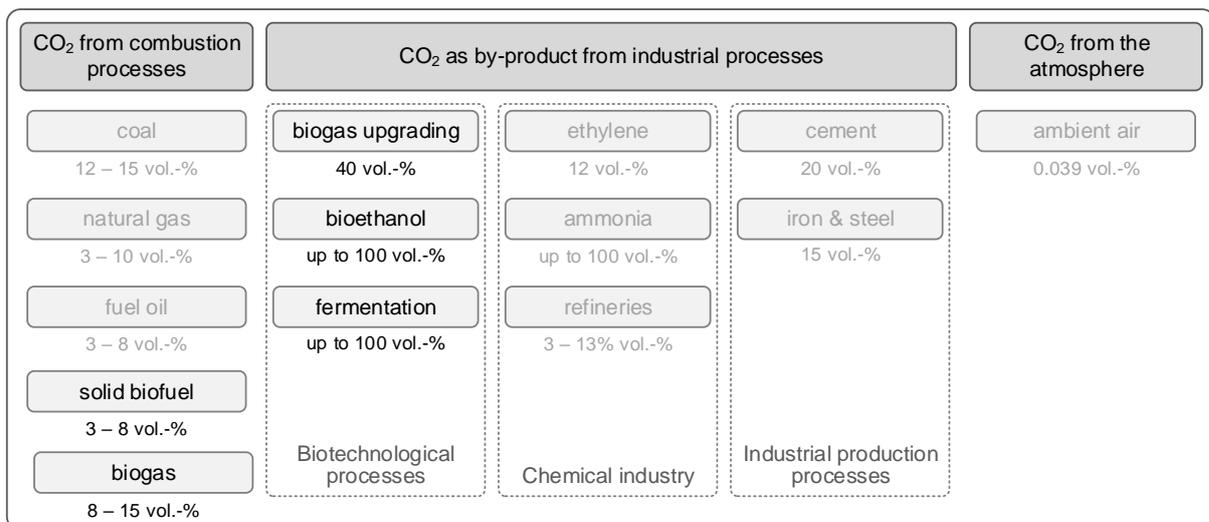
To ensure the climate neutrality of the produced ethylene oxide, the usage of biogenic CO₂ is preferred. Therefore, the main focus is on the use of already available biogenic CO₂ from industrial sources, which is defined as carbon neutral to the environment. [11, p. 11] Using biogenic CO₂ enables the production of fully renewable ethylene and ethylene oxide.

Completing the short assessment, fossil CO₂ sources will be discussed and compared to the biogenic renewable sources based on available quantities and qualities. Further CO₂ sources like ambient air are not in the focus of this project, since the required processes of direct CO₂ capture from air are relatively energy and cost intensive at the actual development stage. [12]

2 POTENTIAL OF GREEN CO₂ SOURCES

Different sources of biogenic CO₂ can be classified as illustrated in Figure 2-1. The main sources are combustion of biomass, CO₂ from biogas upgrading to biomethane and industrial fermentation processes, e.g. brewing processes and other fermentation processes in the food and beverage industry (FAB). Industrial bioethanol is also produced through fermentation [13] but listed here in an own category, since it is used as a biofuel to significant extent and as raw material in several industries different from FAB industry. CO₂ from the atmosphere is not available as a point source from existing industrial plants but as a diffuse source which would demand a high technical effort to separate the CO₂ and yield it as a raw material. For subsequent chemical conversion therefore, ambient air is not counted as an available existing source of biogenic CO₂ here and not further discussed in this assessment. Nevertheless, CO₂ separation from ambient air may still play an important role in the sequestration of CO₂ from diluted and dispersed sources in the long-term, as the technology has the potential for significant further development and optimization. [14]

Figure 2-1: Classification of potential biogenic CO₂ sources including the available typical CO₂ concentration



Source: own illustration Energieinstitut based on [15]

2.1 CO₂ from solid biofuels – combustion of biomass and renewable waste

Solid biofuels are defined here according to Eurostat:

Solid biofuels covers solid organic, non-fossil material of biological origin (also known as biomass) which may be used as fuel for heat production or electricity generation. In energy statistics, solid biofuels is a product aggregate equal to the sum of charcoal, fuel-wood, wood residues and by-products, black liquor, bagasse, animal waste, other vegetal materials and residuals and renewable fraction of industrial waste. [16]

2.1.1 CO₂ potential from solid biofuels in Europe

Solid biofuels are utilized by combustion to the predominant extent but some amounts also statistically contribute to biogas production. The combusted amount however is responsible for the highest biogenic CO₂ emissions in Europe, which account for approximately 437 Mt CO₂/year according to Eurostat statistics of 2016 and IPCC 2006 emission factors for stationary combustion. [1, 2, p. 17] Solid biofuel combustion takes place not only in large plants but also at various small scale facilities like household fireplaces and central heating systems of buildings. The amount of CO₂, which could be utilized is therefore significantly lower than the theoretical potential of 437 Mt CO₂/year, as can also be concluded, if the global statistics for solid biofuels and the fraction of direct heat use is considered (see Chapter 2.1.2).

As can be seen in Figure 2-1, flue gases from the addressed combustion processes consist of only 3-8% CO₂. In flue gases there are many other components that make the utilization of CO₂

in a pure form a technically challenging task. Because of the technical effort, high financial effort is expected, therefore there is a lower economic feasibility obvious in comparison to CO₂ from industrial bioethanol and biogas production based on the source concentration.

An overview of existing and actual initiatives for the development of new CO₂ separation technologies for combustion processes can e.g. be found on the CCS browser [17] of the CO₂ Capture Project (CCP) [18].

2.1.2 Global CO₂ potential from solid biofuels

According to the Global Bioenergy Statistics 2017 of the World Biogas Association (WBA) [19, p. 30] municipal waste, industrial waste and mainly solid biomass account for 54.72 EJ/year (for 2014) worldwide. Municipal waste and industrial waste include non-renewable fractions. 42.88 EJ of this solid biomass energy are converted to direct heat, which means direct consumption of energy sources in the residential, agriculture and commercial sectors (not CHP or heat or electricity only plants) [19, p. 52]. Therefore, only CO₂ deriving from 11.84 EJ¹ could be utilized for Carbon Capture and Utilization, but only 6.86 EJ² of solid biomass are utilized in CHP, electricity only and heat only plants. The respective CO₂ amounts are 1184 Mt and 686 Mt per year.³

2.2 CO₂ from fermentation processes

2.2.1 Liquid biofuels – fermentation of industrial bioethanol

Liquid biofuels are defined here according to Eurostat:

Liquid biofuels includes all liquid fuels of natural origin (e.g. produced from biomass and/or the biodegradable fraction of waste), suitable to be blended with or replace liquid fuels from fossil origin. [...] [16]

¹ Difference of 54.72 EJ and 42.88 EJ

² Summed up the energy utilized 2014 in CHP (2.4 EJ), heat only plants (0.48 EJ) and electricity only plants (3.98 EJ), Source: [19, p.47 and p.49].

³ Conversion from energy to CO₂ with IPCC emission factors [2, p. 17] Approx. 100,000 kg CO₂/TJ

There are several liquid biofuels like biodiesel, biogasoline and bio jet kerosene but especially during the fermentation process resulting in bioethanol, a considerable CO₂ amount is produced. Concurrent to the stoichiometric equation, the gas produced during the fermentation consists of up to 99-100% CO₂. [20]

Basic equation of ethanol fermentation: $C_6H_{12}O_6 \rightarrow 2 C_2H_5OH + 2 CO_2$

Carbon dioxide from bioethanol production is pure enough to be directly utilized in the food and beverage (FAB) industry, e.g. as carbon acid in beverages [21] and it can be expected that it fulfils fundamental requirements for the production of ethylene oxide as well.

There are regulations for the quality of food grade carbon dioxide released by the European Industrial Gases Association (EIGA) [22] and the International Society of Beverage Technologists (ISBT) [23] as presented in Table 2-1. The aforementioned regulations are strict, however for some impurities like water, O₂, hydrocarbons and CO the limitations are not as demanding as for CO₂ gases for the chemical industry according to EN ISO 14175: C1. As examples on the purity requirements for CO₂, the product data sheets from e.g. the Linde Group could potentially be taken into account: BIOGON® C flüssig E290 - Kohlendioxid 3.0 [24] for food grade CO₂ and Kohlendioxid 4.5 [25] for chemical industry CO₂. Depending on the requirements for the ethylene and ethylene oxide synthesis, further purification of the food grade CO₂ or CO₂ for chemical industry may be needed, for example by activated carbon technologies [26, 27]. The requirements of CO₂ input for the ethylene synthesis will be evaluated within the preceding work packages of the current project.

Table 2-1: EIGA limiting characteristics for CO₂ to be used in beverages.

Component	Concentration
Assay	99.9% v/v min.
Moisture	20 ppm v/v max.
Ammonia	2.5 ppm v/v max.
Oxygen	30 ppm v/v max.
Oxides of Nitrogen (NO/NO ₂)	2.5 ppm v/v max. each
Non-volatile residue (particulates)	10 ppm w/w max.
Non-volatile organic residue (oil and grease)	5 ppm w/w max.
Phosphine (only for CO ₂ from phosphate rock sources)	0.3 ppm v/v max.
Total volatile hydrocarbons (calculated as methane)	50 ppm v/v max. of which 20 ppm v/v max. non-methane hydrocarbons
Acetaldehyde	0.2 ppm v/v max.
Aromatic hydrocarbon	0.02
Carbon monoxide	10 ppm v/v max.
Methanol	10 ppm v/v max.

Hydrogen cyanide (only for CO ₂ from coal gasification sources)	0.5 ppm v/v max.
Total sulfur (as S for total content < 0.1 ppm v/v) ⁴	0.1 ppm v/v max.
Taste and odor in water	No foreign taste or odor
Appearance in water	No color or turbidity
Odor and appearance of solid CO ₂ (snow)	No foreign odor or appearance

Source: European Industrial Gases Association (EIGA) [cf. 22, p. 11]

An important aspect to be considered is the fact, that the FAB industry offers possible competing utilization pathways for CO₂ especially from industrial bioethanol production. According to ePURE bioethanol producers in Europe commercialized 0.4 Mt CO₂ utilization in 2016 [3]. The estimations within this project based upon the information available on the producers' websites [4, p. 17] and upon some approximations from ethanol outputs indicate the amount of 1.52 Mt CO₂/year, which is possibly commercialized by the European bioethanol producers in the mid-term future.

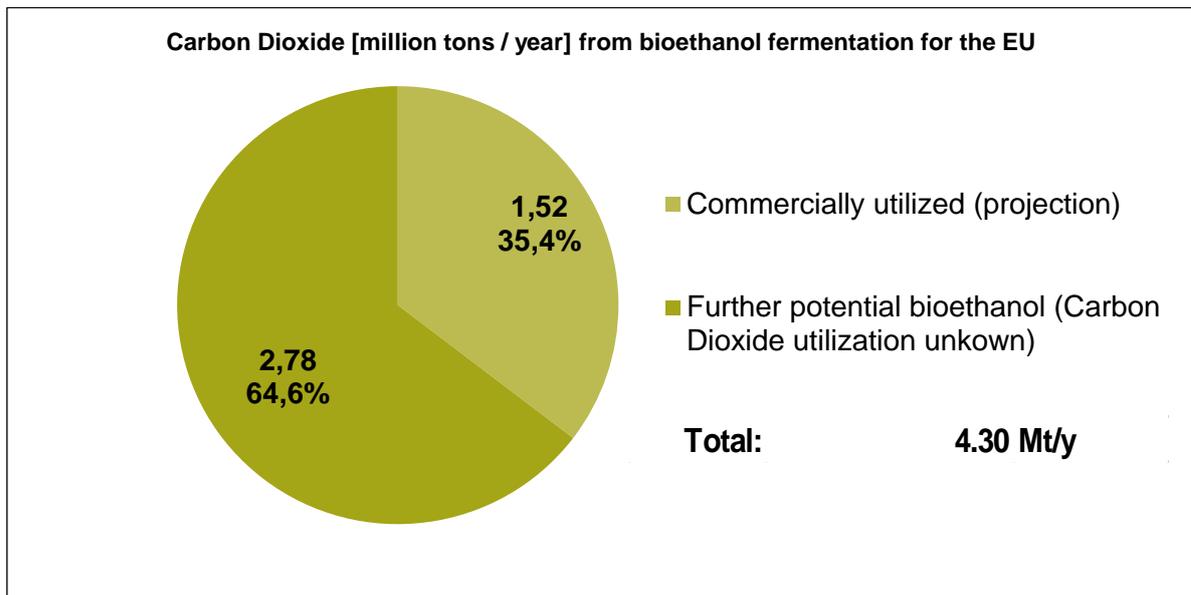
2.2.1.1 CO₂ potential from bioethanol industry in Europe

The total amount of CO₂ produced during bioethanol fermentation is approximately 4.3 Mt CO₂/year according to production statistics from 2016. Most European bioethanol fermentation plants are based in France (17) followed by Germany (8) and the UK (5). Other European countries have none or up to 3 plants. In total there are around 57 plants in Europe of which 43 are present in the European Union. [1, based on 3, 4, p. 17] The total installed production capacity for bioethanol in Europe is about 6.3 billion litres a year while the total production accounts for 5.2 billion litres in the year 2016 [3].

The approximated theoretical amount of CO₂ produced in the European industrial bioethanol industry in 2016 is summarized in Figure 2-2.

⁴ If total sulphur content > 1 ppm v/v, then: Carbonyl Sulphide 0.1 ppm v/v max., Hydrogen Sulphide 0.1 ppm v/v max., Sulphur Dioxide 1.0 ppm v/v max.

Figure 2-2: Amount of CO₂ produced in the bioethanol industry of the EU in 2016 including amount of possibly commercialized CO₂ according to projections.



Source: own illustration Energieinstitut [based on data from 3, and 4, p. 17]

According to ePURE [3], FAB and other industries represent 11% each of the European industrial bioethanol consumption. The remaining 78% are used as fuel. The possibilities to yield CO₂ “end-of-pipe” from the ethanol utilisation pathway in the FAB and other industries is complex and consequently relatively unattractive. Similarly, while gaining CO₂ from ethanol flue gases would theoretically be possible, it is technically and economically not feasible at the current stage since bioethanol is usually used as component of vehicle fuel.

2.2.1.2 Global CO₂ potential from bioethanol industry

The global bioethanol production however is much higher and accounted for 78 billion litres bioethanol produced in 2014. The European fraction is only 8.4%, comparing ePURE figures from 2014 [28, p. 2] to the 2014 global production. Industrial bioethanol from America account for the biggest amount with 88% market share, while Asia ranks similar as Europe, followed by Oceania and Africa. Since CO₂ from bioethanol is very pure and the capture process relatively simple, establishing ethylene and ethylene oxide production in North and South America, where large bioethanol production sites can be found, is basically an option for further consideration of a broad technology roll out of the CO₂-based electrosynthesis of ethylenoxide.

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2.2.2 Fermentation processes in the industry

In addition to the CO₂ deriving from bioethanol industry, CO₂ from fermentation processes in the FAB industry, like brewing processes, are of interest. In the beverage industry mainly beer brewing and wine production lead to considerable CO₂ amounts. Furthermore, the fermentation of acids, e.g. citric acid, produces considerable amounts of CO₂.

According to [6] 41.1 billion litres of beer were brewed in Europe in 2016. Using an average value of 5 vol.-% of alcohol and 5 g/l carbon acid for beer, it can be estimated that 35 g CO₂/l are released during the fermentation process. [29, 30] According to the European annual beer production, approximately 1.44 million tons of CO₂ are released. The CO₂ amounts, which can be utilized, are smaller, since approximately 5,845 out of 8,130 European breweries in 2015 were so called microbreweries with an annual beer output of maximum 1,000 hl [6], which corresponds to approximately 3.5 t CO₂/year. Therefore, the technical effort is quite high to gather large CO₂ amounts. Furthermore, some breweries already utilize their own CO₂ as protective gas for filling. [31, 32] Therefore, most of the CO₂ is not applicable for CCU (Carbon Capture and Utilisation) processes.

A comparable estimation could be conducted for the CO₂ potential from fermentation in European wine production. The average value of the European wine production is approximately 17 billion liters of wine annually. [5] The average alcohol content is 11 vol.-% while the carbon acid content is quite low, around 1 g/l, which correspond to approximately 87 g CO₂/l released during the production process. [33, 34] The carbon acid amount depends on the type of wine. Especially red wine has a very low content and gets decarbonated very often, while the carbonation of white wines and sparkling wines is quite common. The annual CO₂ amount, estimated from the previous average values, is 1.48 million tons CO₂ for the EU wine industry. Similar to beer brewers, wine producers protect their wine against air using CO₂ or use it for carbonation and in practice this CO₂ is not available for chemical syntheses. The small scaled structure of producers this sector is another barrier for implementation of CCU.

2.3 Gaseous biofuels

Gaseous biofuels are defined here according to Eurostat:

Biogas is a gas composed principally of methane and carbon dioxide produced by anaerobic digestion of biomass or by thermal processes from biomass, including biomass in waste. In energy statistics, biogas is a product aggregate equal to the sum of landfill gas, sewage sludge gas, other biogases from anaerobic digestion and biogases from thermal processes. [16]

There are in principle two ways of utilizing CO₂ from biogas, independently of the source of the biogas. Firstly, biogas consists approximately of 60% methane and 40% carbon dioxide. [35,

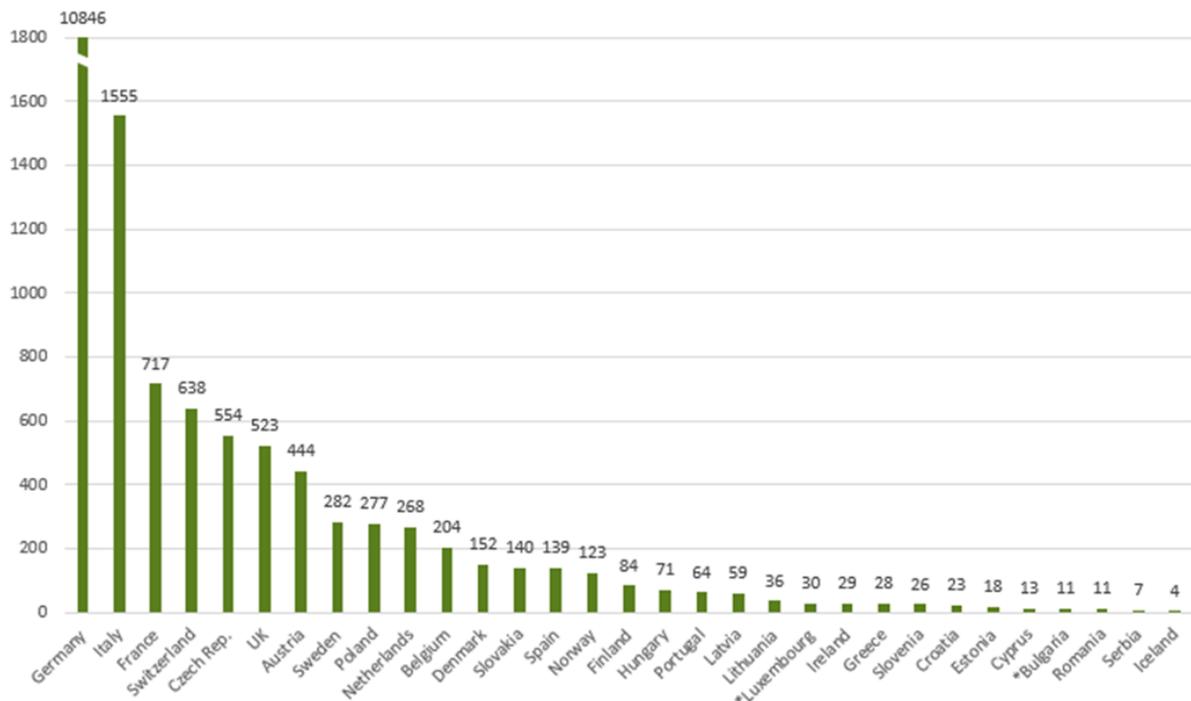
based on 36] Therefore, biogas upgrading to biomethane offers a large potential for the generation of biogenic CO₂. Furthermore, the combustion of biogas and biomethane generates CO₂ as a compound of the flue gas during the generation of heat and power. The following chapters will give an overview of both basic possibilities.

2.3.1 CO₂ from biogas upgrading

2.3.1.1 Biogas upgrading in Europe

In end 2016 there were about 17,662 biogas plants in Europe existing, while about 497 upgrading plants were installed in Europe at early 2017 [7]. Figure 2-3 gives an overview of the number of biogas plants per country in Europe in 2015. Since then the distribution changed marginally.

Figure 2-3: Biogas plant distribution in Europe in 2015



Source: European Biogas Association (EBA) [37]

In 2016 /2017 for example countries like the UK [38], Poland [39], Denmark [40], Norway [41], Lithuania [42], Greece [43–46], Slovenia [47, p. 177] and Serbia [48] expanded their biogas capacities. For Italy different numbers are available from the World Biogas Association [49] to the ones from the European Biogas Association. The updated numbers are listed in Table 2-2.

Table 2-2: Collection of updated data on number of biogas plants in some European countries.

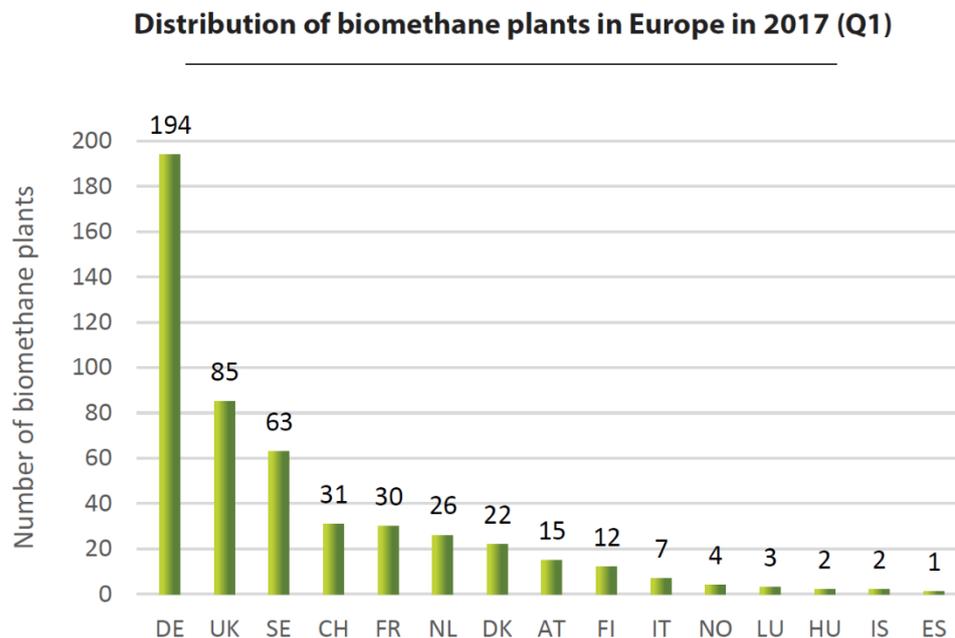
Country	Number of biogas plants (update)
Italy	1,924 (2015)
United Kingdom	578 (2017)
Poland	301 (2016)
Denmark	166 (2017)
Norway	138 (2016)
Lithuania	47 (2017)
Greece	36 (2017)
Slovenia	32 (2016)
Serbia	14 (2017)

Sources are listed in the passage above.⁵

In 2018 the European Biogas Association (EBA) and Gas Infrastructure Europe (gie) in collaboration with several partners published the European Biomethane Map 2018 [7], which includes detailed data from all known European biogas upgrading plants. According to the map, Germany, the United Kingdom and Sweden are pioneers on the field, in terms of the number of upgrading plants, as can be seen in Figure 2-4. Comparing Figure 2-3 and Figure 2-4 it becomes clear, there is still a huge potential for biogas upgrading, which also results in a huge potential for CCU for CO₂ from biogas by combining it with the biogas upgrading wherever surrounding conditions would allow for.

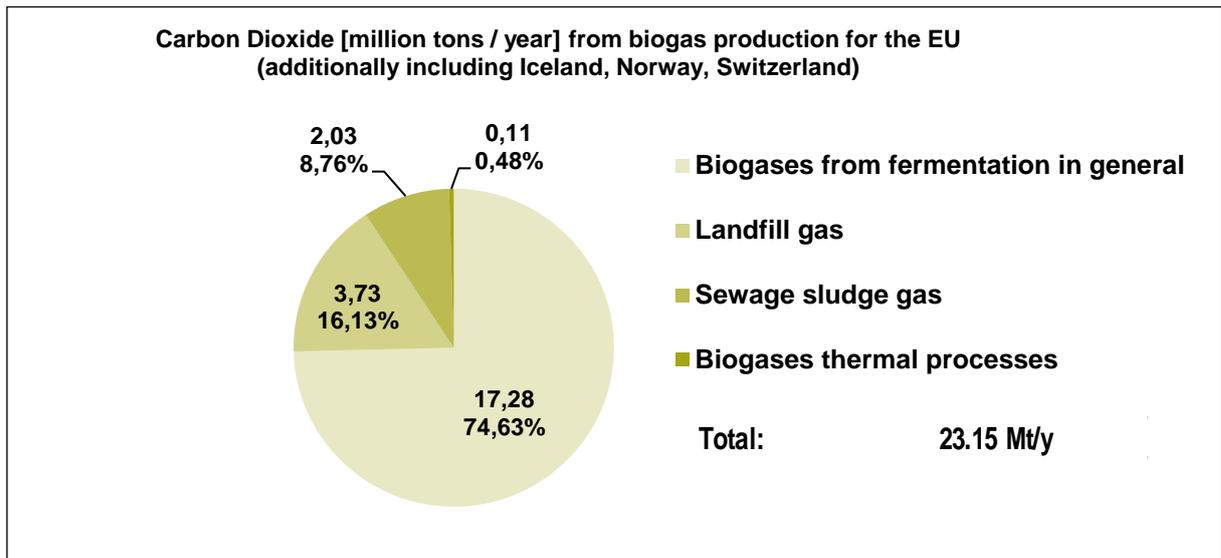
⁵ Data underlie constant change and are only an orientation guide for the development of European biogas economy and implementation of CCU. Eventually there are more countries with changed number of plants compared to 2015, which are not listed here due to insufficient public data

Figure 2-4: European country ranking according to the number of biogas upgrading plants in early 2017

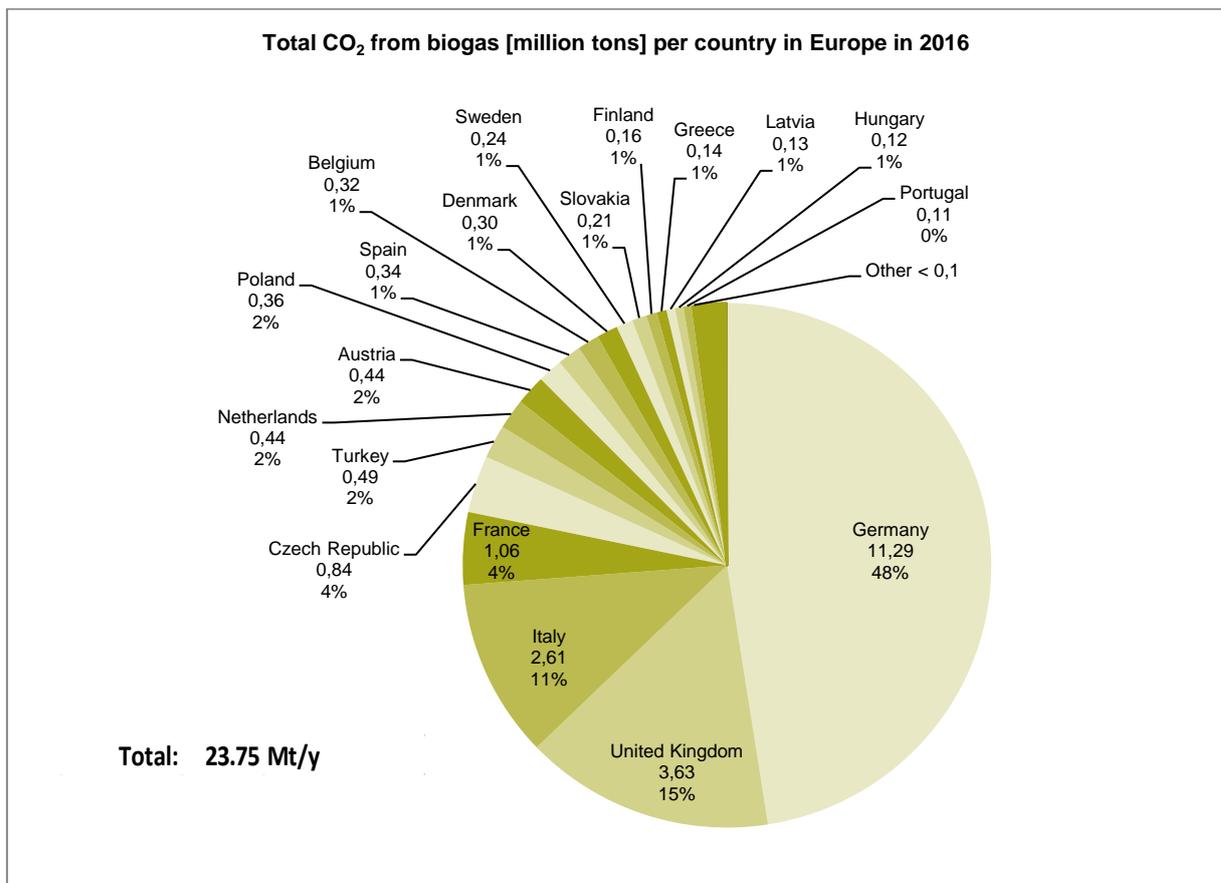


Source: European Biogas Association (EBA) [7].

Since not only the number of biogas and biomethane plants is of interest but the CO₂ potential in specific, annual CO₂ amounts deriving from biogas and biomethane production in Europe are presented here. The numbers include the CO₂ potential from the biogas composition (~ 40 vol.-% CO₂) and biogas upgrading (~ 99 vol.-% CO₂) and exclude the CO₂ emitted during the combustion of biogas in a CHP facility or utilisation of upgraded biomethane. Figure 2-5 and Figure 2-7 show the approximated cumulative CO₂ potential in 2016 in the European Union for biogas and biomethane plants. Figure 2-6 shows the CO₂ potential from biogas production per country for whole Europe. The minor difference in the volumes between Figure 2-5 and Figure 2-7 is originating from different primary data sources. Germany is in first place for most biogas produced except for landfill gas for which the UK accounts for the biggest present amounts. Biogas from thermal processes account for a very small amount of CO₂ and is mostly based in Finland.

Figure 2-5: Cumulative CO₂ potential from biogas production

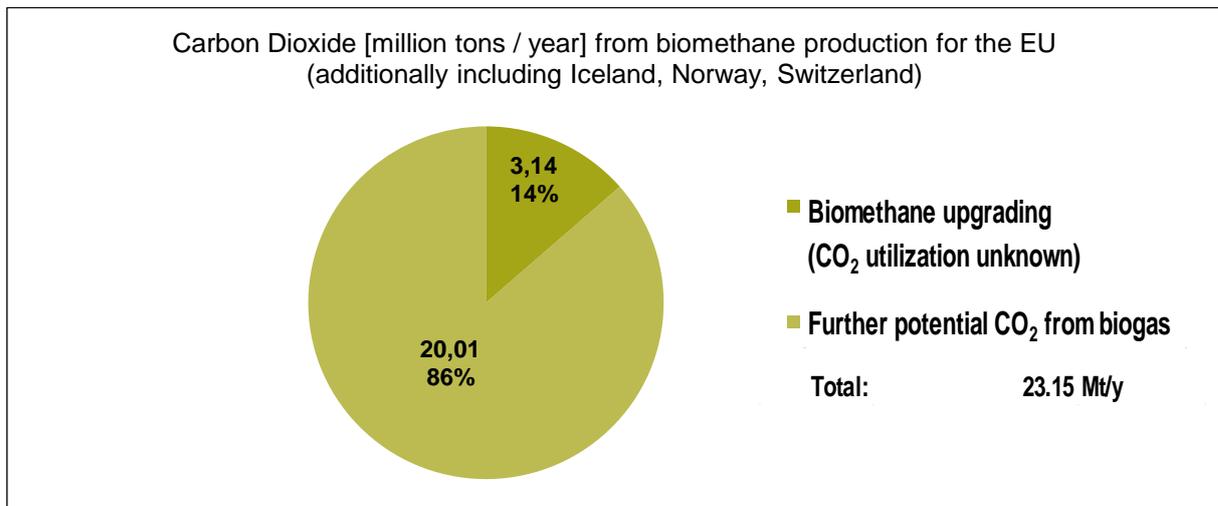
Source: own illustration Energieinstitut based on Eurostat data on EU biogas production in 2016 [1]

Figure 2-6: CO₂ potential from biogas production per country

Source: own illustration Energieinstitut based on Eurostat data on European biogas production in 2016 [1]

As illustrated in Figure 2-7 the approximated CO₂ potential from biomethane upgrading represents only 14% of the cumulated CO₂ from biogas production still excluding the CO₂ emitted during utilisation (combustion of biogas in a CHP facility or utilisation of upgraded biomethane in different applications – heat, electricity or transport).

Figure 2-7: CO₂ potential in 2016 from biomethane upgrading as part of total CO₂ potential from biogas production.



Source: own illustration Energieinstitut based on data from [7]

2.3.1.2 Global potential of biogas upgrading

According to data from the WBA [19, p. 59] in 2014 approx. 1.2 EJ biogas were produced globally. This accounts for a potential of around 40 Mt CO₂ from biogas production assuming the CO₂ content of approximately 40% and the biogas heating value of 21.6 MJ/Nm³ / 6 kWh/Nm³. Around 50% of the global biogas is produced in Europe, while Asia accounts for a third and America for roughly 17%.

2.3.2 CO₂ from combustion of biogas and biomethane

During the combustion of biogas and biomethane, besides to some trace compounds, mainly CO₂ and water are produced. The exact amounts depend on the composition of the fuel gas and the air supply during the combustion. Therefore, only approximate carbon dioxide amounts can be given.

2.3.2.1 CO₂ potential from biogas and biomethane combustion in Europe

In 2016 approx. 695 PJ of biogas were produced in the EU according to Eurostat [1]. Taking data from the EBA [8] into account, 62 PJ biomethane were produced in 2016. This is equal to

8.9% of the total biogas production. Therefore, 633 PJ or approximately 26.5 billion m³ of biogas⁶ are utilized in CHP and other plants, while the remaining part is upgraded. The above estimations are based on the gas composition of 60 vol.-% methane and 40 vol.-% CO₂. Therefore, with an air–fuel equivalence ratio $\lambda = 1$, around 15 vol.-% CO₂ in the flue gas are possible.⁷ Consequently, it can be deduced that around 178 billion m³_{flue gas (wet)} are produced annually, containing roughly 26.5 billion m³ of CO₂. This is equal to 52.5 million tons of CO₂ per year⁸, considering a density of 1.98 kg_{CO2}/m³_{CO2}.

The upgraded biogas is injected into the gas grid in most cases. Therefore, in practice, the CO₂ deriving from the combustion of biomethane is not available for CCU, unlike the CO₂ separated during the upgrading process. In 2017, 73 of 497 biomethane upgrading plants in Europe were not connected to the gas grid [7]. At these plants the biomethane is directly utilized, which means in some cases the CO₂ from combustion could be potentially harnessed for the electrochemical synthesis, except for places where the biomethane is used as biofuel for motor vehicles. In the latest Statistical Report of EBA [51, p. 10] the development of several incentives to increase the use of upgraded biogas as a fuel are presented. Especially in Sweden (88%) and Finland (25%) large amounts of the national production are already used as fuel for vehicles. Other countries like e.g. Estonia, Norway and Italy are planning to strengthen this utilization pathway in the upcoming years.

2.3.2.2 Global CO₂ potential from biogas and biomethane combustion

Taking the global biogas production of 1.2 EJ for 2014 into account, around 110 Mt CO₂/year are released by biogas combustion. The conversion considers a CO₂ fraction of 40 vol.-% of the biogas and the CO₂ from combustion, which leads to an emission factor of 91.5 g CO₂/MJ_{LHV}. Basing the calculations on the emission factor from IPCC 2006 [2, p. 17], which is equal to 54.6 g CO₂/MJ_{LHV} and is based on the calorific value, 65.5 Mt CO₂/year are released. The 65.5 Mt CO₂/year do not include the 40 vol.-% CO₂ fraction from biogas production but only CO₂ from combustion of biogas (approx. 40 vol.-% CO₂, 60 vol.-% CH₄). Summing up the latter and the CO₂ amount from biogas upgrading, which corresponds to the 40% CO₂

⁶ Converted with higher heating value of 6.64 kWh/m³

⁷ Calculations with pdf-sheet "Verbrennung gasförmiger Brennstoffe" from Lehmacher

⁸ Stoichiometric calculation with pure oxygen as reagent for comparison: 49.6 million tons CO₂ per year. Source: Own calculation.

fraction (see Chapter 2.3.1.2), it can be calculated the comparable order of magnitude that around 110 Mt CO₂/year are emitted. This is the same as using 91.5 g CO₂/MJ_{LHV} as emission factor. Small deviations derive from different data sources and rounding errors.

2.3.3 Biogas substrates

Biogases from anaerobic digestion derive from biogas plants with highly different biomass feedstock. Table 2-3 provides an overview of possible compounds of biogas substrates. Most plants are supplied with varying mixtures of substrates. Some substrates demand special treatment and plant design. Depending on the substrates, the composition of the biogas, concerning methane and CO₂ concentrations and trace compounds, varies. Since the CO₂ stream needed for the electrochemical ethylene synthesis ideally is highly pure, some biogas substrates may be not suitable for this application without extensive purification processes of the potentially utilised CO₂.

Table 2-3: Selection of possible substrates for biogas plants.

Category	Possible feedstocks	
Agricultural	energy crops	maize silage
		sugar beet silage
		silage from different grains
		crop residues in general
	manure	pig
		cow
		sheep
		poultry
FAB industry	liquor industry	grain stillage
		potato stillage
	sugar and starch industry	sugar beet residues
	beverage industry	fruit pomace
	food industry	production residues
		slaughter waste and blood
		dairy residues
	Waste industry	
		industrial renewable waste
		sewage sludge
	production residues	leather

Textile industry		fur
		biological textiles
Wood industry	panels and furniture	wood residues
	paper industry	paper and cardboard residues
		pulp residues

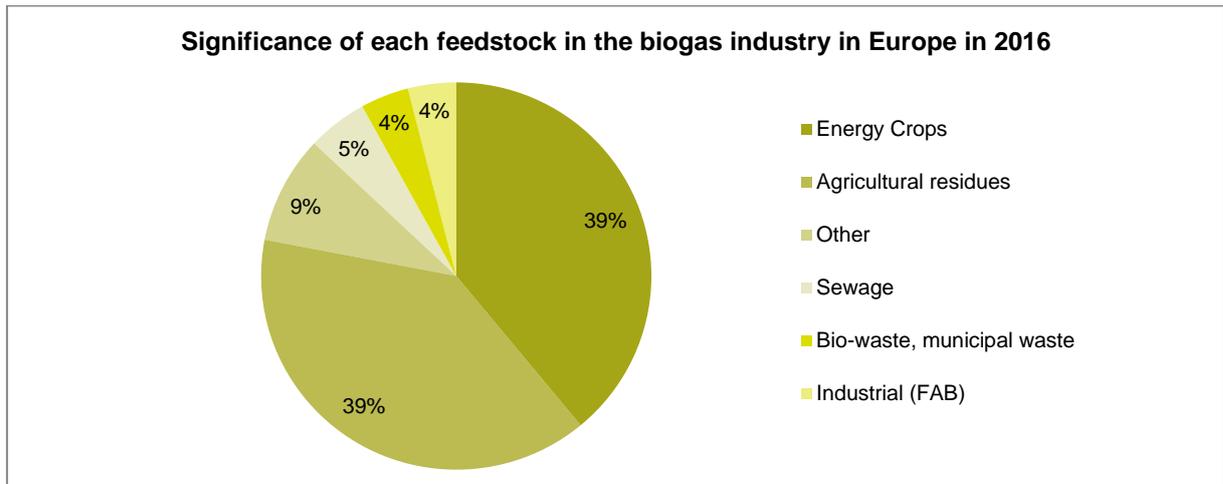
Source [based on 52, p. 17, 53]

According to the Statistical Report of EBA 2017 [51, pp. 7-8] the feedstock use for biogas production differs for every country. Using the substrates mass percentage as an indicator for biogas production (excluding landfill gas), energy crops are the main substrates in Latvia, Austria and Germany while in Greece, Cyprus, France, Serbia, Poland and Italy agricultural residues are the main feedstock. In the UK, Finland, Sweden, Spain, Denmark and especially in Switzerland [51, p. 31], sewage accounts for the largest share. In some countries like Belgium, Croatia and Hungary the distribution is more even.

Considering landfill gas, the statistics shift. Estonia covers about a third of its feedstock origin with landfill waste. [51, p. 51] Two thirds of the produced biogas in Greece is landfill gas [51, p. 56] and for Norway it is almost the half [51, p. 92]. Portugal is exceptional in using landfill gas, since it accounted for over 95% of produced biogas in 2016 [51, p. 99]. Other countries making significant use of landfill gas are the UK, Sweden, Romania, Poland, Ireland, France and Finland.

Figure 2-8 is compiled based on data from EBA [51, p. 7] and shows the share of feedstock use for biogas according to substrate mass percentages and electricity production per substrate in each country for Europe. Agricultural wastes and energy crops represent the highest share with 39% each, followed by “other”, which includes organic waste from households and industry, sewage, FAB and bio-waste/municipal waste. Sewage is underestimated according to EBA.

Figure 2-8: “Estimation of relative significance of each feedstock in the biogas industry in Europe in 2016



Source: own illustration Energieinstitut based on feedstock mass percentages and electricity production per feedstock in each country [...].” [51, p. 7] The share of sewage sludge is underestimated due to missing information on the share of sewage sludge for some countries. The diagram is adapted from Figure 9-EU of the Statistical Report 2017 from EBA [51, p. 7].

The main substrates by mass percentage excluding landfill gas for current biomethane plants are slightly different to the main substrates for biogas in general. Especially bio- and municipal waste, agricultural residues and to some extent unknown feedstocks are of major relevance. In Germany most biomethane plants base on energy crops, followed by agricultural residues and bio-/municipal waste, while in the UK “other” (municipal waste etc.) and agricultural substrates play the biggest role. These two countries are the ones with most biomethane plants (see Figure 2-4). For Sweden, which ranks third among European countries with the most biomethane plants, “other” and sewage are the feedstock for most biomethane plants. [51, p. 106]

2.3.4 Composition of biogas

Depending on the substrates, the plant system, operating temperature and various other parameters, different trace compounds can be found in biogas resulting from biological processes in anaerobic digestion. Typical impurities are water vapour, O₂, N₂, NH₃, H₂, H₂S, siloxanes and biogas specific VOCs. [52, p. 41, 54, p. 33] Table 2-4 provides a more detailed overview of possible impurities and their typical concentrations in the biogas.

Table 2-4: Detailed overview of biogas components.

Components	Concentration range
Main components	
Methane (CH ₄)	50 - 70 mol.-%
Carbon dioxide (CO ₂)	30 – 50 mol.-%
Nitrogen gas (N ₂)	0 – 3 mol.-%
Oxygen (O ₂)	0.0 – 0.5 mol.-%
Hydrogen (H ₂)	0.0 – 1.5 mol.-%
Water vapor (H ₂ O)	1 – 7 mol.-%
Carbon monoxide (CO)	0 – 1 mol.-%
Trace components	
Ammonia (NH ₃)	0 – 308 ppm(mol)
Hydrogen sulphide (H ₂ S)	20 – 850 ppm(mol)
Terpenes	0 – 500 ppm(mol)
Benzene, Toluene, Xylene (BTX)	0 – 7 ppm(mol)
Hydrocyanic acid (HCN)	0 – 0.003 ppm(mol)
Fluorine compounds (R-F, incl. HF)	0 – 1.3 ppm(mol)
Chlorine compounds (R-Cl, incl. HCl)	0.1 – 5 ppm(mol)
Siloxanes (D4 & D5)	0 – 3.4 ppm(mol)

Source: adapted from [55, p. 5]

Rasi et al. give an even more detailed overview of biogas components, depending on the utilised substrates for biogas production. [56] Especially landfill gas often contains high amounts of H₂S and VOCs. Additionally – for example for industrial wastes – several potentially hazardous trace compounds can be part of the landfill gas, for example fluorinated and chlorinated hydrocarbons, aromatic compounds, and higher hydrocarbons. [57] Other common trace compounds are siloxanes, which are also present in sewage sludge gas, since siloxanes are originating e.g. from ingredient for cosmetics, soaps and detergents. Depending on the substrate also agricultural biogas plants can produce biogas with a very high H₂S content, for example deriving from manure feedstock. [58]

2.3.5 Upgrading technologies for biogas

There are several upgrading technologies for biogas available: water scrubbing, amine scrubbing, pressure swing adsorption (PSA), physical scrubbing, chemical scrubbing, membrane separation and cryogenic separation. [7, 54, p. 33, 59] Since biogas upgrading aims mainly on the separation and purification of the methane content in the biogas, trace compounds are often removed together with the CO₂ stream as can be seen in Figure 2-9. Consequently, the CO₂ stream may contain considerable amounts of impurities and is potentially not suitable for most utilization applications for chemical synthesis without further treatment.

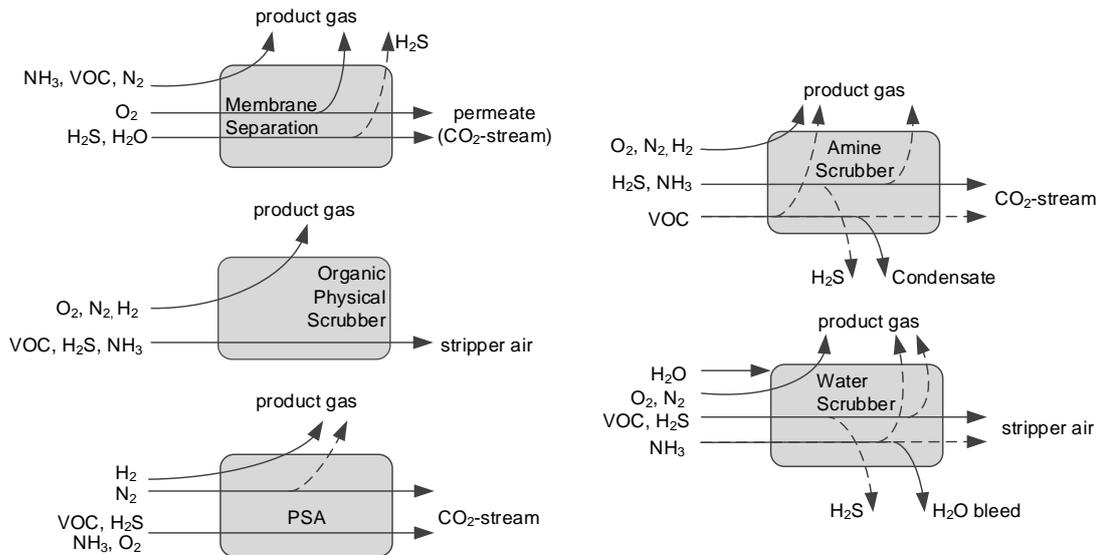


Figure 2-9: Some exemplary paths of impurities from biogas upgrading technologies

Source: own illustration Energieinstitut based on Hoyer et al. [54, p. 33, Fig. 12]

According to [51, p. 13] most current upgrading plants use water scrubbers, followed by chemical absorption, PSA, membrane separation and physical absorption. In Germany, the European country with most upgrading plants, all upgrading technologies are represented, chemical absorption and water scrubbing however are each implemented in 30% of the plants, PSA in 22% of the plants. In Sweden, ranked number three among European biomethane countries, 69% of the biomethane plants use water scrubbers, followed by chemical absorption, PSA and membrane separation. [51, p. 14] For the UK, ranked number two, no information on upgrading technologies is available. [51, p. 115] The only European countries known for implementing physical absorption are Germany, Norway and Switzerland. Combining this information with the path of impurities according to Figure 2-9 most CO₂ from upgrading plants requires further purification before it can be utilized as raw material for electro synthesis of ethylene oxide.

The available CO₂ concentration in biogas upgrading off gases depends on the applied upgrading technology. In processes like membrane separation, amine scrubbing and pressure swing adsorption, relatively high CO₂ contents are reached in the off gas streams (typically <99 vol.-%, CH₄ being the balance). Under certain circumstances, if the level of off gas impurities is low, the off gases of these processes can be readily used for the electrochemical synthesis. This will be tried out within the current project, where the CO₂-rich off gas stream (CO₂ of around 99.5%) from a membrane plant will be used directly for the electrochemical synthesis of ethylene.

On the other side, processes that involve stripping with air like the pressurised water scrubbing produce more dilute CO₂ off gases. This means that CO₂ from such processes would need further gas upgrading steps in order to get rid of air components and increase the CO₂ content.

A review on upgrading technologies for biogas to biomethane from Vijayanand and Singaravelu [60] gives an overview especially for CO₂ separation techniques for biogas, as well as Singhal *et al.* [61] for the transformation of biogas to biological compressed natural gas (bio-CNG). A comprehensive review on biogas generation factors, enhancements of biogas production techniques, upgrading and cleaning techniques offer Al Mamun and Torii [62] as well as Andriani *et al.* [63] and Sun *et al.* [57]. Pellegrini *et al.* [64] gives an overview of the purification costs of biogas, depending on the source of biogas.

A relatively new technique for biogas upgrading is the cryogenic CO₂ separation, which involves many different process steps using very low temperature processes. One example, resulting in partially food grade CO₂, is the CO₂ Wash® process developed by US based Acion Technologies. It applies the effect of impurities solubility in liquid CO₂. After H₂S removal and drying, the biogas is mixed with liquid CO₂. This process results in biomethane, food grade CO₂ and a CO₂-VOC mixture as products. [59, pp. 56-58] Depending on the requirements for the ethylene and ethylene oxide synthesis, further purification of the food grade CO₂ may be needed, for example by activated carbon technologies. [26, 27]

A new technique of CO₂ capture at room temperature using aqueous Na₂CO₃ is presented by Barzagli *et al.* [65]. Chaemchuen *et al.* [66] and Cavenati *et al.* [67] present metal-organic frameworks (MOFs) for upgrading biogas.

Not only since Carbon Capture and Storage (CCS) became more popular in recent time, but also because of quality requirements of the chemical and food and beverage industry, purification processes of the CO₂ are of higher interest. Some impurities have corrosive properties for example, which is a problem in transport and longtime storage [68], others are harmful to chemical processes or toxic in terms of food and beverage industry. For CCU - or ethylene synthesis and ethylene oxide synthesis in specific – not only because of transport but also for the chemical conversion of the CO₂ and possible poisoning of electrochemical equipment, very low impurity concentrations are required. CO₂ purification processes are state-of-the-art processes, but there is still much development work ongoing.

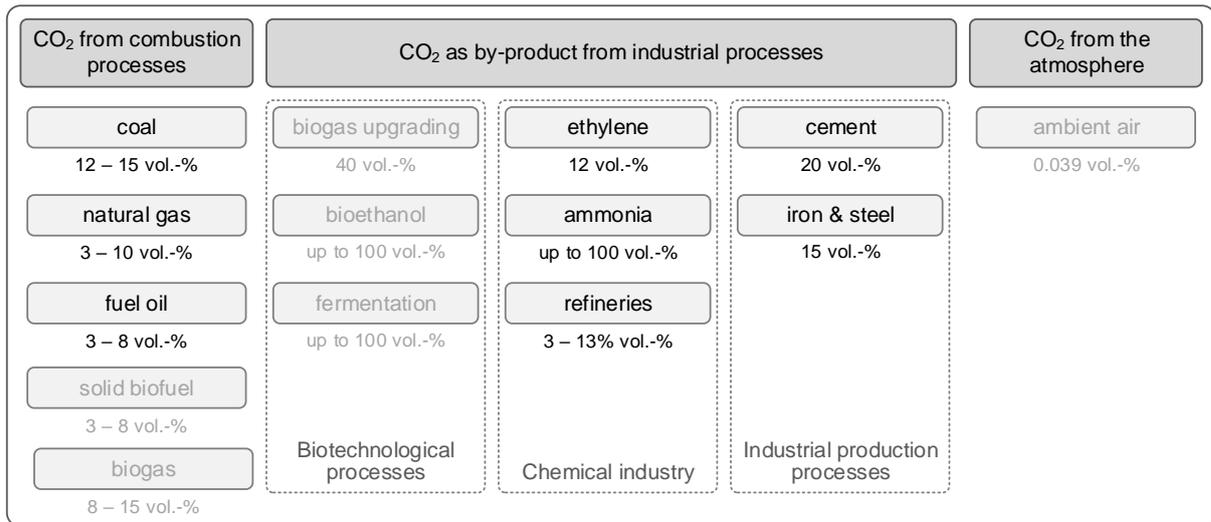
3 POTENTIAL SOURCES OF FOSSIL CO₂

Though the CO₂EXIDE approach is mainly targeting on biogenic, and therefore “green”, sources for CO₂ as feedstock material, the main emitters of carbon dioxide are based on fossil

fuels. Due to increasing interest in utilisation of CO₂ to reach ambitious goals of decarbonisation and closed carbon cycles, these fossil sources will have to be partly considered as relevant input sources as well. Therefore, this section is about to give a rough overview on potentially available carbon sources and their relevance to the CO₂EXIDE process chain.

In the same way as biogenic sources, fossil CO₂ sources can be classified according to their emitting processes and industry sectors. This classification is shown in Figure 3-1 below.

Figure 3-1: Classification of potential fossil CO₂ sources including the available typical CO₂ concentration



Source: own illustration Energieinstitut based on data from [15]

The emissions of CO₂ from fossil sources, especially from energy production and industry, are mainly registered in the Emission Trading System of the European Union (EU ETS). Therefore, the latest report data released by the European Commission in April 2018 was used as primary data source [69]. As data for 2017 is incomplete in this report, year 2016 data was used as reference for subsequent analysis.

3.1 Categorisation of fossil CO₂ sources

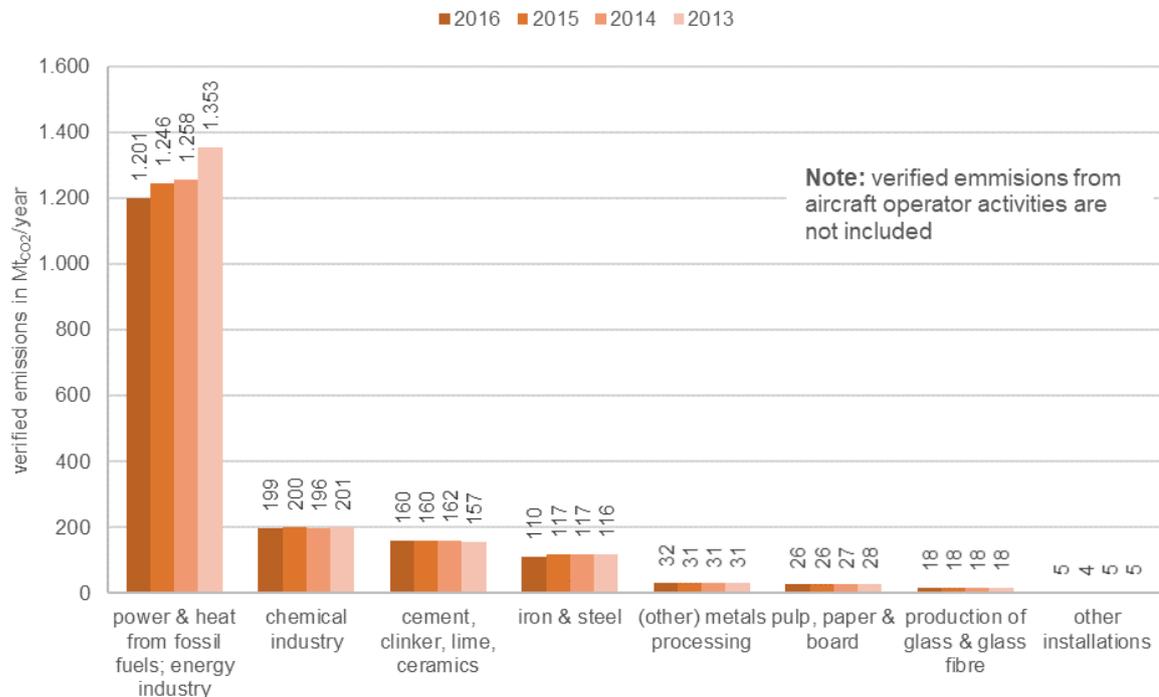
The available data for verified emissions allows a classification of the emissions according to their industrial sector. Since the given information is rather fine-grained and diverse, the data was grouped to following main sectors:

- power & heat from fossil fuels; energy industry chemical industry
- iron & steel
- (other) metals processing
- production of glass & glass fibre
- pulp, paper & board
- other installations
- aircraft operator activities

- cement, clinker, lime, ceramics

This results in an allocation of verified emissions on those sectors as shown in Figure 3-2 below.

Figure 3-2: Total verified CO₂ emissions in the EU per industry sector



Source: own illustration Energieinstitut based on data from [69]

Figure 3-2 clearly illustrates that on the one hand, the energy industry, and therefore the production of power and heat from fossil fuels, is by far the main emitter of fossil CO₂ in the European Union. On the other hand, it is the only sector that continuously shows significant reductions in absolute emissions over the last years. Nevertheless, the use of fossil fuels in the energy sector has to be reduced substantially, or rather completely avoided, to achieve the goals of GHG emission reduction by 80% to 90% compared 1990 levels as stated by the European Commission [70]. Therefore, the utilisation of fossil CO₂ from this sector is excluded in the further analysis.

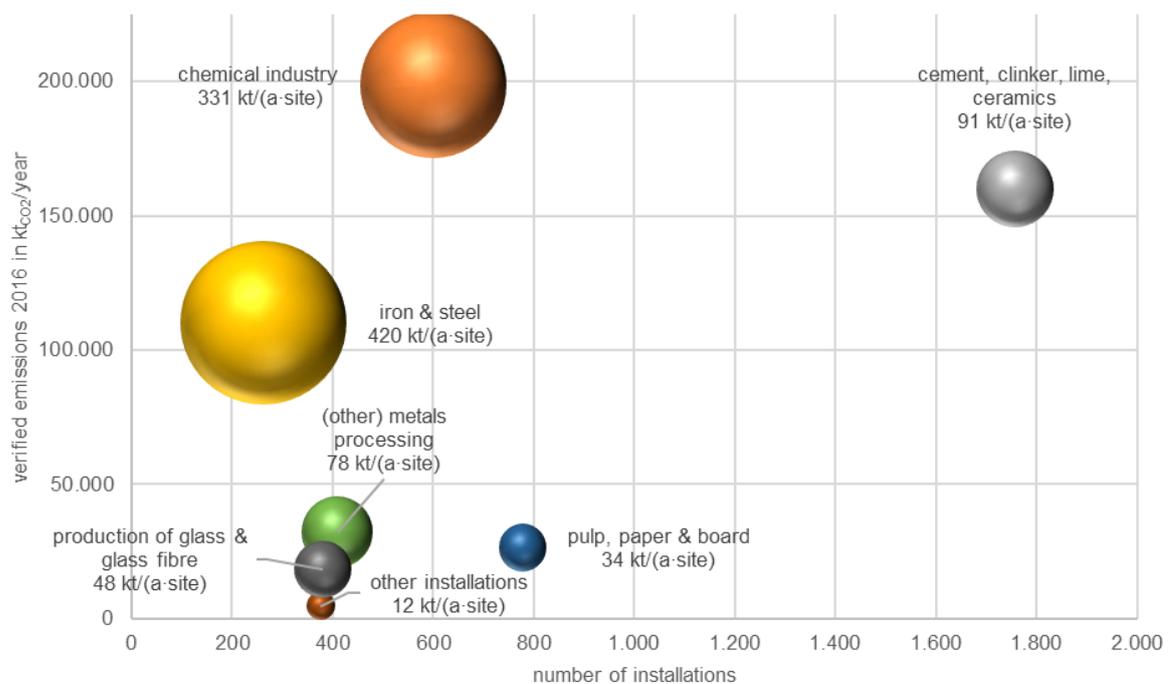
In this context, it also has to be stated that the mobility sector has not been investigated according to its potential for serving as a carbon source for CO₂-based process chains. This is justified by the aspect that efficient capturing from the source is not expected to be feasible in

the mid-term with acceptable capture rates. Additionally, the high decentralisation of the emitters makes an industrial usage of the captured CO₂ unviable.

3.2 Centralisation of emissions as point sources

In order to establish a system, as it is developed in the CO₂EXIDE project, in an industrial scale, the centralised availability of resources is an important aspect. To maximise economic and ecological advantages of such CO₂-based applications, their operation near to carbon emitting processes is highly preferable to reduce costs and efforts for transportation and storage. To get an overview, which industry sectors provide highly centralised emissions of CO₂, average per site emissions have been evaluated based on the categorization and data described above. The results are shown in Figure 3-3.

Figure 3-3: Average CO₂ emissions in the EU per site and industry sector



Source: own illustration Energieinstitut based on data from [69]

Figure 3-3 illustrates the highly centralised CO₂ emissions from iron & steel and chemical industry, providing an average amount of about 420 and 330 kilotons CO₂ per year and site, respectively. Another remarkable sector is represented by the cement industry (including clinker, lime and ceramics production). While average emissions per site are well below the

two major ones, the number of sites in total is significantly higher, which would allow a more distributed installation of CO₂ utilising technologies and therefore be advantageous in site selection.

With regard to these high amounts of centrally available CO₂, together with the fact that many industrial processes are highly established and efficient that are expected to be still available in the mid-term, a consideration of these carbon sources for renewable products is at least reasonable. This especially applies to the steelmaking and cement industry, where a decarbonisation of steel making would imply a complete revision of the process chain. Therefore, these point sources should be considered as well when investigating resource potentials for future CO₂-based process chains at an industrial scale like electrochemical synthesis of ethylene oxide.

4 CONSIDERATION OF TECHNOLOGICAL CAPTURE RATES

The amounts of CO₂ discussed in the previous sections provide an overview on overall direct emissions from different sources. To evaluate the real potentials for utilizable CO₂, it has to be considered that certain technologies for separation come with appropriate efficiencies limiting the amounts of CO₂ that can be captured and used. In the following sections, affordable capture rates and resulting utilisation values are analysed.

4.1 CO₂ capture efficiencies for industrial processes

To get an overview on technically affordable capture rates for industrial processes an appropriate literature review was carried out on that topic. This review basically covers the industrial sectors discussed in the previous sections. Since some of these sectors include various technologically different processes, the analysis was performed on a finer grained level, resulting in a categorisation as provided in the table below.

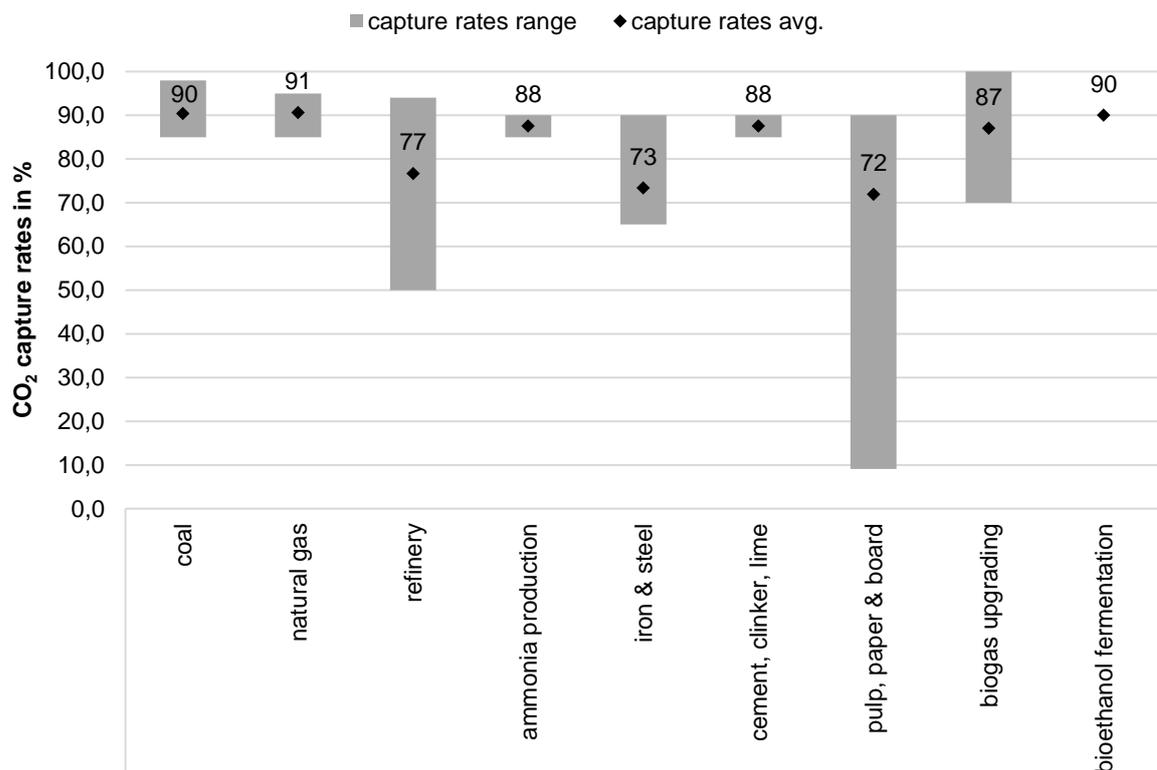
Table 4-1: Categorization of CO₂ providing industrial processes

Main industry sector	Sub-category
power & heat from fossil fuels; energy industry	coal
	natural gas
	energy industry
chemical industry	refinery
	ammonia production
	other chemicals
iron & steel	iron & steel
(other) metals processing	(other) metals processing
cement, clinker, lime, ceramics	cement, clinker, lime

	ceramics by firing (bricks, tiles, ...)
production of glass & glass fibre	glass & glass fibre
pulp, paper & board	pulp, paper & board
biogenic processes	biogas upgrading
	bioethanol (fermentation only)
	bioethanol (fermentation & cogeneration)

The industrial processes covered by the categorisation in Table 4-1 are significantly different from each other in terms of volume flows and purity of CO₂ in their flue or by-product gases. In addition, each process allows the use of one or more different capture technologies being suitable for efficient separation, while efficiency often is a compromise between both, process and capture efficiency. This results in highly different capture rates being technically and economically achievable and therefore being actually used in existing processes and considered state of the art. These results are summarized in Figure 4-1 showing determined ranges and averages for selected processes.

Figure 4-1: Affordable capture rates for various industrial processes (ranges and average)



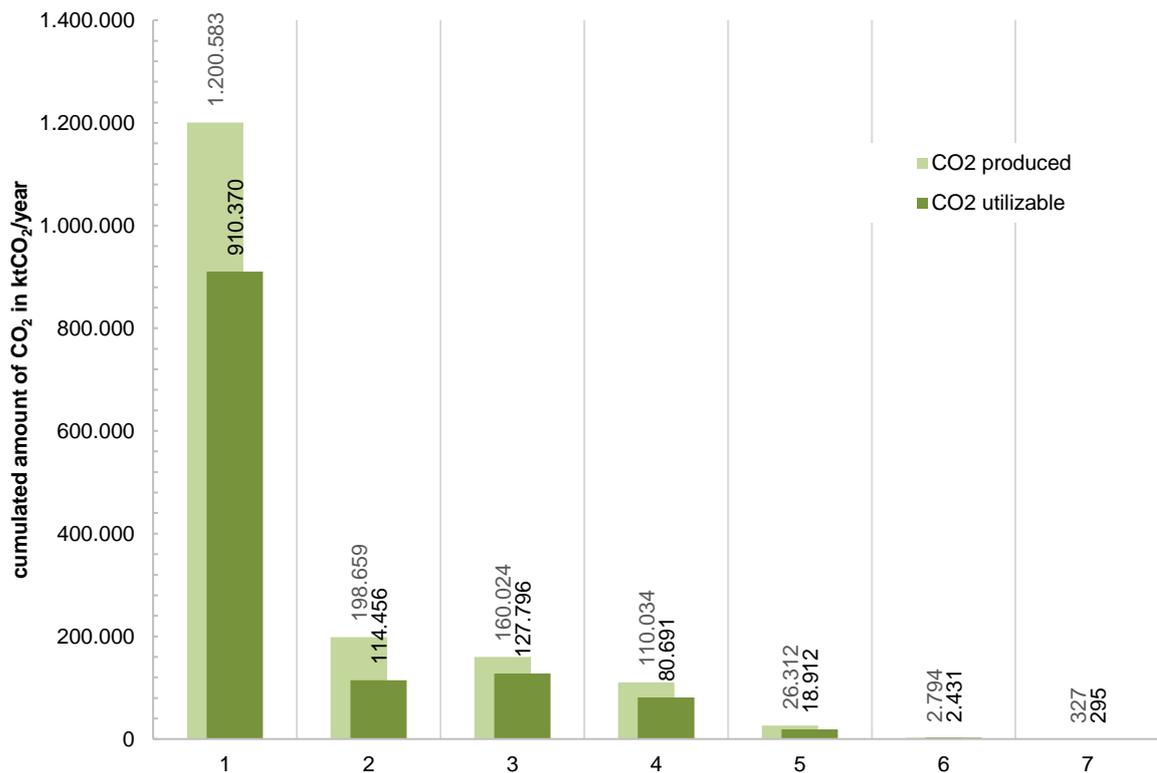
Source: own illustration Energieinstitut based on data from [15, 71–81]

As it can be seen in Figure 4-1, not for all sub-categories listed in Table 4-1 appropriate values for can be provided. This is on the one hand caused by the rough definition related to the available data for the CO₂ potentials which does not further specify the underlying process (e.g. other chemicals, (other) metals processing). On the other hand, some processes and industry sectors do not provide sufficient data to estimate appropriate capture rates (e.g. glass & glass fibre production, ceramics by firing) or do not allow feasible CO₂ capturing at all.

4.2 Resulting utilisation potentials for CO₂

The capture potentials given in the previous section do significantly reduce the amount of CO₂ being utilisable from the total amounts emitted. Presuming the average capture rates as shown in Figure 4-1 the resulting potentials for CO₂ from industrial sources are reduced to the amounts shown in Figure 4-2.

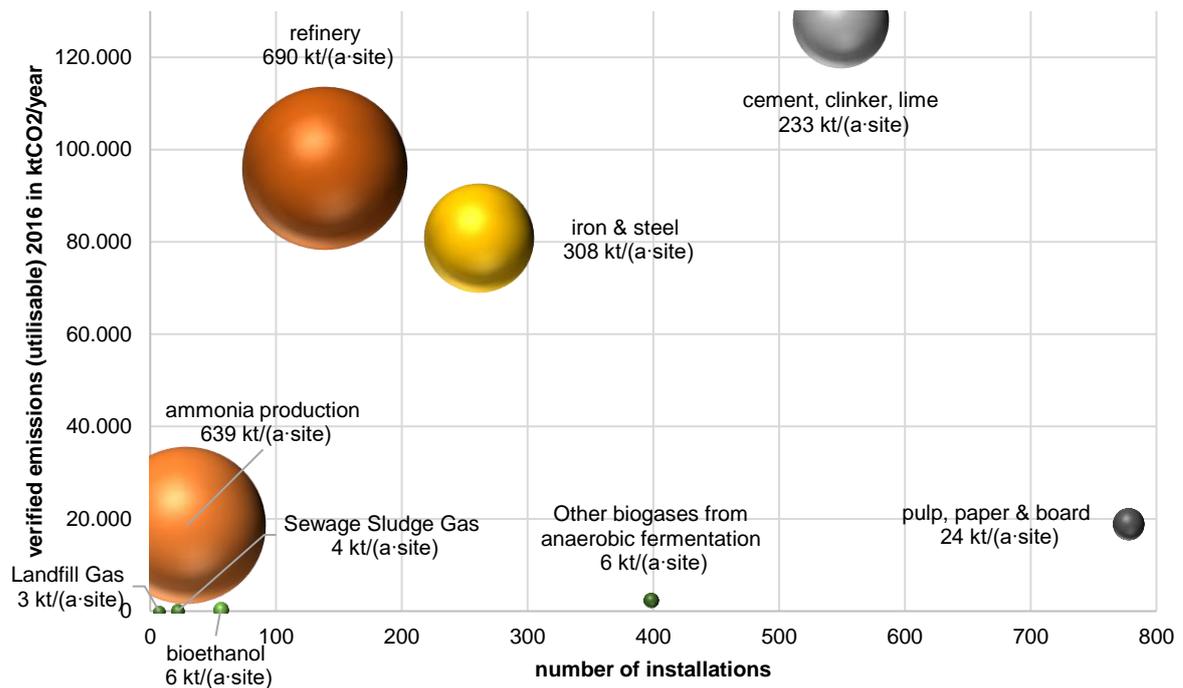
Figure 4-2: Comparison of produced and theoretically utilizable CO₂ per industrial sector



Source: own illustration Energieinstitut

The capture efficiency also has impact on the utilisable CO₂ emissions per site as shown in Figure 4-3 according to the categorisation given in Table 4-1. It can be seen, that refinery and ammonia production processes, followed by iron & steel and cement production, would provide highest amounts on utilisable CO₂ per site if fossil sources are taken into account. In contrast, per site amounts for biogenic sources are rather low. Therefore, for large scale application of carbon capture and utilisation, fossil processes should be considered as a potential source for CO₂, as long as there are no environmental drawbacks and it does not support or prolongate the deployment of processes that can and should instead be substituted by renewable approaches.

Figure 4-3: Utilisable CO₂ potentials from various industrial processes



Source: own illustration Energieinstitut

5 CURRENT COSTS FOR CO₂ CAPTURE

Generally, investment costs for CO₂ sequestration are not easy to define. It is reasonable to set a reference for specific costs according to the used CO₂ source. Affordable sequestration rates strongly depend on the concentration of carbon dioxide in the, usually gaseous, source stream and the underlying emitting process. As the CO₂ sources and the reference values for assessing investment costs exhibit significant variance, it seems more practical – at least for the usage of carbon dioxide in the electrochemical conversion process – to value the needed CO₂ as an operating supply and therefore represent its costs as per ton CO₂, depending on its source and sequestration technology, respectively.

5.1 CO₂ from biogas or bioethanol plants

Biogas plants with feed-in to the natural gas grid lend itself to a source of otherwise unused carbon dioxide as characterised in the previous sections of this report. Specific costs for CO₂ sequestration in such biogas plants are at approximately 12 € cents per standard cubic meter

of methane. Assuming a CO₂ fraction of 40% in the raw gas flow, this would lead to costs of about 90 € per ton CO₂ (for 2012). However, the sequestration, as well as the removal of impurities (like sulphur), is normally done for the retrieval of biomethane that can be fed in to the gas grid, and hence costs are assigned to the methane production. In this aspect, the sequestration of CO₂ is neutral in terms of costs [15, 79].

The costs of carbon dioxide from a bioethanol plant, as a source, would behave in a similar manner. In the fermentation process, a high-quality stream of CO₂ is accumulated as a by-product. If only this method is considered as a potential source, then the sequestration costs would be limited to the costs necessary for the compression of the gas, which can be assumed at about 12–25 €/t CO₂ [15, 71, 74, 81]. If the bioethanol plant uses cogeneration for energy provision, and the CO₂ capture from the cogeneration process is also considered, then the costs would be between 42 € [76] and 111 € [81] per ton CO₂ (capturing and compression).

5.2 Assessment of literature data on carbon capture cost

In Table 5-1 the gathered carbon capture costs for CO₂ supply of the electrochemical conversion are summarized. Compared to the previous sections, the data was extended with CO₂ from fossil sources, though their acceptability for the generation of renewable ethylene oxide has to be discussed (e.g. CO₂ can come from waste gases from industrial processes, that cannot be shifted to use renewable energy, and therefore fossil CO₂ cannot be avoided).

Table 5-1: Average capture costs for CO₂ related to industrial sectors

CO ₂ source		capture costs	Year	exchange rate	Ref.
		€/tCO ₂		USD/EUR	
energy industry; power & heat from fossil fuels	coal	34 – 42	2017	0.83	[71]
		19 – 47	2015	-	[15]
		20 – 63	2015	0.72	[72]
	natural gas	63 – 83	2017	0,83	[71]
		54 – 101	2015	-	[15]
		35 – 75	2015	0.72	[72]
biomass	54 – 101	2015	-	[15]	
chemical industry	refinery	29 – 83	2017	0.83	[71]
		44 – 94	2015	-	[15]
		48 ¹⁾	2012	-	[73]
		97	2014	0.82	[74]
	ammonia production	12	2017	0.83	[71]
		23 – 54	2015	-	[15]
	other chemicals	22	2014	0.82	[74]
		12 – 52	2017	0.83	[71]
iron & steel production	21	2014	0.82	[74]	
	19 – 33	2017	0.83	[71]	
	16 – 41	2015	-	[15, 73]	
cement, clinker & lime production	81 – 83	2014	0.82	[74]	
	22 – 35	2017	0.83	[71]	
	33 – 69	2015	-	[15, 73]	
	17 – 37 ¹⁾	2012	-	[73]	
pulp, paper & board production	82	2014	0.82	[74]	
	18 – 27	2003	0.79	[76]	
	57 – 87	2017	-	[77, 78]	
biogenic CO ₂ sources	biogas upgrading	0 – 90	2012	-	[79]
		5 – 9	2015	-	[15]
	bioethanol fermentation	12	2017	0.83	[71]
		0 – 18	2011	-	[81]
		25	2014	0.82	[74]
		5 – 9	2015	-	[15]
bioethanol fermentation (incl. cogeneration)	83 – 111	2011	-	[81]	
	42	2003	0.79	[76]	
Direct air capture	150 – 320	2012	-	[79]	
	22 ¹⁾	2012	-	[79]	

CO ₂ source	capture costs €/t _{CO2}	Year	exchange rate USD/EUR	Ref.
	150	2010	0.75	[82]
	331 – 423	2011	0.77	[83]
	268 – 309	2013	0.72	[84]
	341 – 475	2014	0.82	[85]
	81 – 201	2018	0.86	[86]

¹⁾ long term prediction

As it can be seen, capture costs for CO₂ are highly dependent on the source used. While capturing from diluted industrial flue gases (combustion of natural gas or solid biomass, refinery) ranges from 50-100 €/t, efforts for sources with high concentrations (biogas upgrading, industrial bioethanol fermentation, ammonia production, etc.) are substantially lower, reaching values clearly below 50 €/t. Due to the low concentration of CO₂, direct air capture shows the highest costs that is additionally covered with high uncertainties according to the low maturity of the technology.

6 CONCLUSIONS

This deliverable report is summarizing the available information on the theoretical carbon dioxide feedstock potential for the CO2EXIDE project. The potential of green CO₂ sources for ethylene synthesis has been explained in Chapter 2. In Chapter 3 fossil CO₂ sources are discussed.

From biogas production (anaerobic digestion process) 23 Mt CO₂ derive as by-product (~ 40 vol.-% CO₂ as by-product in biogas, ~ 60 vol.-% methane CH₄ in biogas) per year [1], of which approximately 3.44 Mt CO₂/year are already separated during biogas upgrading (> 95 vol.-% CO₂ off gas; CH₄ biomethane product gas) [7]. Taking into account the annual biogas production [1] and the annual upgraded biomethane [8] the utilisation of biogas - typically in combined heat and power plants - produces approximately 58 Mt CO₂/year including the CO₂ as by-product from anaerobic digestion and the CO₂ derived from the combustion of methane content.

Summing up CO₂ from solid biofuel combustion (437 Mt CO₂), bioethanol fermentation (4.3 Mt CO₂), wine and beer production (1.44 and 1.48 Mt CO₂), biogas upgrading (3.44 Mt CO₂) and combustion of remaining biogas (58 Mt CO₂) approximately 506 Mt biogenic CO₂ are produced annually in Europe via assessed process routes. The subsequent assessment showed that only part of this CO₂ potential is available in reality for valorisation. Nevertheless the amounts are vast related to the targeted utilization pathway in the CO2EXIDE project.

There are several limiting factors for green CO₂ sources, as it has been explained in more detail in Chapter 2. At first solid, liquid and gaseous biofuels are distributed to many small users, e.g. household fireplaces, motor vehicles and gas heating systems. The CO₂ emitted from these small consumers cannot be utilized, because of the high technical and economical effort for collection and directed utilization. Furthermore, it is very likely that the elaborate capture process would not result in an ecological and sustainable system, which contradicts the intention of Carbon Capture and Utilization. Additionally, CO₂ is already utilized as a raw material in the food and beverage and chemical industry. Other utilization pathways offer water purification, pulp and paper industry, metal industry, welding, electronics, refrigerant gas and fire suppression technology. A comprehensive review on existing and emerging uses of CO₂ and their CO₂ demand was published in [87, pp. 8-14] and [88].

The CO₂ produced during industrial bioethanol fermentation is already utilized to some content, while the CO₂ accumulating in the beverage industry is reused nearly completely, especially from big breweries and wine production sites. CO₂ from industrial bioethanol plants is often utilized as dry ice [89, 90], gaseous fertilizer for green houses [91, 92] or for carbonating beverages. [21, 89] The CO₂ generated during fermentation processes in the beer and wine industry is often used for carbonating wine and beer directly [32, 93] or as inert gas to preserve the beverages. [94, 95] The major potential therefore derives from biogas upgrading plants, remaining CO₂ from bioethanol production and flue gases from biogas combustion whereas the raw biogas (approx. 40 vol.-% CO₂ and 60 vol.-% CH₄) is combusted with air and the derived flue gas represents a lower CO₂ concentration (approx. 8-15 vol.-%). Consequently this requires a quite intense flue gas purification and separation, while biogas upgrading offers large amounts in high concentrations, but provides the side aspect of potentially harmful trace compounds for electro catalytic conversion.

Depending on the kind of biogas – landfill gas, sewage sludge gas, biogas from anaerobic digestion with numerous substrates – various trace compounds can be present within the raw biogas. These impurities can be harmful in many ways to e.g. CHP plants but also to other technologies and chemical reactions applied in carbon dioxide utilization. Chapter 2.3.1 provided more insight towards these potential problems.

Capture costs for CO₂ are highly dependent on the source used. While capturing from diluted industrial flue gases (combustion of natural gas or solid biomass, refinery) ranges from 50-100 €/t, efforts for sources with high concentrations (biogas upgrading, industrial bioethanol fermentation, ammonia production, etc.) are substantially lower, reaching values clearly below 50 €/t. Due to the low concentration of CO₂, direct air capture represents the highest costs which are additionally covered with high uncertainties according to the low maturity of the technology.

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