VALORISATION OF BIOGENIC CO_2 FROM BIOMETHANE PLANTS IN EUROPE: CURRENT STATE AND FUTURE PROSPECTS

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ABSTRACT: Within the scope of the scientific project SEMPRE-BIO (SEcuring domestic PRoduction of cost-Effective BIOmethane) targeting to demonstrate novel and cost-effective biomethane production solutions and pathways which maximise the carbon utilisation in the feedstock, the present research delivers an analysis of current state and future options of the market of biogenic CO_2 valorisation derived from biomethane in Europe focusing on commercial-scale CCU projects. According to the empirical data collection and literature research, an overview of the utilisation sectors of CO_2 is presented and the markets in the selected European countries are described. Currently, the biogenic CO_2 is used for air enrichment in greenhouses, food and beverage industry, and PtX. The change towards the production of high-value biogenic CO_2-based products cannot be observed yet. The use of biogenic CO_2 from biomethane can be expected to increase (projection 46 Mt by 2030 and 124 Mt by 2050) in the light of the volatility of (fossil) CO_2 prices, the expected decline of the fossil point-source CO_2 and the target of climate neutrality in the European Union by 2050 as stipulated by the European Climate Law.
Keywords: biomethane, CCU, biogenic CO_2, CO_2 valorisation

1 INTRODUCTION

In the course of the need of defossilisation of industrial sectors, the transition from fossil to biogenic CO_2 is necessary. Sources providing fossil point-source CO_2 can be expected to decline over time, since increasingly more sectors of the economy will defossilise. Biogenic sources of CO_2, such as those from biogas and biomethane plants, are therefore increasingly in demand. Biogenic CO_2 represents CO_2 from combustion or decomposition of bio-products or biomass and can be referred to the natural carbon cycle. Valorisation of biogenic CO_2 derived from biomethane plants represents a dynamic and steadily growing segment in Europe. Already today, the utilisation of the entire biomethane process chain including biogenic CO_2 for material and/or energy recovery results in ecological and cost benefits. In Europe, there were 1,510 biogas upgrading units with the biomethane production of 4.9 bcm by the end of 2023 [1]. According to the target of 35 bcm of biogas and biomethane production in Europe (EU, EFTA countries, United Kingdom, Serbia and Ukraine) by 2030, as defined within the RePowerEU, more biogenic CO_2 from biogas and biomethane could be captured – namely, 46 Mt by 2030 and 124 Mt by 2050 [2].

Within the scope of the ongoing scientific project SEMPRE-BIO (SEcuring domestic PRoduction of cost-Effective BIOmethane) targeting to demonstrate novel and cost-effective biomethane production solutions and pathways which maximise the carbon utilisation in the feedstock, innovative biomethane production technologies will be demonstrated through 3 case studies with biogenic CO_2 valorisation at different process stages:

(1) Baix Llobregat in Spain (combining proton exchange membrane water electrolysis (PEM) and CO_2 bio-methanation at wastewater treatment plant (WWTP));

(2) Bourges in France (combining thermo-chemical pyrolysis process and bio-methanation);

(3) Adinkerke in Belgium (production of bio-LNG and liquified CO_2 (LCO_2) by cryogenic process, followed by the production of value-added products from LCO_2 and H_2).

There are different CO_2 valorisation routes ranging from the well-established to those still to be explored [2]. The use of CO_2 in agri- und algaculture for yield boosting in greenhouses resp. for algae growth or in food and beverage industry represent state of the art. The production of urea via Bosch-Meiser process, methanol via catalytic CO_2 hydrogenation, methane via CO_2 methanation, concrete curing, CO_2-derived polycarbonates and polyols represent mature technologies (with the technology readiness level (TRL) 8-9) [3]. Other innovative technologies such as production of biopolymers, biochemicals and alternative sources of protein from biogenic CO_2 have TRL 5-7. An overview of the possible applications for valorisation of biogenic CO_2 is shown in Table II in Appendix. Here, Power-to-X (PtX) has to be emphasized within the context of Sempre-Bio project. It stands for the process of conversion of the excess renewable electricity into H_2 through electrochemical reaction and further on by reaction with carbon compounds to product 'X'. Thereby, depending on the type of product and PtX technologies, X is referred to: the power-to-gas (P2G), power-to-liquids (P2L), power-to-chemicals (P2C), power-to-hydrogen (P2H2), power-to-methane (P2M) or power-to-heat (P2H) [4]. If fuels are provided by PtX technologies, the term electrofuels or e-fuels is used. If combining hydrogen with biogenic sources of CO_2, it is a matter of bio-electrofuels or bio-e-fuels [5]. Power-to-Gas describes the process of conversion of renewable electricity in order to produce H_2 via electrolysis ($P2H_2$) which is used with CO_2 from an external source to convert CH_4 (or synthetic natural gas, SNG) through the methanation (P2M) [6].

The present research delivers an analysis of current state and future options of the market of biogenic CO_2 valorisation derived from biogas and biomethane in Europe. Thereby, the focus is set on commercial-scale Carbon Capture and Utilisation (CCU) projects without further consideration of possible Carbon Capture and Storage (CCS) developments. The process of capture of CO_2 emissions in order to utilise the captured CO_2 flow is referred to as Carbon Capture and Utilisation (CCU). Thereby, CO_2 can be used either directly, which means without chemical or biological alteration, or indirectly, which stands for the transformation into the different products such as fuels, chemicals or building materials [7]. In comparison to CCS, the advantage of CCU lies in the higher acceptance of CO_2-based products compared to CCS, lower specific costs per t CO_2, and faster implementation time for CCU projects.

The current biogenic, natural and fossil sources of CO_2 for industrial utilisation in Europe are presented in Figure 1-A. According to [8], almost the half of CO_2 in Europe is currently supplied by the synthesis of ammonia (48 %), followed by CO_2 from refineries and chemical industry (19 %), bioethanol production (16 %), and natural wells (12 %). Hydrogen and combustion processes as sources for CO_2 in Europe play a minor role (5 % in total).

Figure 1-B depicts the estimated European CO_2 demand estimated to be 41 Mt per year which is equivalent to 16% of global demand with 4 Mt of liquid CO_2 [9]. Today, about 2 Mt of biogenic CO_2 are captured at the global scale per year, with 90 % being captured in bioethanol applications representing one of the lowest-cost technologies with the high CO_2 concentration in the process gas stream [10]. According to EU target as stipulated by the Impact Assessment Report of EC from 2024 (accompanying the document on Europe's 2040 climate target, [11]) in accordance with the most ambitious scenario, in total 344 $MtCO_2$/ year could be captured by 2040. However, depending by source, the Impact Assessment Report provides less ambitious numbers for biogenic CO_2 capture from biomethane in the amount of 22 $MtCO_2$/ year by 2040. The amount of CO_2 valorisation for the production of e-fuels can be accounted to 101 $MtCO_2$/year by 2040 [12].

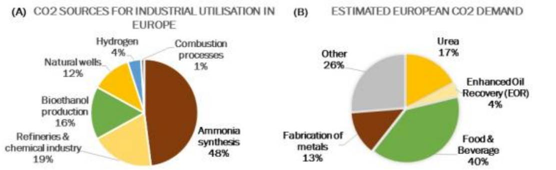

Figure 1: **(A)** The current biogenic, natural and fossil sources providing CO_2 for industrial utilisation in Europe, relative share by weight (source: own illustration based on [8]); **(B)** Estimated European CO_2 demand (source: own illustration based on [9]).

2 METHODOLOGY

In order to provide the analysis of the market development of CO2 from biogas and biomethane in Europe, the empirical data collection by 2 surveys with the semi-standardised questionnaires was carried out addressing the target group of SEMPRE-BIO and external stakeholders in order to identify the operational and planned plant sites capturing biogenic CO_2, their respective production capacities in t bioCO_2 per year or per day resp. kg bioCO_2 per hour as well as the valorisation sectors of captured biogenic CO_2. Complementary to that, the literature review was conducted to provide an overview of the utilisation sectors of (biogenic) CO_2 as well as to collect additional information on CO_2 capture from biomethane which could not be covered by the surveys as described above. During the literature research, different types of documents were consulted such as research papers, European and national project results, technical reports, presentation slides, case studies, company websites, references of plant manufacturers, official documents relevant for the admission procedure of biomethane plants, permission requests, notifications of permission, and press articles. For the collection of the scientific papers and the identification of biomethane plants with CO_2 valorisation, the keywords were "CO_2 valorisation" or "CO_2 and biomethane" in combination with the respective country name and the focus on commercial-scale CCU projects.

As a result, the status quo and the future prospects of the market development of CO_2 valorisation from biomethane can be provided for 12 European countries. Italy, Sweden, Denmark, Spain, Portugal and Ukraine (all partly) represent countries covered by empirical data collection. The response rate of empirical data collection can be found in Table I.

Table I: Survey responses by representatives of the EU biomethane projects as of 06/2023 (source: [13])

Countries covered	Number of respondent organisations	Type of respondent organisation
Italy	3	association, industry, research and consulting
Sweden	2	association, research
Ukraine	1	association
Portugal	1	research and consulting
Spain	3	research and consulting, consulting, academia
Denmark	1	academia

The separate annual survey of biomethane plant operators in Germany was further conducted, where 247 German biomethane plant operators were contacted and the response rate amounted to 13 %. Besides, external biomethane stakeholders from selected additional countries (the United Kingdom, the Netherlands, Germany and Poland) were contacted to participate in the survey due to the current and future relevance of biomethane production in combination with biogenic CO2 valorisation in these countries. In order to identify further biomethane plants with CO_2 valorisation, the additional literature research was carried out for Austria, Belgium, Denmark, Germany, France, Italy, the Netherlands, Norway, Sweden, Switzerland, and the UK.

The following depictions do not claim to be complete, but rather provide an insight into the currently changing market of biogenic CO_2 valorisation on the basis of the determined data sample. The difference of the current research – compared for instance to the overviews provided by [2] or [14] – lies in the comprehensive market research combined by the methodological steps of both empirical data collection and desk research, the specific focus on commercial-scale CCU installations contrary to only the demo and/ or pilot sites, and as the result the broad coverage of different countries and valorisation sectors of biogenic CO_2 from biomethane instead of focusing on only one specific region or utilisation type.

3 RESULTS AND DISCUSSION

2.1 Analysis of CO_2 valorisation in Europe

Based on the results of literature research and conducted surveys, an insight is provided into the currently growing market of biogenic CO_2 valorisation from biomethane in Europe. In total, 59 sites in operation and 62 announced sites could be identified (cf. Figure 2). The United Kingdom (UK), the Netherlands and Italy are currently leading the way with respect to the number of the plant sites with biogenic CO_2 valorisation with 59 % in total, followed by Germany and France with 24 %. The Netherlands and the UK can be seen as the pioneers in CO_2 valorisation from biogas upgrading with CO_2 utilised primarily for air enrichment in greenhouses in order to speed up the photosynthesis rate and to increase the yields. One of the first CO_2 capture units for the use of CO_2 in greenhouses was commissioned by Eco Fuels in 2011 in Well, the Netherlands [15].

For the planning stage, the high number of sites especially in Germany (39 %) can be attributed to the national empirical data collection. The UK continues to secure its leading spot with 18 % of the planned future installations [13], [16], [17].

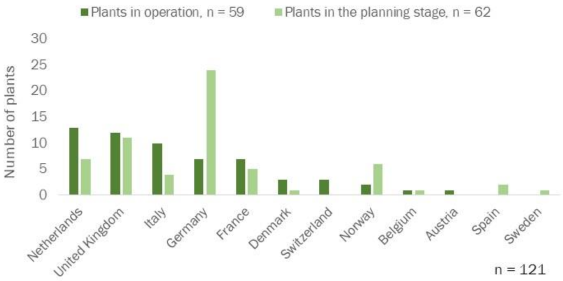

Figure 2: Biomethane plants with CO_2 valorisation (commercial-scale CCU) in Europe as of the end of 2023, the planning stage refers to the installation of CO_2 capture units; United Kingdom including Scotland and Northern Ireland (source: based on [13], [16], [17])

With respect to the estimated CO_2 capture volume from both the plants in operation and in the planning stage, 800,000 tCO_2/a can be assumed with the average of 6,600 tCO_2/a per plant. However, with respect to the capacity of the average biogenic CO2 capture unit, there are differences in the markets at the country level. Whereas i.e. Denmark set on very large capture capacities of biogenic food-grade CO_2 with its flagship project in Korskro with the annual capacity of 16,250 t/a, which are able to cover 25 % of its national CO_2 demand [13], [18], Italy introduced mainly middle to large-scale capacities of around 7,200 t/a of biogenic CO_2. Now, new markets emerge in France and Germany, whereby due to the smaller biogas upgrading capacities in France in comparison to Germany. French CO_2 capture units both in operation and under construction tend to have capacities in the smaller range of around 3,200 t/ a of biogenic CO_2 (with the exception of a few examples).

The planning horizon of the announced projects (planning stage) ranges from the end of 2023 (25 %) for the years 2024-2025 (73 %) and for the years to come up to 2027 (one unit) [13], [16], [17]. The forecast for the biomethane plants with CCU both in operation and in the planning stage in 2025 and 2026, is an assumption of around 150 plants in Europe, which is equivalent to ~10 % of the European biogas upgrading plants as of the end of 2023.

With respect to the type of biogenic CO_2 valorisation from biomethane, 85 mentions could be identified (cf. Figure 3). Thereby, multiple types of uses per one capture site are possible. The focus of the current use of biogenic CO_2 from biomethane is on greenhouses (34 %), the food and beverage industry (26 %), Power-to-X (PtX) technologies (11 %), as cooling agent or for the dry ice production (both 8 %). Healthcare sector, pharmaceutics and chemical sector with currently respectively 2 % play only a minor role. For the announced facilities, an increase of CO_2 use in the food and beverage sector with 47 % and for PtX with 22 % can be stated. The valorisation of biogenic CO_2 in greenhouses moves somewhat into the background with 13 % [13], [16], [17]. A change towards the production of high-value biogenic CO_2-based products cannot be observed yet. If there are no direct sales of the produced CO_2 to the final customers and sales contracts are concluded with the large suppliers of industrial gases such as Air Liquide S.A., the Linde Group, the Messer Group GmbH, Nippon Gases or others, the actual final uses and the respective exact amounts are traceable with additional effort or might remain unknown.

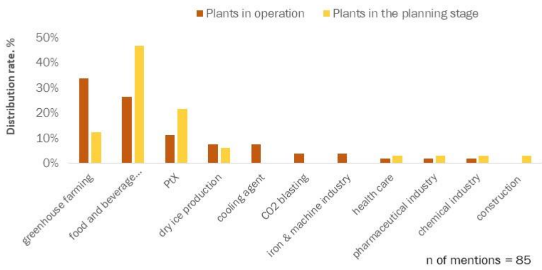

Figure 3: Distribution rate of different types of CO_2 valorisation at operational (by the end of 2023) and announced CO_2 capture sites at biomethane plants in Europe (operational and announced commercial-scale CCU); number of mentions (source: based on [13], [16], [17])

There is an emerging market for CO_2 valorisation after biogas upgrading at bio-LNG plants. It is expected that Germany, Italy, and the Netherlands will be leading the bio-LNG production in Europe by 2025. From 134 announced bio-LNG plants for the years 2024-2027, 32 are to expect to valorise their biogenic CO_2 stream [1], [19]. As the result of the surveys and literature research, 17 bio-LNG facilities with CO_2 capture units could be identified with 5 each announced in Norway (due to the fact of its first mover status starting bio-LNG production in 2012) and Germany (which corresponds with German envisaged expansion target capacity of 8.1 TWh/a of bio-LNG by 2025 and is equivalent to 42 % of the European total bio-LNG production capacity) [1].

The safety of CO_2 derived from biogas plants for the application in the food and beverage industry in Europe was manifested in the document 70/17 Carbon Dioxide Food and Beverages Grade, Source Qualification, Quality Standards and Verification released by the European Industrial Gases Association (EIGA) in 2017. According to that, CO_2 from anaerobic digestion (AD) based on energy crops is on par with CO_2 from yeast-based fermentation (ethanol production), whereas CO_2 from co-digestion or organic waste requires additional care in evaluation [20]. With respect to the purity grades, 72 % of the CO_2 capture sites in operation produce biogenic

CO_2 in food-grade quality according to the specification of e.g. EIGA, which can be valorised not only in food and beverage industry but also in other applications with high purity requirements. The applications to be commissioned with low quality requirements (here, CO_2 is an essential cost-relevant factor for the production of synthetic natural gas (SNG) from H_2 and CO_2, algae, e-methanol, or perhaps for new greenhouses) will have specific advantages (even with increasing competition for biogenic CO_2) to use CO_2 from unpressurised or low-pressure upgrading, or simultaneously from smaller plants.

The overview of the substrates used in operational biomethane plants with CCU is provided in Figure 4. In accordance with that, the major share of substrates (20 %) used in the operational biomethane plants is presented by the energy crops in combination with manure and/ or agricultural, industrial or organic waste. In 14 % of all biomethane plants in each case sewage sludge, agricultural and industrial waste or manure in combination with agricultural, industrial and/ or organic waste are used for biomethane generation. Energy crops are used in solely 12 % of the operational biogas upgrading units with CCU. The use of manure without any additional co-substrates in the amount of 3 % is due to the fact of the economies of scale and larger capacities of biomethane facilities in comparison to biogas. For 15 % of biomethane installations there is no information provided on the specific type of substrate.

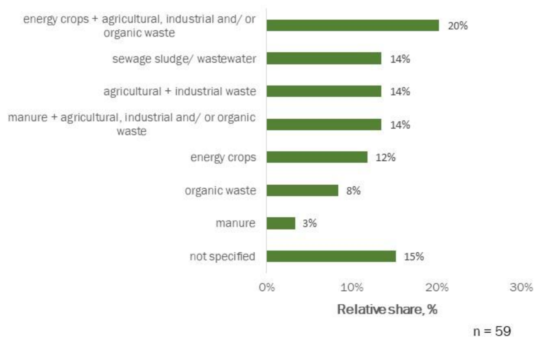

Figure 4: Substrates used in operational biomethane plants with CCU (source: based on [13], [16], [17])

With respect to the applied technologies, cryogenic separation plays at the end of 2023 a minor role (merely 1 % of the biogas upgrading technologies in operation at the European biomethane plants) [1]. Though, the importance of cryogenic upgrading may increase with supra-regional CO_2 utilisation or for cold CO_2 applications such as CO_2 blasting or the production of dry ice. In the context of Sempre-Bio project, the cryogenic separation is used in the case study located in Adinkerke, Belgium. With respect to that, the innovative part is downscaling and operation of cryo-upgrading demo site. Further, two different technological configurations will be designed and constructed to obtain value-added products from the liquified carbon dioxide and hydrogen: 1) hybrid fermenter and 2) solar photobioreactor.

More specifically within SEMPRE-Bio, polyhydroxyalkanoates (PHA) and polyhydroxybutyrates (PHB) will be produced by employing a fermentation process culturing *Cupriavidus necator*, a chemolithoautotrophic bacterium that grows on mixtures of H_2 and CO_2 with no dependence on light availability. This bacterium naturally produces PHB using the CO_2 as a carbon source [21], showcasing a promising avenue for sustainable biopolymer production.

The metabolic pathways involved in the production of organic acids (i.e., caproic acid and succinic acid) will be explored within SEMPRE-BIO. Both caproic acid and succinic acid have been chosen as they exhibit a growing market demand. The caproic acid market is projected to reach USD 52.8 million by 2027, growing at a Compound Annual Growth Rate (CAGR) of 5.6 % over the analysis period 2020-2027. The global succinic acid market size was valued at USD 222.9 million in 2021 and is expected to expand at a CAGR of 9.7 % from 2022 to 2030 [22]. SEMPRE-Bio will shed light over the promising valorisation alternatives for caproic and succinic acid production using recovered CO_2 and agri-industrial by-products, in particular digestate, as growing medium.

The utilisation of waste streams, such as wastewaters and CO_2 emissions, as nutrient sources have a twofold positive impact on single cell protein (SCP) production costs and environmental benefits. SEMPRE-Bio will focus on the production of alternative protein while valorising CO_2 recovered from biogas. Additionally, it will assess the microalgae and purple bacteria growth upon using nutrients derived from digestate. The CO_2 conversion into high-value protein biomass is affected by several key parameters, mainly related to strain selection and operational conditions during cultivation. Some of the most reported microalgae strains compatible with consumption in the EU, showing high proportion of crude protein, and exhibiting good CO_2 fixation rates (0.77-2.22 g/L/day) include *Chlorella vulgaris, Parachlorella kessleri, Tetradesmus obliquus* [23], [24].

2.2 Costs and prices of CO_2

With respect to the cost assessment, the capture of CO_2, as well as the removal of impurities, is usually done for the upgrading of biomethane, which can be fed into the gas grid. In this manner, the capture of CO_2 is often seen as neutral in terms of costs in case the costs are assigned to the methane production [25]. However, as CO_2 capture provides another product in addition to biomethane production, the costs can be split accordingly. In the overall evaluation, the total costs are to be assessed in relation to the total revenues from all products provided. Moreover, the installation of a CO_2 capture unit requires, obviously, investments which differ at country level.

The specific costs of CO_2 capture from different industrial processes are depicted in Figure 5. The depiction is based on the values provided by [25] differentiated by the biogenic, natural and fossil sources of CO_2.

Whereas the overview of the costs by [25] cover different ranges, the most conservative values were chosen in order to illustrate the specific cost ranges in the following depiction. Biogenic sources comprise biomass from industrial processes (flue gas from the combustion of solid biomass with low concentration of CO_2), biogas upgrading to biomethane, bioethanol fermentation using co-generation for energy provision, where the CO_2 will be captured from co-generation process such as natural gas fired co-generation, and solely bioethanol fermentation (here, the capture costs will be equivalent to the compression costs of the gas). Natural source is represented by direct air capture (DAC) – here, the specific site or location of the DAC unit, economies of scale, and electricity costs are of relevance while the specific DAC costs might vary at the broader scale than indicated in the following depiction. With respect to the fossil sources, other chemicals represent ethylene (oxide) production as can be found in [26]. Contrary to [26], [25] indicate the capture costs of CO_2 from flue gas of natural gas-fired power plants higher than the capture costs from flue gas of coal-fired power plants.

As shown in Figure 5, the costs of provision of biogenic CO_2 from biogas upgrading in the range 0 – 90 EUR/tCO_2 can compete with the production cost of CO_2 from fossil sources. However, lower costs for CO_2 capture can be taken into account for existing biogas plants that would opt for additional subsequent upgrading. Besides, biogenic CO_2 capture from biogas upgrading (CO_2 concentration 40 vol.-%) is also more competitive than DAC (CO_2 concentration 0.039 vol.-% in the atmosphere).

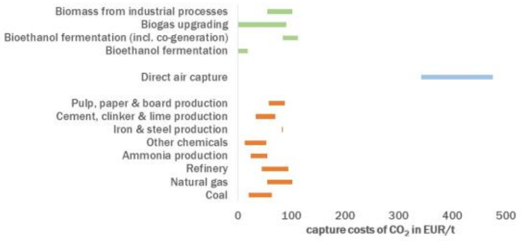

Figure 5: Ranges for the production cost of CO_2 from various industrial sectors, differentiated by biogenic, natural, and fossil sources of CO_2 (source: own illustration based on [25])

The price of (fossil) CO_2 is subject to the cost of natural gas in case of fossil-based fertiliser production and distance to CO_2 production site (transport by road by truck meaning empty return in order to avoid contamination of CO_2 tanks by impurities/ other gases resulting from different demanded gas qualities) [27], the resulting regionality of the sourcing of CO_2 and the seasonality of the demand for CO_2, followed by the very long transport distances making transport costs prohibitive. The price of biogenic CO_2 depends on biomethane plant size and CO_2 capture capacity (economies of scale), state of aggregation (gaseous or liquefied), pressure level, required degree of purity, and substrate input.

In 2022, the shortage on CO_2 was reported for some European countries, such as the United Kingdom, Italy, Poland or France [28], [29]. The reasons for that are of a similar nature, first of all due to cutting of the CO_2 production by some major fertiliser producers in the United Kingdom, Norway and Germany due to the increase in energy costs. In addition, transport difficulties and the exceptionally hot weather in summer months can be named (ibid.). As the reaction, the food and beverage industry for instance in the United Kingdom appealed to the government to develop contingency plans in order to ensure CO_2 supplies [30].

The volatility of (fossil) CO_2 prices was reported across Europe. In the United Kingdom, in comparison to £200/t CO2 in 2021 the prices spike over £1,000 t CO_2 up to £4,500 per t CO_2 were observed in 2022 [31]. In France, before 2022 CO_2 price was reported to be around EUR 50-200/t CO_2, with an average of around EUR 120-150/t CO_2 for regular consumers not far from production sources [32]. However, it can be expected that CO_2 commodity prices will ease in the mid- and long-term.

In case of the provision of biogenic CO_2, biogas or biomethane plant size and CO_2 capture capacity (economies of scale resulting in the cost degression) as well as the seasonality and regionality are important factors governing the price of biogenic CO_2 making it competitive especially in the light of the elevated natural gas prices. Europewide, the price of biogenic CO_2 derived from anaerobic digestion was calculated to be 200 EUR/t without the price premium for its biogenic origin [33].

2.3 Project examples

As an example for direct sales of biogenic CO_2 to customers, Apsley Farms in the Bourne Valley in the UK operates direct sales of its biogenic CO_2 using their in-house lorry fleet of CO_2 tankers supplying CO_2 for different industry sectors such as automotive, food and beverage, metal fabrication, water treatment, oil & gas, and dry ice [34]. In Denmark, biogenic CO_2 from the Korskro showcase project is traded under the own trade mark GO' CO_2 [18]. By buying the locally produced CO_2 at the biomethane plant in MéthaTreil, France, for their greenhouses, a local vegetable grower Vinet Frères group secured a fixed, non-seasonal price for CO_2 covering 35 % of their annual CO_2 demand [35].

One prominent example for the production of multiple goods in the course of the CO_2 valorisation is the biomethane plant at the c-Port on the Coastal Canal in Friesoythe (district of Cloppenburg, federal state Lower Saxony, north-west of Germany). It is one of the biggest bio-LNG plants in Europe which was built by the German plant constructor revis bioenergy GmbH with the first line commissioned in the fourth quarter of 2023. The first line of biomethane production should run on 485,000 t/a of chicken dry manure, turkey, horse, duck manure, cow dung, and solid fraction of cattle and pig manure – the manure can be even separated on the agricultural farms in the region by the plant operator nordfuel GmbH. From 2024 on, the total substrate amount should be 1,000,000 t/a of dung and manure. The upgrading capacity can be amounted to 7,400 m^3STP/h. Part of the produced biomethane will be injected into the gas grid, one further part will be compressed and used as CNG in the company's own delivery fleet and the main part of the produced biomethane will be liquefied to 45,000 t/a of bio-LNG. In addition, 8,000 t of ammonia will be separated during the digestate treatment and intended to be supplied to the chemical industry, whereas the solid digestate fraction will be pelletised to 100,000 t/a of digestate pellets.

In parallel to that, 103,000 t/a of biogenic CO_2 should be produced in two different qualities – food-grade CO_2 and CO_2 for industrial applications. Depending on the quality, the produced CO_2 can be potentially used in the chemical industry or for the production of dry ice. An additional possibility for valorisation of 90,000 t/a of biogenic CO_2 is provided by the fact of an announced plant for production of 60,000 t/a of e-methanol for the maritime sector representing renewable fuel of non-biological origin (RFNBO). The announced facility was planned in Friesoythe near the c-Port with the commissioning date in the 4th quarter of 2027. The planned electrolyser capacity for generation of green H_2

for e-methanol production can be amounted to 85 MW_e, while the required renewable energy should be supplied locally. However, the key data can be subject to change [36], [37], [38], [39].

2.4 Future prospects

As of today, biogas and biomethane sites are often far away from the industries with CO_2 demand. This may change with the erection of new capture units or by merging the CO_2 produced at the different plant facilities via existing (as in the case of the Netherlands) or to be installed CO_2 pipelines. Combining the decentralised points of sustainable sources of, e.g. N_2 and H_2, decentralised small-scale biogenic CO_2 production facilities may enable creation of new sustainable business models for biogas and biomethane plant operators.

The proximity to customers, local and biogenic origin, green label, high purity grades and almost complete absence of impurities, safeguarded projected supply amounts and the possibility of the fixed non-seasonal price are obviously competitive advantage of biogenic CO_2 from biogas and biomethane in comparison to its fossil-derived counterpart. If biogenic CO_2 becomes scarcer, the competition for CO_2 worth transporting will increase.

As a part of portfolio diversification strategy in individual cases, fossil-owned stakeholders are taking over the field of valorisation of CO_2 from biogas in the context of the general switch towards renewables. This is, for instance, true for Shell's gas distributor Gasnor which acquired 50 % of the shares in Renevo AS producing bio-LNG, biogenic CO_2, and biofertiliser in the autumn 2020. The Danish Nature Energy Biogas A/S, which is the largest biogas producer in Denmark, was acquired by Shell Petroleum NV in September 2023. This trend may continue in the future.

By 2050, CCU demand can be expected to be more than 6-fold higher than the total current CO_2 demand. According to the various studies projecting the future demand for CO_2 by 2050, a large range in the potential EU demand between 250 and 800 $MtCO_2/a$ for CCU, e.g. for e-fuel production, can be stated [40].

In the light of the pronounced climate neutrality in the EU by 2050 and the required defossilisation of industrial sectors, the production of biogas and biomethane with subsequent CO_2 capture and valorisation will continue to increase in the future.

The current analysis can be used for the market assessment and the overall evaluation including techno-economic as well as ecologic assessment by the greenhouse gas (GHG) emissions balances of the innovative biomethane processes and their market uptake. One further aim is to contribute to the development of the methodological approaches delivering the starting point for the accounting for GHG emissions credits and the costs for different products (biogenic CO_2, bioenergy, digestate etc.). Specific to Sempre-Bio project, the overall assessment will be carried out towards the end of the project lifetime and demonstrate whether and under what conditions the selected technologies can provide methane and biogenic (liquid) CO_2 more efficiently and cost-effectively than conventional processes.

4 CONCLUSIONS

The present analysis provides an overview of already established and emerging markets of biogenic CO_2 valorisation from biomethane in Europe. It can contribute to the sectoral comparison of CO_2 utilisation from biomethane but also other than that sources (such as of other biogenic, natural or fossil origin). It provides the initial point and the reference for the overall evaluation including techno-economic and ecological assessment as well as the market uptake of the conventional and selected innovative biomethane processes. It can be further used as the first approach for the assessment of possible new and sustainable business models for biogas and biomethane plant operators in the light of the volatility of (fossil) CO_2 prices, the expected decline of the fossil point-source CO_2 and the target of climate neutrality in the European Union by 2050 as stipulated by the European Climate Law.

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APPENDIX

Table II: Possible options of biogenic CO_2 valorisation, based on [18], [41], [42], [43]

Sector	Possible applications
Agriculture	• Air enrichment in greenhouses • Insect pest control
Algaculture	• Algae production
Energy production	• Power-to-Gas • E-fuels • Algae biomass to biogas or biodiesel
Food and beverage industry	• Cooling food (i.e., modified atmosphere packing) • Carbonation of mineral waters and soda • Wine and beer production • Food processing (chilling, temperature controlling freezing, pH control) • Stunning animals before slaughtering • Supercritical CO_2 as solvent for decaffeination of coffee beans, for production of flavours and essential oils
Building industry	• Cement • Concrete • Aggregates (filling materials)
Chemical industry	• Production of urea, methanol, dimethyl ether (DME) • Production of building blocks for biopolymers manufacturing (PHA/PHB)
Iron & machine industry	• Laser cutting • Welding in black steel • Shielding gas
Healthcare sector	• Laparoscopy (surgical procedure) • Dry ice for sending samples • Cooling eggs and sperm in fertility clinics
Pharmaceutical industry	• pH control • Dry ice for the transport of stem cells • Controlling oxygen levels in cell culture
Other	• Fire extinguishers • R744 (CO_2-based refrigerant) used in air conditioning systems • Industrial cleaning (solvent-free)