Energy Reports 15 (2026) 108903

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

What is the climate and economic impact of incorporating food-grade CO_2 production in biomethane production plants? A Swedish case study

Stephanie S. Cordova [a], Jan Moestedt [b,c], Josefine Rasmussen [d], Gustav Edholm [f], Gabriella Olsson [f], Erik Nordell [e], Marcus Gustafsson [a,*]

[a] Division of Environmental Technology and Management, Department of Management and Engineering, Linköping University, Linköping 581 83, Sweden
[b] Department of Molecular Sciences, Swedish University of Agricultural Sciences, Uppsala 750 07, Sweden
[c] Department of Development, Tekniska verken i Linköping AB (publ.), Box 1500, Linköping 581 15, Sweden
[d] Division of Business Administration, Department of Management and Engineering, Linköping University, Linköping 581 83, Sweden
[e] Department of Biogas production, Tekniska verken i Linköping AB (publ.), Box 1500, Linköping 581 15, Sweden
[f] Independent Researcher

ARTICLE INFO

Keywords:
Biogas upgrading
Biogenic CO_2
CO_2 utilization
Willingness to pay

ABSTRACT

Biomethane production plays a significant role in the bioeconomy and for defossilization. However, the potential of CO_2 utilization from biomethane is largely untapped, with only a handful of existing cases in Europe. Diverse applications of CO_2 exist, but food-grade liquefied CO_2 is usually demanded by the market, requiring biomethane facilities to implement conditioning steps, increasing costs. By applying life cycle assessment and costing, this study identified the effects of introducing food-grade CO_2 production in an existing biomethane production plant. Interviews were conducted to assess consumers' willingness to pay for biomethane with lower climate impact. The results showed that when the captured CO_2 is used to substitute fossil-based CO_2, there is a potential emissions reduction of approximately 220 %. There is also a minor reduction of emissions (around 2 %) with only CO_2 capture by reducing the methane slip. Moreover, an increase of around 7 % in costs is expected in biomethane systems producing CO_2, without considering potential income from sales. In the studied Swedish context, private actors are willing to pay a higher price for fuel with lower climate impact since it can be used in marketing, while public actors are neutral or negative to a price increase.

1. Introduction

Biomethane systems support the bioeconomy and contribute to a sustainable, secure energy transition. In addition to being a well-established and mature technology for producing renewable energy from organic waste (cf. (Alengebawy et al., 2024; Lora Grando et al., 2017)), anaerobic digestion provides societal and environmental benefits, such as efficient organic waste management and the generation of valuable by-products like biofertilizers and biogenic CO_2 (bio-CO_2), supporting the sustainable development goals (Hagman and Eklund, 2016; Obaideen et al., 2022). The use of digestate as a biofertilizer for nutrient recycling and replacement of mineral fertilizers is being implemented in some cases (Feiz et al., 2021; Lindfors et al., 2022), while CO_2 from biogas remains underutilized despite its high purity. Through the introduction of policies like REPowerEU, the EU is aiming to increase biomethane production in Europe to 35 bcm by 2030 (European Commission, 2022), up from 3 bcm in 2020 (EBA, 2021). The expected increase in biomethane production signifies a higher availability of bio-CO_2 (e.g., (Cordova et al., 2022)), which can be turned into valuable products.

Commercial biogas upgrading technologies effectively separate bio-CO_2 from biomethane at high purity levels, resembling carbon capture technologies. In contrast, other sources of CO_2 often exhibit lower purity (Hansson et al., 2017; Naims, 2016), which can lead to increased costs

Abbreviations: Bio-CNG, Compressed biomethane compressed natural gas of biological origin; Bio-LNG, Liquefied biomethane liquefied natural gas of biological origin; CCU, CO_2 capture and utilization; LCA, Life cycle assessment; LCC, Life cycle costing.

* Corresponding author.
E-mail addresses: stephanie.cordova@liu.se (S.S. Cordova), jan.moestedt@tekniskaverken.se (J. Moestedt), josefine.rasmussen@liu.se (J. Rasmussen), gustav.edholm@hotmail.se (G. Edholm), olsson_gabriella@hotmail.com (G. Olsson), erik.nordell@tekniskaverken.se (E. Nordell), marcus.gustafsson@liu.se (M. Gustafsson).

https://doi.org/10.1016/j.egyr.2025.12.040
Received 23 July 2025; Received in revised form 21 November 2025; Accepted 6 December 2025
Available online 12 December 2025

for capture and purification. Despite its biogenic origin and potential for utilization, bio-CO_2 generated during biomethane production is typically released into the atmosphere (Cordova et al., 2022), as it is considered part of the short-term, natural carbon cycle (Rypdal et al., 2006). Integrating CO_2 utilization into the system can further enhance the climate benefits of biomethane by substituting fossil-based CO_2 (Gustafsson et al., 2024). Bio-CO_2 can be employed as a substitute in various applications, including the food and beverage industry, or as a feedstock for the synthesis of fuels and materials (IEA, 2019). With advancements in CO_2 utilization technologies, global demand for CO_2 is projected to increase substantially, from 0.2 Gt in 2022 (Statista, 2024a) to as much as 6 Gt by 2050 to meet the potential demand for renewable chemicals and fuels (Galimova et al., 2022).

Currently, most of the CO_2 on the global market is derived from fossil fuels, primarily from ammonia production, but also biomass fermentation (IEA, 2019), and needs to comply with food-grade quality standards regardless of the use (Cordova et al., 2025). However, the lack of diversity among CO_2 sources leaves the market vulnerable and indirectly reliant on fossil fuel prices; for instance, the food industry has experienced shortages of CO_2 (Food Processing, 2022; Makortoff, 2022). In biomethane production, food-grade CO_2 can be achieved through additional purification steps. Examples include Recycling Energie AG in Switzerland and Nature Energy in Denmark, which produce 4000 tonnes (Liebetrau et al., 2024) and 16,250 tonnes of food-grade CO_2 from biogas annually, respectively (IEA Bioenergy, 2020).

CO_2 utilization (CCU) in Sweden is still under development, and barriers like high costs, infrastructure and logistics issues, uncertainties regarding the most effective configuration of technological elements, and a complex policy landscape hinder broader implementation (Cordova et al., 2025). Even though CO_2 from biomethane production has high purity, there are also some costs related to conditioning CO_2 for transport like drying, purification, cooling, and liquefaction, which are needed for CO_2 storage (Andersson et al., 2021) but are also required for food-grade CO_2 production. High costs could affect the economic performance of the biomethane production system. Previous research suggests that sales of CO_2 can provide additional revenues to biomethane production plants (Cordova et al., 2022; Esposito et al., 2019). CCU could improve the environmental and economic performance of biomethane production (Esposito et al., 2019; Gustafsson et al., 2024), avoiding environmental trade-offs and mitigating any additional detrimental effects (Gustafsson and Cordova, 2024). Moreover, actors in the CO_2 market anticipate that CCU can provide a competitive advantage by improving the green image of companies (Cordova et al., 2025). Still, there is little knowledge on to what extent the additional income can compensate for the cost or if consumers are willing to pay for biomethane with better environmental performance.

There is limited literature on the economic and environmental effects of incorporating food-grade CO_2 production on biomethane upgrading systems. Some of the available literature utilizes software simulations to optimize biogas upgrading and CO_2 liquefaction without focusing on reaching food-grade CO_2 quality (e.g., (Hashemi et al., 2022; Naquash et al., 2022; Yousef et al., 2017; Yusuf and Almomani, 2023)). Although simulations facilitate technological development, their results are limited to the variables considered in the model, highlighting the need for empirical studies that account for requirements that might emerge during implementation. An exception is a case study performed by Esposito et al. (2019), who assessed the economic and technological feasibility of producing both biomethane and food-grade CO_2 using membrane-based upgrading technology (Esposito et al., 2019). Their study demonstrated the capability to produce 7000 tonnes of CO_2 annually at a purity level exceeding 99.9 %, meeting food-grade standards. They also found that sales can partially cover the expenses with a selling price of 25 EUR per tonne of CO_2. However, it is unclear whether the income was able to compensate for the total costs. Therefore, more research is needed to determine the environmental and economic effects of incorporating food-grade bio-CO_2 production in real cases.

This research aims to study the impacts on the climate and economic performance of an existing biomethane facility introducing food-grade bio-CO_2 production. A biomethane facility in Sweden is studied, applying a life cycle perspective in climate and economic assessment to identify potential trade-offs in the current system. Furthermore, this study will compare cost estimates to the consumers' willingness to pay for biomethane with improved climate performance. Hence, this study addresses the following research questions:

- How is the climate and economic performance of biomethane affected by food-grade bio-CO_2 production?
- How can improved climate performance influence consumers' willingness to pay for biomethane?

Based on a real case under development in Sweden, this research contributes with empirical data on food-grade bio-CO_2 production in biomethane systems. Knowledge of the system can minimize uncertainties associated with required inputs and technology, facilitating implementation and impact estimation. Moreover, this study also contributes to understanding the effects on the willingness to pay for low-emission fuel, which helps to capture additional values from the biomethane system.

2. Methodology

A reference scenario, based on an existing biomethane upgrading plant with a capacity of 125.6 GWh, was compared to two alternative scenarios: one where CO_2 is captured, liquefied, and purified to food-grade quality, and another where the liquefied food-grade CO_2 is used to substitute fossil CO_2. The scenarios were quantitatively assessed through life cycle assessment (LCA) and life cycle costing (LCC) to estimate the climate performance and economic feasibility of the biomethane system. In the LCA, the system boundaries were extended to encompass both the production and end-use phases of biomethane, assuming its application in a combustion engine. Accordingly, the model covers the full life cycle, from substrate collection and anaerobic digestion to final energy use. Additionally, the system includes the use of by-products, namely biofertilizer and bio-CO_2, and the substitution of alternative products. The economic model was also based on plant capacity and electricity use and complemented with prices from existing literature (see Section 2.2).

Moreover, biomethane users across various sectors in Sweden were interviewed to assess their potential willingness to pay for a product with a reduction of CO_2 emissions. A description of the employed methods is provided in Sections 2.2–2.4.

2.1. Case description

The system under analysis upgrades 125.6 GWh of raw biogas per year. Most of the biogas is produced in the same facility through the anaerobic digestion of mainly food waste, slaughterhouse waste, and industrial organic waste, while 16 % is derived as a byproduct of the municipal wastewater treatment plant located 1 km from the upgrading plant. The biogas plant is located in Linköping, Sweden, and operated by Tekniska verken i Linköping AB (publ.). It includes facilities for the pretreatment of household and industrial food waste (removal of impurities and dilution with liquid substrates and tap water to achieve a pumpable slurry), hygenization (thermal treatment of all ingoing substrates >70 °C for at least 1 h), and digestion (three parallel digesters of each 3700 m^3, post digestion in a 6000 m^3 digester and a final digestion step of 6000 m^3 also dedicated for removal of fertilizer for transport to arable land). Finally, the produced raw gas is upgraded by an amine scrubber, resulting in a separation of the CH_4 and CO_2, reaching close to 99 % purity in both streams. Impurities such as H_2S are primarily removed by precipitation with iron chloride in a combined addition with trace elements (Moestedt et al., 2016). Part of the separated CH_4 is further purified in a second amine scrubber to reduce CO_2 to below 5 ppm and then liquefied (resulting in bio-LNG) by reducing the temperature to −165 °C. The separated CO_2 is presently released into the atmosphere.

The new food-grade CO_2 production system will be collocated at the plant to produce 13,000 tonnes of bio-CO_2 per year. Following a future expansion of the biomethane facility, the plant's total capacity will be increased to 20,000 tonnes. This will not cover all of the future CO_2 production, but exceeding this limit would require a chemical industry permit under the Environmental Permits Ordinance (Swedish Parliament, 2016), which falls outside the scope of typical biomethane operations. The facility will include pre-cooling, filtration, compression, drying, liquefaction, and short-term storage. Filtration by active carbon is used to remove impurities like VOC and H_2S to achieve a CO_2 without organic or sulfur impurities. In the dryer, the gas is cooled to 2 °C using water in a heat exchanger, which separates the gas through condensation in a demister. A dryer vessel is used to capture moisture by a sorbent. The dewpoint after the drying step of the CO_2 is minimally at −50 °C. After drying, the CO_2 is sent to a stripper that includes a reboiler and a condenser. The reboiler serves as the cooling step for the CO_2 to reach a temperature of −30 °C and 14–15 barg, using CO_2 as a refrigerant. At this temperature, liquid CO_2 starts to form in droplets and is separated in the stripping column. The vapor leaving the stripper contains any non-condensable gas, including oxygen, nitrogen, methane, and parts of the CO_2 that are redirected to the upgrading facility. The liquefied CO_2 produced reaches food-grade quality according to the European Industrial Gases Association for food and beverage-grade CO_2 (EIGA) (EIGA WG-8, 2016), which is assured through multiple online and off-line analyses. The CO_2 is finally sent to short-term batch storage to be loaded in trucks for distribution by an external buying company.

2.2. Climate impact assessment

The functional unit for the LCA is 1 MJ of biogas upgraded to compressed biomethane (bio-CNG) and liquefied biomethane (bio-LNG), with a share of 41 % and 59 %, respectively, based on the case study. The evaluated alternatives were (i) the base scenario (without CO_2 capture), (ii) CO_2 capture and liquefaction, and (iii) CO_2 capture, liquefaction, and substitution of fossil-based CO_2.

Calculations were performed in SimaPro v9.6, utilizing data from Ecoinvent v3.10 supplemented with information on renewable fuels in Sweden from f3 – The Swedish Knowledge Centre for Renewable Transportation Fuels (Hallberg et al., 2013; Källmén et al., 2019). When possible, background data specific to Sweden were selected to ensure a close representation, with European data used when Swedish data was unavailable. Detailed input data for the model can be found in the Appendix. The ReCiPe 2016 Midpoint (H) impact assessment method was employed in calculations, which is commonly used for LCA (Huijbregts et al., 2016).

The model includes a collection of substrates (food waste, slaughterhouse waste, and industrial organic waste), anaerobic digestion, use of digestate, biogas upgrading, and distribution, using case-specific data and applying substitution of alternative CO_2 production (Fig. 1). Substrates are collected from various sources using trucks powered by diesel, HVO, bio-LNG, and bio-CNG. Emissions from both production and combustion were modeled using Ecoinvent v3.10 and data from f3 – The Swedish Knowledge Centre for Renewable Transportation Fuels (Hallberg et al., 2013; Källmén et al., 2019). Since substitution was applied, the transport of an equivalent amount of waste from England to the site (COWI, 2015; Linköpings, 2020) is included to compensate for the electricity that would have otherwise been generated through waste incineration. Also, the amount of CO_2 emitted when biomethane is combusted is assumed to be offset by an equivalent amount of CO_2 captured during biomass growth in the short-term carbon cycle (0.039 kg CO_2/MJ of bio-CNG (Gustafsson et al., 2021)). Those CO_2 emissions were added in the use phase, along with the GHG emissions from combustion in an engine (Hallberg et al., 2013). Moreover, digestate is utilized in agriculture as a replacement for mineral fertilizers. It is assumed that the nutrients and soil amendments from biofertilizer – plant-available ammonium nitrogen, phosphorus, sulfur, potassium, magnesium, and calcium – substitute equal quantities of inorganic alternatives (Tufvesson et al., 2013). The system includes upgrading, which is performed by an amine scrubber, polishing and liquefaction (for bio-LNG), compression (for bio-CNG), and electricity use for distribution. Methane slip is included in anaerobic digestion and biogas upgrading. The climate impact of the raw biogas produced in the municipal wastewater treatment plant was obtained from Ecoinvent. In the database, biogas from wastewater treatment comes without climate burden, which aligns with this model, as biogas is considered a byproduct of a waste treatment process. However, emissions from pumping the biogas to the upgrading facility were omitted due to the short distance and the low energy consumption. Similarly, the transportation of biomethane to the user was excluded, as the upgrading facility includes a filling station. The required heat for biomethane production is obtained from waste incineration in the same municipality.

The scenarios that included CO_2 liquefaction were modeled using case-specific data, including energy (0.2 MWh/t CO_2) and material consumption (0.6 kg activated carbon/t CO_2). No additional refrigerant is required in the process, as it utilizes available CO_2 from the system. During the CO_2 liquefaction process, methane slip from biogas upgrading can be recovered, preventing methane emissions to the atmosphere.

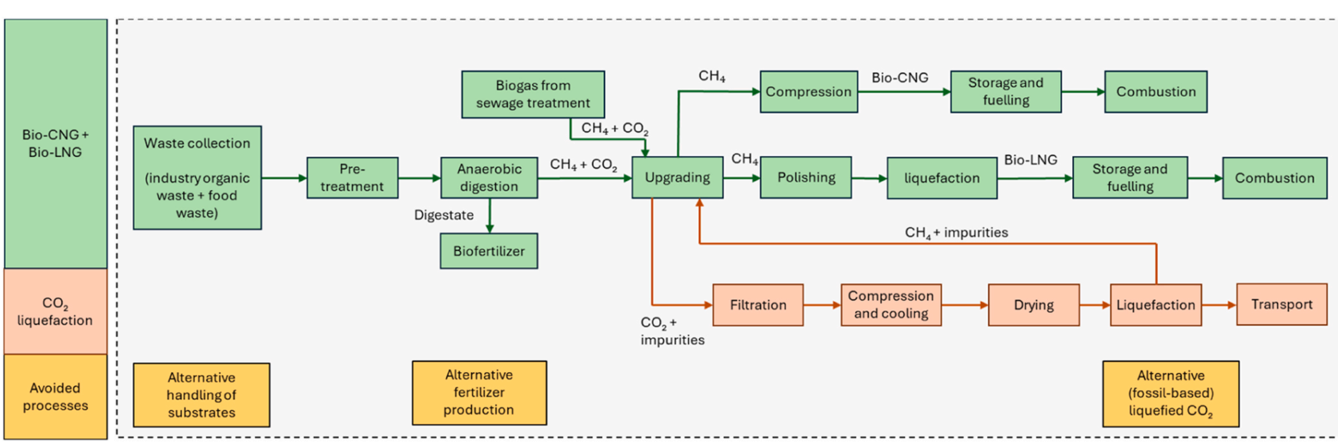

Fig. 1. Diagram of the modeled biomethane production system, including CO_2 liquefaction and substitution of fossil-based CO_2. The lower part of the diagram shows alternative avoided processes.

The scenario that included the substitution of fossil-based CO_2 accounts for the avoided production and transportation of the same amount of fossil-derived CO_2. It is assumed that the fossil-based CO_2 would otherwise be imported from the Netherlands, which was the leading CO_2 exporter by 2022 (Statista, 2024b), thereby eliminating the need for transportation over a distance of 900 km. Moreover, it is assumed that the liquified bio-CO_2 is transported 100 km to a final user.

2.3. Life cycle costing

To cover potential future expansion in biomethane production, the life cycle costing is based on a CO_2 liquefaction plant with a capacity of 20,000 tonnes per year. The calculations include capital and operational costs, where the actual case-specific capital costs of the plant, including installation costs, are 5081,400 EUR (Swedish Environmental Protection Agency, 2025). The plant will be constructed within an existing biomethane plant, and hence, the price of land, site preparation costs, and administrative offices are not considered in the capital costs. The annuity factor (AF) is used to calculate the annual capital costs (Eq. 1), with a depreciation period (N) of 15 years and an interest rate (i) of 6 % (Gustafsson and Svensson, 2021).

$$AF = \frac{i}{1-(1-i)^{-N}} \quad (1)$$

Operational costs were calculated, including operation and maintenance, energy, distribution, and labor. A factor of 2.5 % of the total equipment was used to calculate operation and maintenance costs without energy costs (Gustafsson and Svensson, 2021). The cost of electricity was set to 38 EUR/MWh (Statista, 2024a). Distribution costs of 21.9 EUR/tonne were based on trucks with a 34-tonne capacity and a transport distance of 100 km (Berg, 2021). Labor-related costs were calculated assuming that only one additional operator is required in the biogas upgrading facility for the CO_2 liquefaction plant, with a basic monthly wage of 3205.71 EUR/month (Statistics Sweden, 2024). An additional 25 % of the labor costs were added for supervision, along with a direct salary overhead of 40 % of the combined operating labor and supervision costs (Lawson et al., 2021; Seider et al., 2009). The total operational costs per tonne of CO_2 and MJ of biomethane were calculated considering the total costs per year and the total CO_2 production (13,000 t/year), with a production of 125.6 GWh in Case 1. Moreover, the costs were calculated for the projected production of 20,000 t/year, with an assumed increase of biomethane production of 183.35 GWh in Case 2. The projected production was calculated with a CO_2 density of 1.976 kg/Nm^3 CO_2 (Pubchem, 2005), a share of 35.5 % of CO_2 and 64.5 % of methane in the raw biogas, and an energy content of 9.97 kWh/Nm^3 of biomethane.

The increase in total biomethane production costs was calculated based on the average production and distribution costs of biomethane. The production costs of biomethane vary depending on factors such as plant scale and substrate type (D'Adamo et al., 2023; Gustafsson and Svensson, 2021), ranging from 28 to 109 EUR/MWh, with typical values around 70 EUR/MWh (Börjesson et al., 2016; D'Adamo et al., 2023; Gustafsson and Svensson, 2021; O'Shea et al., 2017; Pääkkönen et al., 2019; Vo et al., 2018). A cost of 100 EUR/MWh was assumed to account for potential price changes due to inflation. Given that the selling price of CO_2 is still uncertain, a range of 0–200 EUR/t CO_2 was assumed to estimate the potential revenue for the biomethane facility. The lower bound represents a case in which CO_2 has no market value while the upper bound was selected in line with assumptions made in previous studies (i.e Huber et al., 2024; Pietzcker et al., 2021; Tekin et al., 2024).

2.4. Sensitivity analysis

For the climate performance, a sensitivity analysis was performed for three variables: CO_2 distribution distance, the amount of fossil CO_2 substituted, and the electricity source used in the facility. The distribution distance was varied from 100 to 900 km. The electricity mix was changed from the Swedish mix (38.28 g CO_2 eq/kWh) to the European mix (334.33 g CO_2 eq/kWh), based on data from Ecoinvent v3.10 (Ecoinvent, 2023). Additionally, the share of fossil CO_2 replaced was varied from the reference value of 100 % to 50 %. In the economic analysis, transportation costs were varied by $\pm$100 %, where $-$100 % represents local use, and + 100 % represents a twice as long transport distance.

2.5. Willingness to pay

Willingness to pay is a concept representing the price a customer is willing to pay for a product or service, that is, the value they associate with the product or service (Le Gall-Ely, 2009). In this study, the concept is used to assess the willingness to pay for biomethane with improved climate performance and compare it with cost estimates. The willingness to pay was assessed through interviews with users or potential users of biomethane, including companies and organizations from both the public and private sectors (Table 1). All companies and organizations interviewed except Retailer B use biomethane today, either as fuel or for process energy. In total, 13 interviews were conducted, six of which were during the spring of 2024 as part of a master's thesis and the remaining seven in the spring of 2025.

The interviewed companies and organizations include haulage contractors, transportation companies, retailers, municipalities, and industrial companies from the chemical and food industries, respectively. One of the interviewed companies is a public transportation company. In Sweden, public transport is managed on a regional level, where public transportation companies are responsible for the daily operations and subject to public funds and regional strategies and political decisions. In municipalities, fuel use is primarily associated with municipal service vehicles, including light trucks and refuse trucks (Ottosson et al., 2020).

The interviews were performed in a structured format with five questions, followed by five statements where the respondents were asked to assess to which degree they agreed or did not agree. The assessment included five levels, ranging from negative [(–), (-)] to neutral [0] to positive [(+), (++)]. The option "n/a" was added when the respondent was unable to answer or if the statement was not applicable.

Table 1
Interview descriptives.

Organization/ company	Public/ private sector	Role of respondent	Time of interview
Haulage contractor A	Private	CEO	Spring 2024
Haulage contractor B	Private	CEO	Spring 2024
Transportation & logistics provider	Private	Head of Sustainability	Spring 2025
Retailer A	Private	Sustainability manager logistics	Spring 2024
Retailer B	Private	Sustainability manager	Spring 2024
Retailer C	Private	Sustainability manager	Spring 2025
Food industry	Private	Environmental and property manager	Spring 2025
Chemical company	Private	Head of Procurement	Spring 2025
Public transportation company	Public	CEO	Spring 2025
Medium-sized municipality A	Public	Environmental strategist	Spring 2024
Medium-sized municipality B	Public	Sustainability strategist	Spring 2025
Large-sized municipality A	Public	Environmental strategist	Spring 2024
Large-sized municipality B	Public	Environmental strategist	Spring 2025

Medium-sized municipality: < 100 000 inhabitants; Large-sized municipality: > 100 000 inhabitants

Table 2
Description of questions and grading assessment.

Indicator	Question	Grading	
Using fossil-free fuels/energy sources today	Are you using fossil-free fuels today?	(++)	Uses only fossil-free fuels/energy sources (100 %)
		(+)	Uses fossil-free fuels/energy sources for the most part (>50 %)
		(0)	Uses fossil-free fuels/energy sources to some extent (~50 %)
		(-)	Uses fossil-free fuels/energy sources to a lesser extent (<50 %)
		(–)	Does not use fossil-free fuels/energy sources (0 %)
Improved climate performance facilitates marketing	Does improved climate performance facilitate marketing for the company?	(++)	The greater the climate benefit, the better the marketing
		(+)	A good climate benefit helps you
		(0)	Does not have an impact
		(-)	Does not help us
		(–)	Climate benefit is bad marketing
Financial incentives are a means for choices with improved climate performance	Do financial incentives facilitate making choices with improved climate performance?	(++)	There are many financial incentives to support choices with improved climate performance
		(+)	There are some financial incentives to support choices with improved climate performance
		(0)	There is no support, but we manage to make choices with improved climate performance anyway
		(-)	No specific incentives available; would be needed
		(–)	No financial incentives available, would not be relevant
Improved climate performance facilitates meeting regulations and/or goals, e.g., for emissions	Does improved climate performance facilitate meeting regulations and/or goals, e.g., for emissions?	(++)	We need better climate performance to reach goals or requirements
		(+)	Improved climate performance could help to reach future goals and requirements
		(0)	We already fulfill goals and requirements
		(-)	We have no goals or requirements that are dependent on improved climate performance
		(–)	Improved climate performance does not matter
There is a willingness to pay for improved climate performance	Are you/your customers willing to pay for improved climate performance?	(++)	Strong willingness to pay
		(+)	Could be willing to pay more
		(0)	Neutral
		(-)	Not able to pay more
		(–)	Not willing to pay more

It should be acknowledged that the interview sample is limited in numbers and collected at two points in time. A longer period between two waves of interviews may lead to temporal effects and differences in the results due to, for example, changes in policy conditions or other external differences. However, no critical differences in the results could be noted. To limit the potential sample bias due to the very limited sample size, users and potential users of biomethane from a broad range of sectors were selected and including both the public and private sector. Yet, the sample size remains small and future studies of larger samples are encouraged.

3. Results and analysis

3.1. Climate impact assessment

Fig. 2 presents the results of the base scenario (without CO_2 liquefaction), the scenario with CO_2 liquefaction, and the scenario with fossil CO_2 substitution. The climate performance of the base scenario is approximately 12 g CO_2 eq/MJ, with the largest contributor being substrate transportation, which partially relies on renewable fuels. Emission reductions occur due to digestate use, which replaces mineral fertilizers. Additionally, CO_2 uptake during biomass growth largely offsets greenhouse gas emissions from combustion when the biomethane is used.

Incorporating CO_2 liquefaction improves climate performance by 1.6 % compared to the base scenario. This modest gain results from the energy required for liquefaction and the prevention of methane slip. When CO_2 substitution is included, the improvement reaches 221 %, as all produced CO_2 is assumed to replace imported liquefied fossil-based CO_2 in the market, also eliminating transportation-related emissions. This results in a net-negative climate impact of −14 g CO_2 eq/MJ for the biomethane system.

3.2. Economic analysis

Table 3 presents the economic results, including both capital and operational costs. Among the operational costs, transportation and energy account for approximately 80 % of total expenses, with transportation representing the largest share (see Appendix).

The total costs are approximately 78 EUR and 61 EUR /t CO_2 for production capacities of 13,000 (Case 1) and 20,000 (Case 2) t CO_2/year, respectively. These values represent the minimum selling price. If the CO_2 cannot be sold (i.e., its selling price is 0 EUR/t), the overall biomethane production cost increases by 8.1 % and 6.7 %, respectively (Fig. 3). Considering CO_2 market prices, in Case 1, a selling price of 50 EUR/t CO_2 results in a loss of 3 % in biomethane production. In Case 2, the cost increase is smaller, and the CO_2 production costs are closer to the selling price. The two cases reach breakeven at a CO_2 price of approximately 60 and 80 EUR/t, respectively.

3.3. Sensitivity analysis

When using the European electricity mix in the model (Fig. 4), the climate impact of the base case increases by 68 % compared to the Swedish electricity mix. Incorporating CO_2 liquefaction into that system leads to an increase of 8 %. In this scenario, the benefits of reducing methane slip are outweighed by the additional emissions from electricity consumption. In the substitution scenario, a reduction of 122 % is achieved compared to the base scenario. The total climate impact still reaches a negative value, −4.5 g CO_2 eq/MJ, corresponding to a 69 % increase compared with using the Swedish electricity mix.

Fig. 5 illustrates the impact of varying the substitution of fossil-based liquefied CO_2 on overall climate performance. When using the Swedish electricity mix, a reduction in climate impact is achieved even with a relatively small degree of substitution. The results indicate that at least 50 % of substitution is required to achieve negative emissions. With the

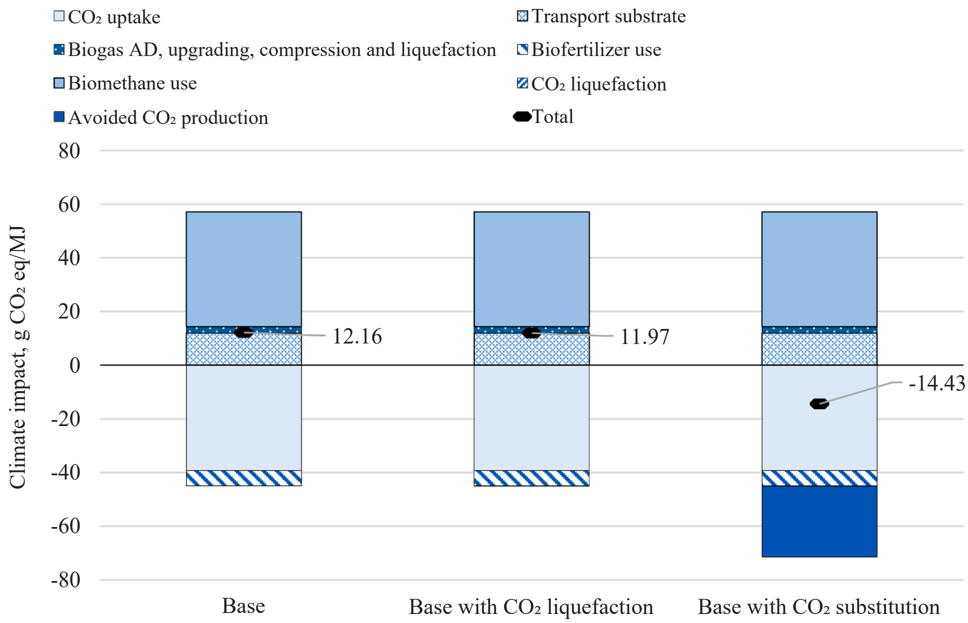

Fig. 2. Climate change impact of bio-CNG and bio-LNG without CO_2 capture (base), including CO_2 capture and liquefaction, and capture and substitution of fossil CO_2.

Table 3
Results of economic analysis with production of 20,000 and 13,000 t CO_2 per year.

	Unit	Case 1 (13,000 t CO_2)	Case 2 (20,000 t CO_2)
Annual capital costs	EUR/year	523,195	523,195
Annual operational costs	EUR/year	490,352	697,618
Cost of CO_2 production	EUR/t CO_2	77.97	61.04
	EUR/MJ biomethane	0.0022	0.0018

European electricity mix, 50 % substitution results in a climate impact comparable to the base scenario with low-carbon electricity, while achieving negative emissions requires substitution levels closer to 100 %.

The economic assessment revealed that transportation accounts for a large share of operational costs. Doubling transportation expenses increases the biomethane production costs by 2 % compared to the base scenario (Fig. 6). Under these conditions, the total production costs rise to 100 EUR/t CO_2 for Case 1 and 83 EUR/t CO_2 for Case 2. Conversely, if transportation is avoided altogether, the cost of CO_2 decreases substantially, to 56.1 EUR/t CO_2 and 39.1 EUR/t CO_2 for Case 1 and Case 2, respectively. In contrast, climate impacts are less sensitive to transportation distance (see Appendix), as the substitution of fossil-based CO_2 represents the largest contributor to emissions savings.

Although transportation costs in the studied case will be covered by an external company responsible for CO_2 distribution, they still influence the market price at which the biomethane facility can sell the captured CO_2. In other words, even if the biomethane plant does not pay for transportation directly, higher distribution costs can reduce the net revenue from CO_2 sales, as distributors may demand a lower purchase price to offset their logistical expenses.

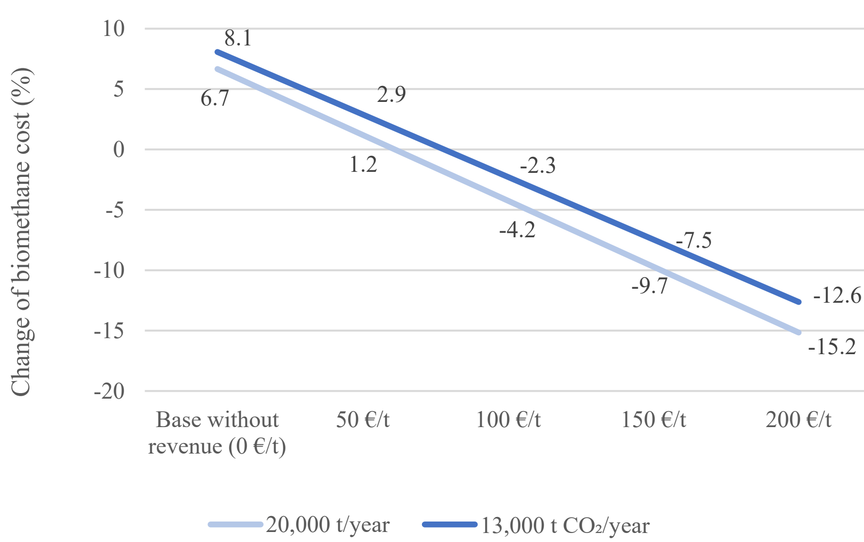

Fig. 3. Change of biomethane production cost with CO_2 liquefaction varying the CO_2 price.

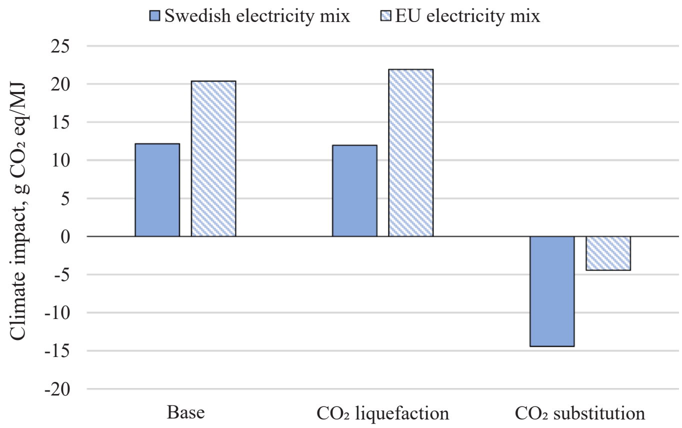

Fig. 4. Climate change impact with Swedish or European electricity mix of bio-CNG and bio-LNG without CO_2 capture (base), including CO_2 capture and liquefaction, and capture and substitution of fossil CO_2.

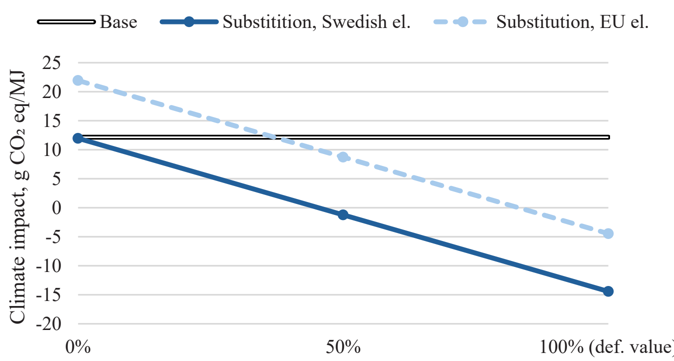

Fig. 5. Climate change impact with Swedish or European electricity mix and varying substitution of fossil-based CO_2.

3.4. *Consumers' willingness to pay*

The results on consumers' willingness to pay for biomethane with improved climate performance are presented in Table 4. The first question concerned the extent to which they used fossil-free fuels or energy sources today and served to provide insight into their current use of fossil-free sources and biomethane. All except for the chemical industry company used 50 % or more, of which Haulage Contractor B and the public transportation company used 100 % fossil-free fuels and energy sources. The chemical industry company also used fossil-free energy, but less than 50 %. Except for the haulage contractors, where there was a difference between the two grades for this question, the results were very similar for companies and organizations within the same industries, with no difference (municipalities) or only a one-grade difference (retailers).

The second question concerned whether improved climate performance would facilitate marketing. Haulage Contractor A and the public transportation company responded that it had no impact (0). The respondent from the public transportation company explained that for them, it is not the fuel itself that is their "USP" (unique selling point); that is, it is not what they base their marketing on. Rather, it is to travel collectively with public transportation instead of individual passenger cars. For Haulage Contractor A, it had been positive for marketing earlier, but that is no longer the case, mainly due to increased prices and other financial reasons. The remaining companies, as well as the municipalities – except for Large Municipality B – were positive or very positive regarding improved climate performance and marketing opportunities. For example, the transportation & logistics company motivated it as "Making the transition to being fossil-free is one of our most strategically important questions, as well as for our customers." However, Large Municipality B was the only one that expressed a negative response (-). This was explained by the respondent, who stated that they did not use climate performance in their marketing, so it did not help them.

The third question concerned the availability of financial incentives and whether they facilitated making choices with improved climate performance. For this question, there was a greater variation among the respondents (Table 4), with grades ranging from (-) to (+) and three respondents being unable to answer (n/a). The respondent from Large Municipality B considered it a political issue and, therefore, was not able to provide an answer. Both the respondents from the transportation & logistics company and Retailer C found it to be too complex and were unable to take a position. Three respondents (Haulage Contractor A, the chemical industry, and the medium-sized municipality A) indicated that no financial incentives were available, but they would be needed. On the other hand, Haulage Contractor B, Retailer B, and the public transportation company agreed that there were no financial incentives available but that they managed to make choices with improved financial performance nonetheless (0). The remaining companies indicated that financial incentives were available, which also helped them make choices with improved climate performance. Examples mentioned included, for instance, tax exemptions, the possibility for investment funds, or being covered by the European Emission Trading System (EU ETS). The chemical industry company also elaborated on how some incentives on fuels in Europe, such as the reduction obligation promoting renewable fuels (European Commission, 2018), imply value-based pricing for biomethane, which makes it more difficult to compete as it drives costs for other actors in the value chain, such as materials producers.

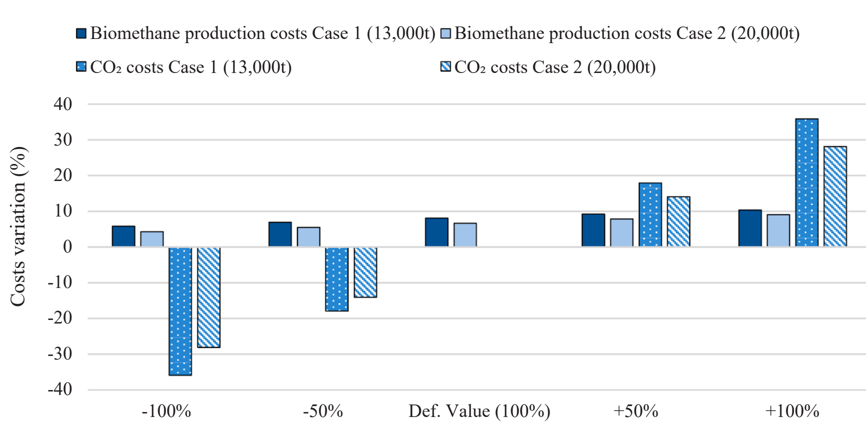

Fig. 6. Impact of transportation costs on biomethane and CO_2 price variation.

Table 4
Results on the willingness to pay for biomethane with improved climate performance. Assessments range between five levels, from negative [(–), (-)], neutral [0] to positive [(+), (++)]. n/a indicates when a respondent was unable to provide an answer.

	Private sector								Public sector				
	Haulage and transportation			Retailers			Other industries		Public company	Municipalities			
Question	Haulage contractor A	Haulage contractor B	Transp. & logistics	Reatiler A	Retailer B	Retailer C	Slaughter-house	Chemical industry	Public transp.	Medium-sized municipality A	Medium-sized municipality B	Large-sized municipality A	Large-sized municipality B
Are you using fossil-free fuels/energy sources today?	0	(++)	0	(+)	(+)	0	(+)	(-)	(++)	(+)	(+)	(+)	(+)
Does improved climate performance facilitate marketing for the company?	0	(+)	(++)	(++)	(+)	(+)	(+)	(++)	0	(+)	(++)	(+)	(-)
Does financial incentives facilitate in making choices with improved climate performance?	(-)	0	n/a	(+)	0	n/a	(+)	(-)	0	(-)	(+)	(+)	n/a
Does improved climate performance facilitate in meeting regulations and/or goals, e.g., for emissions?	(+)	(++)	0	(++)	(+)	(+)	(+)	(-)	(–)	0	(+)	(-)	(-)
Are you/your customers willing to pay for improved climate performance?	(+)	(++)	(+)	(+)	(+)	(+)	0	(-)	(–)	(-)	n/a	(–)	n/a

The fourth question concerned whether improved climate performance facilitated meeting regulatory requirements or goals, for example, regarding emissions. All private sector companies – except for the chemical industry company – answered positively to this question: that they either were fulfilling their goals and requirements or that they would benefit (+, ++) from improved climate performance to reach their goals and requirements. The large municipalities, as well as the chemical industry company, claimed to not have any goals or requirements that were dependent on improved climate performance (-). The public transportation company even claimed that improved climate performance did not matter for their goals and regulatory requirements (–). This was explained from the perspective of energy efficiency, as they consider electricity to be more efficient than biomethane for their needs, meaning that improved climate performance of biomethane would not make a difference.

For the fifth and final question, whether they or their customers would be willing to pay for improved climate performance, the same pattern can be delineated: private sector companies are in general positive (+) or very positive (++), whereas public sector organizations indicated being more negative and thus having a lower willingness to pay. The food industry was the only one that indicated “Neutral” (0). Two of the municipalities were unable to provide an answer. Both discussed this as a budgetary issue; Large Municipality B also discussed it as a political question.

The two final questions present the largest differences, where there are grades on the whole scale (from (–) to (++)). What can be noted is that, in general, the public companies and organizations (the public transportation company and the municipalities), together with the chemical industry company, responded more negatively to these questions. Reasons cited by public organizations for a lower willingness to pay included, for example, budgetary constraints. The public transportation company motivated their answer (–) that either customers need to pay more or there needs to be additional funds, in the end, from the taxpayers, and that is not the case. Private sector companies are generally not restricted by the same limitations, as also evident in the responses, particularly to the fifth question.

4. Discussion

This article presented a climate and economic assessment of biomethane production integrated with food-grade liquefied bio-CO_2 production, based on a real-case facility under construction at the time of the study. It also evaluated consumers’ willingness to pay for biomethane with a low climate impact. All emissions were attributed to the biomethane, making the two by-products of the system (biofertilizer and bio-CO_2) climate neutral. This means that the CO_2 user receives a product with no associated emissions, which serves as a selling point for the biomethane producer. This advantage is further amplified when bio-CO_2 replaces fossil-based CO_2, as the Renewable Energy Directive (RED) III (EC, 2024) recognizes this substitution as a valid means of reducing climate impact for renewable fuels. Nevertheless, this improvement in climate performance assumes that bio-CO_2 replaces fossil-based CO_2 when the potential can be limited in the short term. The typical source of fossil-based sources of CO_2 is ammonia production (IEA, 2019), which can be emitted to the atmosphere if not utilized. Moreover, biomethane can compete with other sources of bio-CO_2 in Sweden like ethanol production (e.g., (Lantmännen, 2024)). This can limit the current market for new sources of bio-CO_2 until demand increases, thereby reducing the potential to substitute fossil-based CO_2 in the short term.

The climate performance was calculated based on site-specific data of the biomethane and CO_2 liquefaction plant. In the base case, the climate impact is around 12 g CO_2 eq/MJ. Reported values in the literature have similar magnitude, but the results vary depending on the methodology, substrate, and system boundaries (e.g., (Collet et al., 2017; Gustafsson and Cordova, 2024; Prussi et al., 2020)). For instance, the same facility shows emissions of 2.29 g CO_2 eq/MJ for bio-CNG and

5.4 g CO_2 eq/MJ for bio-LNG when applying the Swedish Sustainability criteria (SvenskBiogas, n.d), which are based on the RED II (Swedish Energy Agency, 2021). Furthermore, site-specific characteristics can influence the results. The base model reflects the real case by incorporating heat from waste incineration and a share of raw biogas sourced from a municipal wastewater treatment plant. Since biogas from wastewater treatment is a process byproduct, it is considered to have no climate burden; however, it contributes to higher biomethane production yields. Moreover, heat sourced from alternative processes may carry a higher climate impact, thereby affecting the results. Nevertheless, the relative impact of including CO_2 liquefaction and fossil-based CO_2 is not affected by these assumptions since the processes do not require additional heat.

The electricity mix plays a critical role in the overall impact as the main input for CO_2 liquefaction is electricity. For instance, using the European mix increases emissions compared to the Swedish mix, and hence, renewable energy is advised to avoid the generation of additional impacts. The energy required for biomethane production is 0.08 kWh/MJ, and an additional 0.2 kWh/kg CO_2 is required for the whole liquefaction process. The literature suggests an energy consumption of around 0.14 kWh/kg CO_2 for CO_2 compression and liquefaction (e.g., (Andersson et al., 2021; Lee et al., 2015)). Additional considerations can be taken by biomethane producers when choosing the CO_2 liquefaction technology. Hashemi et al. (2022) evaluated the optimal conditions for liquified biomethane production, which includes chemical absorption as an upgrading technology producing liquefied CO_2 as a byproduct. Their results showed that the selection of the refrigeration cycle has the highest impact on the economic and thermodynamic optimization of the upgrading and liquefaction system, a finding also reported by Naquash et al. (2022). In another study, Yousef et al. (2017) investigated a cryogenic separation process for biomethane upgrading that also produces high-purity biomethane and CO_2, with energy requirements of 0.25 kWh/Nm^3 . Cryogenic separation utilizes the different sublimation points of methane and impurities, operating at temperatures below −50 °C for separation (Bauer et al., 2013). Although it yields high-purity CO_2 and CH_4, the technique is still under development, and current commercial models remain energy-intensive (Adnan et al., 2019; Bauer et al., 2013). Additionally, a change to a cryogenic or other separation process is only suitable for new biomethane plants, as it requires a complete redesign of the upgrading system.

The economic assessment showed that the production of food-grade liquefied CO_2 represents an expense for biomethane plants, which benefit from economies of scale. Esposito et al. (2019) suggest that sales of CO_2 can compensate to some extent for the cost of biomethane production, making a simple analysis based on revenues with a selling price of 25 EUR per tonne, yet this assumption still results in higher prices than natural gas and did not consider capital and operational costs. Huber et al. (2024) performed a study of synthetic fuel production considering a variation of CO_2 prices, potentially affected by carbon pricing schemes. That CO_2 market has shown volatility and links with other markets, especially the energy, metal, and financial markets (Pakrooh and Manera, 2024). Reported CO_2 prices vary widely, from 3 to 15 USD/t for CO_2 derived from ammonia production to above 400 USD/t CO_2 in niche markets (IEA, 2019). Nevertheless, biomethane plants show a good economic performance compared to other CO_2 sources (Rodin et al., 2020), benefiting from the high purity and biogenic origin of the CO_2. In this case study, the results indicate a breakeven price for CO_2 of approximately 60–80 EUR per tonne, which is consistent with values reported in the literature and suggests the economic feasibility of the process. In practice, the CO_2 price may also vary with the business model chosen by the biomethane producer. Currently, food-grade CO_2 is the only commercial available quality in Sweden (Cordova et al., 2025). This requirement allows distributors to minimize contamination risks and avoid additional logistical investments, even though food-grade quality may not be necessary for the final user. If the biomethane producer sells directly to end-users rather than through a distributor, it opens new market segments and enables local synergies with existing off-takers. However, this model also incurs additional costs related to aspects such as logistics and customer communication, and scaling. Moreover, pricing can fluctuate based on the specific application. For instance, smaller volumes (e.g., for animal stunning), larger volumes (e.g., for e-fuels) or fluctuating demand (e.g., seasonal or hourly variations in horticulture) may lead to higher costs for producers to guarantee matching demand and supply, as they must ensure supply consistently matches demand.

The reduction in climate impact achieved by the substitution of fossil-based CO_2 can serve as a selling point for biomethane production facilities, potentially offering a competitive advantage over other energy sources. At a CO_2 selling price of around 50 EUR per tonne, production and investment costs approach breakeven levels, particularly when benefiting from economies of scale. Additionally, variations in pricing methodologies among biomethane producers contribute to inconsistencies in the market (Ottosson and Danell, 2024). Consumers' willingness to pay for low-emission products varies across different consumer segments. Public actors and industries showed a neutral or negative willingness to pay, whereas private actors in the transport sector demonstrated greater acceptance, likely due to more flexible budget allocations. Those expressing a lower willingness to pay also noted limited perceived benefits from improved environmental performance relative to their organizational goals and requirements. This aligns with findings by Ottosson and Danell (2024), who reported limited customer awareness regarding the benefits of biogas systems.

5. Conclusion

This research provides contributions for academia, practitioners, and policy makers in relation to a CO_2 liquefaction system and its economic and climate impact, as well as performance and technical requirements to reach food-grade quality, based on a real case. As CO_2 liquefaction is not widely implemented in biomethane production facilities, the results presented in this study can help practitioners to reduce uncertainties for future projects. For the studied case, it is shown how integrating CO_2 liquefaction and conditioning to food-grade quality helps reduce emissions by mitigating methane slip when a low-carbon-intensity energy mix is used. Additionally, substituting fossil-based CO_2 with bio-based alternatives yields further emission reductions, enhancing the overall climate benefits and contributing to the bioeconomy.

The study provides several market implications. The economic analysis indicates how climate benefits come with increased production costs, which preferably should be offset by revenues from CO_2 sales. However, uncertain CO_2 market prices contribute to uncertainty and inconsistencies in the market. In addition, while low CO_2 prices can enable cost recovery and a promising business case, biomethane's existing price premium over fossil fuels – potentially reducing consumers' willingness to pay – can also undermine profitability. This provides further market limitations. Finally, biomethane users recognize the marketing advantages of utilizing low-emission fuel; however, these benefits are insufficiently linked to achieving regulatory compliance or meeting goals. The mixed responses from the interviews regarding incentives highlight the need for well-defined policies to promote the utilization of biomethane and bio-CO_2. This challenge is particularly evident in public companies, where premium pricing requires strong political commitment given budget constraints. On the producer side, a more supportive policy framework could encourage investment in bio-CO_2 production to secure additional revenue sources.

While the results provide a comprehensive evaluation of how CO_2 liquefaction and the replacement of fossil-based CO_2 influence the climate performance of biomethane production systems, it also poses some limitations as it employs site-specific information such as the energy mix and transportation distances. Future research can explore comparative analyses across other cases, considering different upgrading technologies, plant scales, and liquefaction system designs. Such studies could provide a broader understanding of viable production pathways suited to the diverse conditions of biomethane plants. Additionally, incorporating potential CO_2 end-users and infrastructure requirements could help assess the full impact of logistics and identify opportunities for synergies. Further studies can also evaluate the environmental impact of CO_2 liquefaction and conditioning across a broader set of impact categories to avoid trade-offs.

CRediT authorship contribution statement

Erik Nordell: Writing – original draft, Validation. **Marcus Gustafsson:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Gustav Edholm:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriella Olsson:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jan Moestedt:** Writing – original draft, Visualization, Validation, Supervision, Resources, Conceptualization. **Josefine Rasmussen:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Cordova Stephanie:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We want to express our gratitude to the actors who generously gave their time to participate in the study. This research has received funding from The Kamprad Family Foundation for Entrepreneurship, Research & Charity [grant number 20230043].

Appendix

The data for biomethane production and transportation distances of organic waste were measured on-site during 2023. The avoided mineral fertilizer was calculated based on the values presented in Table A2, using the molecular weights of the compounds available in Ecoinvent.

In the substrate transportation subprocess, transportation data for 2023 were aggregated by fuel type and by distance from collection sites to the biomethane production plant to ensure confidentiality and comply with the LCA methodology.

Due to the lack of specific processes for transportation using bio-CNG, bio-LNG and HVO in Ecoinvent, proxy processes were for technosphere inputs and non-exhaust emissions. The process "*Transport, freight, lorry 16–32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16–32 metric ton, EURO6 | Cut-off, U*" was used as proxy for technosphere inputs associated with transportation with bio-CNG, bio-LNG and HVO, considering the energy use values provided in Table A3.

For non-exhaust emissions, the process "*Transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % {RoW}| transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % | Cut-off, U*" was used for proxy. Exhaust emissions were modeled using Table A4.

Because Ecoinvent does not include a process for HVO production, the well-to-tank emissions were sourced from Källmén et al. (2019), using the Swedish HVO mix derived from various feedstocks, as shown in Table A6.

Table A1
Data for biomethane production, CO_2 liquefaction, and substitution

Subprocess	Value	Unit	Dataset in model (Ecoinvent)
Anaerobic digestion			
Water	2.59E-04	tonne/MJ_{CH_4}	Tap water {Europe without Switzerland}| market for tap water | Cut-off, U
Iron	1.40E-06	kg/MJ_{CH_4}	Iron(III) chloride, without water, in 40 % solution state {GLO}| market for iron(III) chloride, without water, in 40 % solution state | Cut-off, U
Methane Slip	2.63E-08	kg_{CH_4}/kg_{CO_2}	Methane, biogenic
Electricity	7.47E-06	MWh/MJ_{CH_4}	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Heat	1.88E-05	MWh/MJ_{CH_4}	Heat, for reuse in municipal waste incineration only {SE}| market for heat, for reuse in municipal waste incineration only | Cut-off, U
Biofertilizer (avoided)			
Plant-available nitrogen (NH4-N)	1.94	kg/$tonne_{biofertilizer}$	Inorganic nitrogen fertiliser, as N {SE}| market for inorganic nitrogen fertiliser, as N | Cut-off, U
P_2O_5	0.69	kg/$tonne_{biofertilizer}$	Inorganic phosphorus fertiliser, as P2O5 {SE}| market for inorganic phosphorus fertiliser, as P2O5 | Cut-off, U
Sulfur	0.30	kg/$tonne_{biofertilizer}$	Sulfur {GLO}| market for sulfur | Cut-off, U
K_2O	1.33	kg/$tonne_{biofertilizer}$	Inorganic potassium fertiliser, as K2O {SE}| market for inorganic potassium fertiliser, as K2O | Cut-off, U
MgO	0.17	kg/$tonne_{biofertilizer}$	Magnesium oxide {GLO}| market for magnesium oxide | Cut-off, U
Ca	2.75	kg/$tonne_{biofertilizer}$	Calcium carbonate, precipitated {RER}| market for calcium carbonate, precipitated | Cut-off, S
Ammonia (emission to air)	0.12	kg/$tonne_{biofertilizer}$	Ammonia, SE
N_2O (emission to air)	1.94E-04	kg/$tonne_{biofertilizer}$	Dinitrogen monoxide
Transport of substrate			
Transport by road (bio-LNG)	0.44	tonkm/MJ_{biogas}	Inputs from technosphere proxy from: Transport, freight, lorry 16–32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16–32 metric ton, EURO6 | Cut-off, U

(continued on next page)

Table A1 (*continued*)

Subprocess	Value	Unit	Dataset in model (Ecoinvent)
			Non-exhaust emissions to air proxy from: Transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % {RoW}| transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % | Cut-off, U
Transport by road (diesel)	0.226	$tonkm/MJ_{biogas}$	Transport, freight, lorry 16–32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16–32 metric ton, EURO6 | Cut-off, U
Transport by road (HVO)	0.105	$tonkm/MJ_{biogas}$	Inputs from technosphere proxy from: Transport, freight, lorry 16–32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16–32 metric ton, EURO6 | Cut-off, U Non-exhaust emissions to air proxy from: Transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % {RoW}| transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % | Cut-off, U
Transport by road (bio-CNG)	9.79E-4	$tonkm/MJ_{biogas}$	Inputs from technosphere proxy from: Transport, freight, lorry 16–32 metric ton, EURO6 {RER}| market for transport, freight, lorry 16–32 metric ton, EURO6 | Cut-off, U Non-exhaust emissions to air proxy from: Transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % {RoW}| transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % | Cut-off, U
Transport ship (avoided)	2.97E-01[a]	$tonkm/MJ_{biogas}$	Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U
Transport by road (avoided)	6.08E-02[a]	$tonkm/MJ_{biogas}$	Transport, freight, lorry > 32 metric ton, EURO5 {RER}| market for transport, freight, lorry > 32 metric ton, EURO5 | Cut-off, U
Anaerobic digestion wastewater treatment plant			
Biogas from wastewater treatment plant	1.62E-01	MJ/MJ_{CH_4}	Biogas {RoW}| treatment of sewage sludge by anaerobic digestion | Cut-off, U
Biogas upgrading			
Electricity	2.28E-06	MWh/MJ_{CH_4}	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Heat	1.84E-05	MWh/MJ_{CH_4}	Heat, for reuse in municipal waste incineration only {SE}| market for heat, for reuse in municipal waste incineration only | Cut-off, U
Activated carbon	6.63E-09	kg/MJ_{CH_4}	Activated carbon, granular {RER}| activated carbon production, granular from hard coal | Cut-off, U
Amine	4.64E-07	kg/MJ_{CH_4}	Monoethanolamine {GLO}| market for monoethanolamine | Cut-off, U
Methane slip	1.53E-08	$tonne_{CH_4}/MJ_{CH_4}$	Methane, biogenic
Carbon dioxide biogenic (emission to air)	3.25E-05	kg/MJ_{CH_4}	Carbon dioxide, biogenic
CNG and LNG polishing			
Electricity (LNG polishing)	2.57E-05	MWh/MJ_{CH_4}	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Heat	3.15E-05	MWh/MJ_{CH_4}	Heat, for reuse in municipal waste incineration only {SE}| market for heat, for reuse in municipal waste incineration only | Cut-off, U
Electricity (CNG polishing)	8.01E-06	MWh/MJ_{CH_4}	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Electricity (CNG distribution)	1.89E-06	MWh/MJ_{CH_4}	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
CO_2 liquefaction[c]			
Electricity	0.2	$MWh/tonne_{CO_2}$	Electricity, low voltage {SE}| market for electricity, low voltage | Cut-off, U
Activated carbon	0.6	$kg/tonne_{CO_2}$	Activated carbon, granular {RER}| activated carbon production, granular from hard coal | Cut-off, U
Methane slip (avoided)	4.89E-04	$tonne/tonne_{CO_2}$	Methane, biogenic
Carbon dioxide biogenic (emission to air)	0.1	$tonne/tonne_{CO_2}$	Carbon dioxide biogenic
CO_2 substitution			
Liquefied CO_2 (avoided)	1	$tonne/tonne_{CO_2}$	Carbon dioxide, liquid {RER}| carbon dioxide production, liquid | Cut-off, U
Transport by truck (avoided)	900[b]	$tkm/tonne_{CO_2}$	Transport, freight, lorry > 32 metric ton, EURO6 {RER}| market for transport, freight, lorry > 32 metric ton, EURO6 | Cut-off, U
Transport by truck	100[b]	$tkm/tonne_{CO_2}$	Transport, freight, lorry > 32 metric ton, EURO6 {RER}| market for transport, freight, lorry > 32 metric ton, EURO6 | Cut-off, U

[a] Assumed transportation distance from England to Sweden (COWI, 2015; Linköpings, 2020).
[b] Assumed transportation distance from the Netherlands to Sweden (Statista, 2024b).
[c] Data provided by Tekniska verken, obtained from technology providers.

Table A2
Nutrient content of digestate

Parameter	Value (kg/t)
Plant available nitrogen (NH_4-N)	2.5
Total phosphorus (P-tot)	0.3
Total potassium (K)	1.1
Sulfur (S)	0.3
Calcium (Ca)	1.1
Magnesium (Mg)	0.1

The data for nutrient content of digestate were measured on site during 2023.

Table A3
Tank-to-wheel energy use

Parameter	Value	Unit	Reference
Diesel and LBG tank-to-wheel energy use	3.66E-02	kg/tkm	Ecoinvent: Transport, freight, lorry > 32 metric ton, EURO6 {RER}| market for transport, freight, lorry > 32 metric ton, EURO6 | Cut-off, U
CBG tank-to-wheel energy use	4.32E-02	kg/tkm	(Börjesson et al., 2016)*
HVO tank-to-wheel energy use	4.59E-02	kg/tkm	Proxy from Ecoinvent: Transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % {RoW}| transport, freight, lorry 28 metric ton, fatty acid methyl ester 100 % | Cut-off, U

* Börjesson et al. (2016) reported that energy consumption is 18 % higher per kilometer than for diesel.

Table A4
Exhaust emissions for HVO, biol-CNG, and bio-LNG (Hallberg et al., 2013)*

Substance	Unit	HVO	bio-CNG	bio-LNG	Dataset in model (Ecoinvent)
Methane (CH_4)	kg/tkm	3.96E-06	1.11E-04	1.02E-04	Methane, biogenic
Nitrous oxide (N_2O)	kg/tkm	1.23E-05	1.11E-05	1.02E-05	Dinitrogen monoxide
Carbon monoxide (CO)	kg/tkm	9.87E-04	8.85E-04	8.14E-04	Carbon monoxide
Nitrogen oxides (NO_X)	kg/tkm	1.13E-04	1.70E-06	1.56E-06	Nitrogen oxides, SE
Sulphur dioxide SO_2	kg/tkm	2.74E-07	0	0	Sulfur dioxide, SE
Non-methane volatile organic compounds NMVOC	kg/tkm	3.55E-05	3.55E-05	3.26E-05	NMVOC non-methane volatile organic compounds, SE
PM, unspecified	kg/tkm	2.46E-06	2.21E-06	2.03E-06	Particulates, unspecified

* The data were originally provided in kg/MJ and converted to kg/tkm based on Table A3.

Table A5
Well-to-tank emissions for HVO (Källmén et al., 2019)*

Substance	Unit	Rapeseed oil	PFAD as residue	Tall oil	Slaughterhouse waste as residue	Used cooking oil as residue	Dataset in model (Ecoinvent)
Carbon dioxide (fossil)	kg/kg	1.59E+ 00	5.81E-01	1.35E+ 00	1.28E+ 00	4.75E-01	Carbon dioxide, fossil
Carbon dioxide (biotic)	kg/kg	2.16E+ 00	2.92E-03	4.53E+ 00	2.04E-02	2.26E-03	Carbon dioxide, biogenic
Carbon monoxide	kg/kg	6.29E-03	7.31E-04	3.33E-03	7.87E-04	4.53E-04	Carbon monoxide
Nitrogen oxides	kg/kg	7.57E-03	2.97E-03	7.75E-03	1.43E-03	6.61E-04	Nitrogen oxides, SE
Nitrous oxide	kg/kg	3.34E-03	1.60E-05	5.40E-05	2.27E-05	1.33E-05	Dinitrogen monoxide
Sulphur dioxide	kg/kg	4.39E-03	1.75E-03	5.85E-03	1.15E-03	2.60E-04	Sulfur dioxide, SE
Methane (fossil)	kg/kg	3.98E-03	1.76E-03	3.26E-03	3.89E-03	1.64E-03	Methane, fossil
Methane (biotic)	kg/kg	4.67E-05	2.58E-06	4.52E-04	1.79E-05	2.01E-06	Methane, biogenic
NMVOC	kg/kg	1.36E-03	2.41E-04	1.26E-03	4.92E-04	1.44E-04	NMVOC, non-methane volatile organic compounds, SE
Particles (> PM10)	kg/kg	1.79E-03	4.55E-06	8.91E-04	1.16E-04	4.41E-06	Particulates, > 10 µm
Particles (PM2.5 - PM10)	kg/kg	3.51E-04	3.37E-06	2.65E-04	2.95E-05	2.12E-06	Particulates, > 2.5 µm, and < 10um
Particles (PM2.5)	kg/kg	9.16E-04	6.34E-05	1.23E-03	1.14E-04	8.98E-06	Particulates, < 2.5 µm

* The data were originally provided in kg/MJ and subsequently converted to kg/kg based on an energy density of 44.1 MJ/kg (Källmén et al., 2019).

Table A6
Composition of the Swedish market for HVO 2016 (Källmén et al., 2019)*

Type of feedstock	%
Hydrotreated Vegetable Oil – Used cooking oil (UCO)	40.00
Hydrotreated Vegetable Oil – Slaughterhouse waste	20.00
Hydrotreated Vegetable Oil - PFAD	24.21
Hydrotreated Vegetable Oil – Tall oil	7.37
Hydrotreated Vegetable Oil - Rapeseed oil (New allocation alternative)	8.42

* Källmén et al. (2019) reported the composition of the Swedish HVO market based on data from the Swedish Energy Agency for the life cycle inventory of HVO fuels. Although the Agency's data included 4 % corn and 1 % soybean, these feedstocks were not included due to their minor shares and limited data availability.

Table A7
Capital costs

Cost item	Factor		Value	References
Total costs			5081,400*	(Swedish Environmental Protection Agency, 2025)
Annuity costs		0,103 *Calculated using* Eq. 1	523,194.99	

* 0.094 EUR/SEK (2022) (Exchanges rates, 2025a)

Table A8
Operational costs

Cost item	Factor		Value Case 1 (13,000 t CO_2)	Value Case 2 (20,000 t CO_2)	References
Operation and maintenance	0.025	*of total purchased equipment (0.3 of capital costs)*	38,110.50	38,110.50	(Gustafsson and Svensson, 2021; Peters et al., 2003)
Energy costs			100,160.00	154,092.31	(Statista, 2024a)
Transportation			284,761.90	438,095.24	(Berg, 2021)
Labor			67,319.91	67,319.91	
Wages			38,468.52	38,468.52	(Statistics Sweden, 2024)*
Supervision	0.25	*of wages*	48,085.65	48,085.65	(Lawson et al., 2021; Seider et al., 2009)
Overhead	0.4	*of wages + supervision*	19,234.26	19,234.26	(Lawson et al., 2021; Seider et al., 2009)
Total Operational costs			490,352.31	697,617.96	

* 0.0837 EUR/SEK (2023) (Exchanges rates, 2025b)

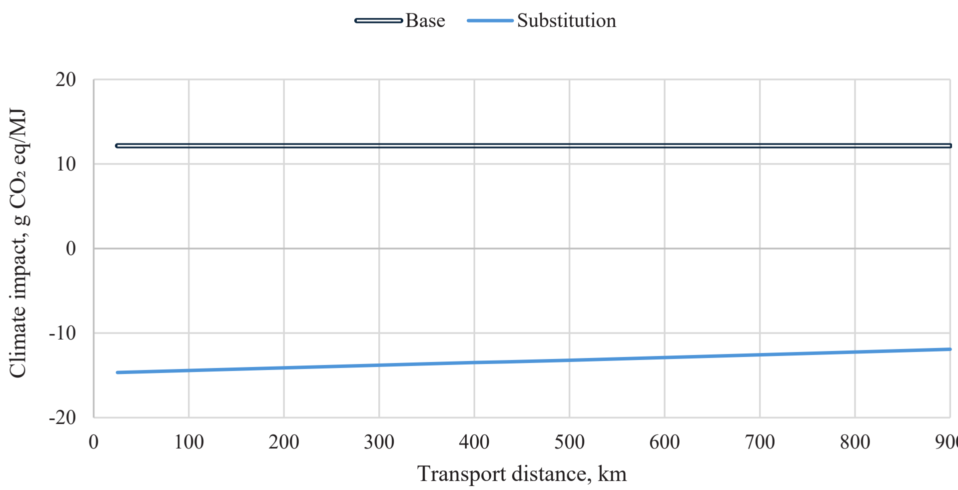

Figure A1. Climate change impact of the biomethane plant, including substitution of fossil-based CO_2 with varying transportation distance

Data availability

Data will be made available on request.

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