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To what extent can small-scale bio-CCS from biogas upgrading contribute with net-negative emissions?

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ABSTRACT

Carbon capture and storage (CCS) of CO_2 from biogas upgrading units has been proposed as a way to achieve negative CO_2 emissions. This study evaluated the climate performance and energy efficiency of such a bio-CCS system from a life cycle perspective, encompassing management, transport and storage of the separated biogenic CO_2. The results demonstrated a climate impact of 0.10 tonne CO_2-eq emitted/tonne CO_2 captured, corresponding to 90% carbon efficiency. Relative to biogas production, the emissions from the CCS value chain amounted to 3.9 g CO_2-eq/MJ biomethane, with an energy demand of 0.056 MJ/MJ biomethane or 1450 MJ/tonne captured CO_2. On adding the benefit of stored carbon (−38 g CO_2/MJ biomethane) to an emissions factor for Swedish biogas from bio-based waste, its value decreased to −15.4 CO_2-eq/MJ biomethane. Sensitivity analyses highlighted the importance of utilising renewable energy sources, but also showed that a clear net-negative emissions balance can be achieved even under non-ideal circumstances, such as for long transport distances and fossil-based energy supply. These results indicate that coupling a CCS system to biogas upgrading has the potential to deliver net-negative greenhouse gas emissions, even with conservative assumptions regarding renewable energy availability and large transport distances relative to the small CO_2 volumes mostly available from biogas systems.

1. Introduction

Mitigating climate change will require large transformations in energy systems in coming decades (Reinert et al., 2021). All available mitigation strategies must be evaluated and implemented in parallel and on top of this the need for negative emissions is substantial (Ming et al., 2021). Negative emissions can be achieved through various options for greenhouse gas removal (GGR), but concerns remain regarding whether these can be implemented sufficiently rapidly and at sufficiently large scale (Nemet et al., 2018). A portfolio of different greenhouse gas removal technologies (GGRTs) is likely required to meet demand in a timely fashion and spread associated risks (Hilaire et al., 2019).

GGRTs have been defined as intentional human efforts to remove greenhouse gas (GHG) emissions from the atmosphere (Minx et al., 2018). One approach currently attracting considerable interest is bioenergy with carbon capture and storage (bio-CCS), which typically refers to extracting carbon dioxide (CO_2) from exhaust gas in a heat and/or power plant operating on biomass (Ng et al., 2020). Its deployment has been primarily driven by climate objectives (Hayat et al., 2024). Since CO_2 emissions with biogenic origin are considered climate-neutral, capturing and storing these would result in negative emissions (Golmakani et al., 2021). However, previous studies have shown that not all bio-CCS pathways deliver net negative GHG emissions, and contextual and country-specific research is necessary to evaluate this (Hayat et al., 2024).

More recently, attention has been directed at applying CO_2 capture technology to exhaust gas from biogas upgrading; the process where CO_2 is removed to give a higher concentration of methane (CH_4) to be utilized for energy or transport purposes (Golmakani et al., 2021). If the biogas is to be used as vehicle fuel or in a gas grid, impurities are removed, and the concentration of CH_4 is increased to around 97% or more (Swedish Energy Agency 2020). Under current practice, the CO_2 from the upgrading step is released to the atmosphere, but it could instead be collected in a CO_2 capture process (Li et al., 2017). Addition of CCS to a biogas upgrading unit has recently been suggested as a possible bio-CCS application that can be retrofitted to existing plants relatively easily (e.g. Rosa et al., 2021). Also, many new biogas production plants are under construction as biogas production in Sweden is set out to double according to the granted applications for public

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Nomenclature

Bio-CCS	Carbon capture and storage at biogenic sources
CBG	Compressed biogas
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CH_4	Methane
CO_2	Carbon dioxide
GGR	Greenhouse gas removal
GGRT	Greenhouse gas removal technology
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
LNG	Liquid natural gas
MJ	Megajoule (10^6 joules)
PED	Primary energy demand

funding to expand the biogas production capacity (Swedish, 2025).

Technologies for separating CO_2 have been available for decades, with several alternatives having reached high technical maturity (Cruz et al., 2021). The most common alternatives are chemical absorption and physical separation (Leung et al., 2014). Other approaches include membranes, cryogenic separation, water scrubbing and looping cycles such as chemical or calcium looping (Bauer et al., 2013). Each has its different properties and the most suitable approach for a certain setting may depend on a number of factors, such as initial and final CO_2 concentration, operating pressure and temperature, composition and flow rate of the gas stream, cost, contaminants and energy demand (Leung et al., 2014). A CO_2 capture rate of around 85–90% is commonly assumed for conventional CCS systems as the energy demand increase rapidly at high capture rates (Rosa et al., 2021, Jackson and Brodal, 2018). Quality regulations for pipeline injection and vehicle fuel use demand a high level on biomethane purity, causing biogas upgrading systems to have a much higher separation rate (around 99.5%) than other point sources of CO_2 emissions (Bauer et al., 2013). Also, there is no loss of energy efficiency, since the gases are separated regardless of whether CO_2 is captured, making this CCS route especially interesting. Carranza-Abaid et al. (2021) specifically investigated the most technically favourable carbon capture process to add to a biogas upgrading unit when the end-product is intended for utilization or storage and concluded that both physical and chemical scrubbing are suitable options. For biogas upgrading in Sweden, water scrubbing has been the prevalent CO_2 separation technology, while more modern plants more often chose amine-based technology (Energigas Sverige, 2025).

Once CO_2 has been collected, it can be stored or utilized. However, additional steps such as purification, compression or liquefaction and transportation are needed, and affect energy demand and costs (Löfblad et al., 2022). Transportation alternatives include pipeline, ship, railway, truck, tank container or a combination of these, depending on distance, terrain and capacity (Fasihi et al., 2019). Transportation choice is often based on costs, which are largely dependent on the relation between volume and transport distance (e.g. Kjärstad et al., 2016). An official inquiry identified marine shipping as a relevant means of transport for CO_2 from Swedish facilities within the foreseeable future (SOU, 2020). A promising storage facility project close to launch in Europe is the Longship project in Norway, which was deemed appropriate for Swedish users in a recent study (Löfblad et al., 2022). However, the many steps along the CCS value chain all need to be developed and scaled up in parallel for CCS to become a viable commercial option (Det Kongelige Olje- og Energidepartementet, 2020). European geological storage resources for CO_2 are estimated to be more than sufficient to meet CCS requirements under net-zero emission scenarios, but there remain technical, social, political and economic barriers to developing European CO_2 transport and storage networks (Rosa et al., 2021). Quantifying the emissions along the transport chain is also needed (Johansson and Kjärstad, 2019).

Although biogas plants with upgrading technology are large relative to other biogas plants, they are quite small in comparison with other point-source emitters of CO_2 where CCS could be considered, such as combined heat and power plants (Cordova et al., 2022). However, since CO_2 concentrations and purity in the residual gas from the biogas upgrading step are very high, inclusion of CCS may be justified from a technical, economic, and environmental standpoint, especially under the assumption that necessary infrastructure and logistics surrounding transportation and storage of CO_2 are likely to be gradually established and available anyway (ibid.). These aspects have been discussed, primarily from a technical point of view, by e.g. Poblete et al. (2020); Carranza-Abaid et al. (2021); Cruz et al. (2021); Golmakani et al. (2021); Rosa et al. (2021); Garcia et al. (2022); Dawood et al. (2025), but more in-depth environmental analysis of the entire CCS-system has yet to be performed.

According to Cordova et al. (2022), stakeholders are interested in implementing CCS, but knowledge of its additional GHG emissions is essential to ensure high reliability and integrity of the CCS system and avoid unintentional burden shifting or green washing. Life cycle assessment (LCA) has been identified as a suitable methodology for evaluating GGRTs, as it considers all phases of the life cycle of the studied system and allows multi-functionality to be reflected (Reinert et al., 2021). Terlouw et al. (2021) added the criteria of holistic perspective on the system emissions the entire life cycle); a net negative emissions balance, and long-term storage reliability of removed emissions. A deeper understanding of circumstances surrounding GGRTs and ability to evaluate their performance have also been called for Hilaire et al. (2019). There is a large body of scientific literature addressing the life cycle implications of biogas systems (see e.g. Feiz et al. 2022), but none with the focus on its ability to act as a GGRT. Therefore, there is a need to address the climate impact and energy requirement of bio-CCS from biogas plants.

The aim of the present study was to assess the management steps necessary for storing the CO_2 obtained when upgrading biogas to vehicle fuel quality from a life cycle perspective. Specific objectives were to (i) investigate and quantify each process constituting the CCS system with respect to climate emissions and energy demand; (ii) relate these amounts to system functionality (biomethane and captured CO_2) in order to evaluate efficiency; and (iii) conclude to what extent net negative emissions can be achieved from deployment of small-scale bio-CCS.

2. Material and methods

The option of capturing and storing the CO_2 from biogas upgrading was compared to the current conventional option where the CO_2 is released to the atmosphere after the upgrading process from a life cycle perspective. The methodological framework comprises four main phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation of the results, and leads to a quantitative assessment of the environmental impacts for the studied system. When evaluating GGRTs, a functional unit (FU) that reflects the function of CO_2 removal should be used to illuminate the climate performance of the system and allow comparison between different GGR options (Terlouw et al., 2021). In the case of multi-functional systems, as is the case with many GGRTs, use of two functional units is merited to facilitate relevant comparisons (Goglio et al., 2020). Coupling bio-CCS with biogas production eventuate the multi-functionality of comprised vehicle fuel and GGR, represented by the two system outputs biomethane and CO_2 removal, which were reflected in this study by the respective functional units of *tonnes of CO_2 captured* and *megajoules (MJ) of biomethane produced and used as vehicle fuel*. The system was evaluated with respect to primary energy demand (PED) expressed in MJ, and global warming potential (GWP) expressed as CO_2-equivalents (CO_2-eq) in a 100-year time horizon (GWP_{100}), as defined in AR6 (IPCC, 2021). This was combined with the functional units to define two indicators: the Energy penalty, which related the energy demand of the CCS system to the useful energy output in the form of biogas (Equation 1):

$$Energy\ penalty = \frac{PED}{E_{biogas}}$$

and the GWP efficiency that related the climate impact to the system with the captured GHGs (Equation 2):

$$GWP\ efficiency = 1 - \frac{e_{emitted}}{e_{captured}}$$

2.1. System description

2.1.1. System boundaries

Focus of this study was on the additional activities related to introduction of CCS from biogas upgrading, compared to a reference system represented by normal operation of a biogas plant without CCS (Fig. 1). This study design highlights the impact of CCS and enables relevant comparisons. Biogas plants show large variations in design and operating conditions and need to be assessed individually (Börjesson et al., 2016). The life cycle impact of the biogas production process may show a rather wide range and many previous studies have evaluated e.g. substrate composition, methane leakage, upgrading technology, handling of digestate and system boundaries such as the use of substitution of fossil-based fuel or fertiliser (see e.g. Feiz et al. 2022). The life cycle impact of the biogas production process was not modelled in this study, but the emphasis was on the parts related to the addition of CCS. However, since we also compared the performance of the bio-CCS to a typical biogas plant, data from a previous LCA study by Börjesson et al. (2016) were used, as described in 2.1.2. A selection of LCA studies of climate impact of biogas systems can be found in the supplementary material. Since an existing biogas plant was used as reference, construction of the biogas plant itself was excluded from the analysis. Operation of the upgrading unit was considered included in the reference biogas production system, since it was in use whether the CCS system was active or not.

The scope of this study included the entire system of CO_2 capture, liquefaction, transport and storage. Impacts from raw material demand and manufacturing of critical machinery, transport infrastructure and facilities needed to support the added CCS step were included, with associated impacts divided on a yearly basis over the system lifetime. When suitable, the lifetime was set to match the technical operating life (25 years) of the Aurora storage facility.

2.1.2. Biogas system

The biogas production plant used as a reference system was assumed to be produced at a co-digestion plant with annual production capacity of 100 GWh (360 TJ) biomethane. This plant size is in accordance with newer plants built in Sweden recently but could also represent multiple smaller plants in cooperation. The molar composition of the raw biogas produced in the digester depends on the feedstock but is typically 40–75% CH_4 and 25–55% CO_2 (Poblete et al., 2020). In this study, the molar proportion of CO_2 was set to 40%, which equates to roughly 14, 100 tonnes of CO_2/year, and the fate of this CO_2 was the basis of the assessment. The raw biogas was pre-treated using an active charcoal filter for removal of hydrogen sulphide and other impurities before upgrading using an amine scrubber, with the resulting biomethane used as vehicle fuel. The efficiency of the upgrading unit was set to 99.9%, so the exhaust gas contained 0.06% of the CH_4 and 99.9% of the CO_2 (Börjesson et al., 2016; Kvist and Aryal, 2019). A summary of inventory data and assumptions can be found in the Supplementary material. All CO_2 separated from the biomethane in the upgrading unit was considered to be released to the atmosphere in the reference scenario and captured and stored in the CCS scenario.

The life cycle impact of the CCS-system was related to the life cycle impact of a relevant biogas system described by Börjesson et al. (2016). Its system boundaries included transport of feedstock to the plant, capital infrastructure and its end of life, upgrading of biogas by amine scrubbing, and distribution and use of biomethane (as vehicle fuel), as well as the use of the digestate as fertiliser. The plant was assumed to perform anaerobic digestion under Swedish conditions of an average mixture of substrate containing (wet matter basis): food waste 21.5%, slaughter waste 10.5%, industrial waste 28.5% and manure 39.5%. Its associated well-to-wheel GHG emissions were 18.6 g CO_2-eq/MJ biomethane and PED was 0.31 MJ/MJ biomethane.

2.1.3. CCS system

The CO_2 flow from the amine scrubber was assumed to be captured

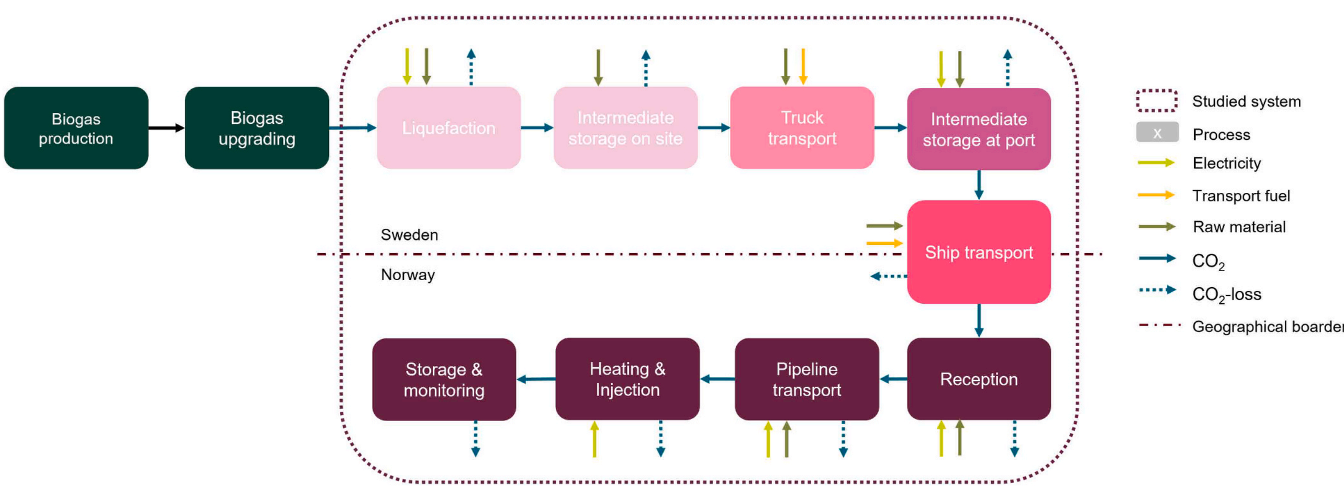

Fig. 1. System overview including a detailed breakdown of the carbon dioxide transport and storage system. During biogas upgrading in the reference biogas production system, CO_2 is separated from CH_4 to achieve highly concentrated biomethane gas. With the carbon capture and storage (CCS) system in place, the CO_2 is instead captured and stored, while operation of the biogas production system is unaffected. The colours of the CCS sub processes indicate the five post-biogas production subsystems listed in Table 1, and the arrows show material and energy flows that are relevant for the evaluation of the energy demand and climate impact of each process.

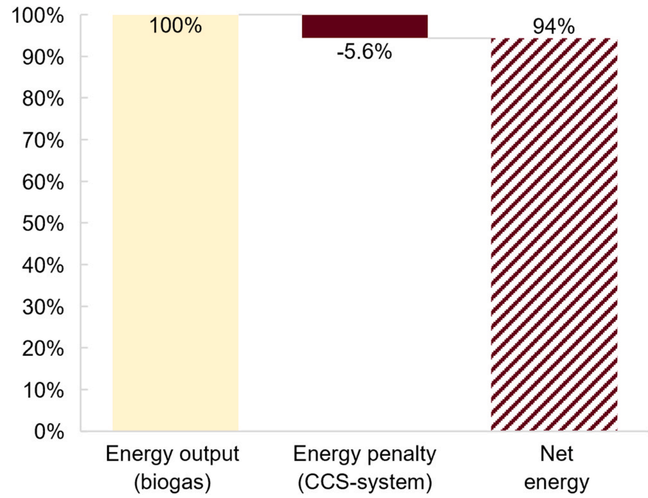

Fig. 2. Life-cycle energy demand of the carbon capture and storage (CCS) transport and storage chain normalised against the amount of energy delivered in the form of biomethane for use in vehicles (based on Börjesson et al. 2016).

Table 1
Description of the chosen system boundaries and division into subsystems of the carbon capture and storage (CCS) scenario.

Subsystem	Description
Biogas system	Biogas production system, including biogas upgrading, utilisation and digestate management
Liquefaction	Liquefaction and intermediate storage on-site
Land transport	Land-based transport via truck to port
Port	Intermediate storage at port, loading onto ship, electricity for ship while docked
Marine transport	Marine transport with hybrid ship, including fuel slip
Storage	Offloading, electricity for ship while docked, intermediate storage, operation of pipeline and injection
CCS total	All processes from Liquefaction through Storage

and transported from the plant to a long-term CO_2 storage facility through some additional process steps (Fig. 2). The Aurora storage site in the North Sea was chosen for CO_2 storage, since it is geographically close to Sweden, it is close to commercial, large-scale operation and it has excess capacity that will be available for external parties (Equinor, 2019). Thus, the design and dimensions of the transport and storage part of the system were based on the "Northern Lights" concept described in Equinor (2019) and Gassnova (2020a). Based on this, the flow chart rendered in Fig. 1 was constructed and the CCS chain post-biogas production was divided into five subsystems (Table 1).

After amine upgrading, the only additional process needed to meet the gas quality requirements of the storage facility was a unit for reducing the humidity through drying and liquefying the CO_2 (see Supplementary material). The liquid CO_2 (LCO_2) was assumed to be transferred to an intermediate storage unit on-site before transport from the production plant to the port by truck. At the port, the CO_2 was assumed to be transferred to an intermediate storage unit before being loaded onto a ship, taken to the reception facility, transferred through a pipeline to the injection site, and reheated and injected into the bedrock below the seabed.

2.2. Data collection and assumptions

Liquefaction involved lowering the pressure and temperature of the CO_2 to −26 °C and 15 bar to reduce the volume prior to transport and thus meet the requirement for ship transport (Equinor, 2019). These initial process steps were assumed to be performed at the production plant, their operation requiring 105 kWh electricity per tonne of CO_2, based on a cautious assumption according to Zahid et al. (2014), who reviewed a variety of studies reporting electricity demand of 105–120 kWh/tonne CO_2 under conditions varying somewhat with regard to temperature and pressure and, based on the results, proposed a modified liquefaction system for post-combustion capture that lowers the energy use to 97 kWh/tonne CO_2. This is in line with later findings by Jackson and Brodal (2018) of electricity demand for CO_2 liquefaction of 90–120 kWh/tonne CO_2. Other peripheral equipment, such as control systems, was assumed to make a negligible contribution to the overall impact and was not included in the analysis.

The Nordic electricity consumption mix, with life cycle emissions of 93.2 CO_2-eq/kWh, was assumed throughout the study (Sandgren and Nilsson, 2021). However, since this value had a large impact on the results, it was also the subject of sensitivity analysis.

The truck(s) used for transport were assumed to utilise 0.3 L diesel/km and to transport a container with a total gross weight of 45 tonnes and loading weight of 22 tonnes (Andersson et al., 2021). Data on the environmental impact from construction of vehicles and container were taken from Wolff et al. (2020) and IGC Engineering (n.d). For the diesel fuel, the GHG emissions of average diesel sold in Sweden in 2020 (75.7 g CO_2-eq/MJ: Swedish energy agency, 2021) were assumed, with the addition of a factor for its extraction from Ecoinvent (2025). Additionally, the impacts of construction and maintenance of roads were estimated based on studies by Trunzo et al. (2019) and Stripple (2001).

The intermediate storage at the biogas plant was assumed to consist of six mobile semi-trailers, with a total capacity matching four days of LCO_2 production, as proposed by Gassnova (2020a). Intermediate storage at the sending port was assumed to be in stationary storage tanks of the same size as at the receiving port, as described in Gassnova (2020a). Both storages were assumed to have steel as their main component, with associated GHG emissions of 2.066 tonne CO_2-eq/kgsteel and primary energy demand of 72 MJ/kg steel (Ecoinvent, 2025). The size and net weight of the containers necessary to cover the CO_2 flow were estimated from supplier data (Chart Industries, 2018; IGC Engineering, n.d). Some additional new infrastructure would have to be constructed to receive, store and load the CO_2 onto the ship, but its impact was neglected. Some additional electricity demand also resides to reliquify the fraction of CO_2 (0.03%) that vaporises during storage (Zahid et al., 2014).

Marine transport was assumed to take place on a 130-m cargo ship designed specifically for CO_2 transport, with a capacity of 7500 m^3 LCO_2 at 15 bar and −26°C. All ship specifications complied with Equinor (2019). Thus, the ship was assumed to be powered by liquid natural gas (LNG) and to have 45 min of battery operation capacity for use when approaching and departing from port. Its offloading capacity was assumed to be 800 m^3/hours, requiring nine hours of operation for the entire CO_2 volume of 7500 m^3. Ship and battery manufacturing was rated based on Kameyama et al. (2014), Chatzinikolaou and Ventikos (2014) and Wolff et al. (2020). The impact of constructing and operating the ship was allocated to the studied system based on its CO_2 volume. Assuming Sweden operates one ship that departs from the port of Stockholm, the sea distance would be around 1750 km to the reception terminal in Norway, which would correspond to a cycle of around 1 week.

The receiving facility was assumed to consist of a new port, storage tanks for CO_2, an administration building and a tunnel connecting to the pipeline, with all associated data collected from Equinor (2019). When the ship docked, the CO_2 was assumed to be moved to intermediate storage tanks and from there carried through a 100 km long pipeline on the bottom of the North Sea to the injection point, where it was finally injected into the storage space 1000–3000 m under the seabed. Operating the storage site was assumed to require 51 MWh of electricity annually according to Equinor (2019). The overall climate impact and energy use for operating the transport and storage facilities were allocated by weight of the stored CO_2.

The risk of considerable near-term CO_2 leakage from bedrock storage is regarded as very low, with a limit set to less than 0.0008% leakage per year (Alcalde et al., 2018). Leaked CO_2 is also unlikely to reach the atmosphere due to secondary trapping in the overlying geological structures (Deng et al., 2017). However, some leakage from the transport chain is probable and was set to 2.6%, with most occurring during ship transport (IPCC, 2018). Although the lost CO_2 was of biogenic origin, it was included as system emissions since it was considered an important parameter when assessing the overall reliability of the CCS system. As data availability was deemed low, CO_2 leakage was subjected to sensitivity analysis.

With CCS, the small amount of CH_4 (around 0.06% for an amine upgrading unit according to Börjesson et al., 2016) released from the upgrading process to the atmosphere with exhaust gases would instead be captured. The Aurora storage facility currently has no restriction on methane content, meaning that this could be part of the stored gas, or it could be enriched and utilised for energy purposes. Leakage of CH_4 from the production process is quite impactful on the total climate impact of the biogas product (Iordan et al., 2016; Scheutz and Fredenslund, 2019). However, the stored CH_4 emissions were not included in the main results as there are some uncertainties regarding e.g. to what extent CH_4 would be allowed in the CO_2 stream by the storage facilitator as it will alter the demeanour of the stored gas and how much of it might boil of and be lost in the conditioning and transport steps due to it having different properties than CO_2 (Blanco et al., 2012).

2.3. Sensitivity analysis

To determine the respective impact on the overall results, a one at a time sensitivity analysis was run on five parameters: transport distance, truck fuel, electricity generation, CO_2 losses, and the climate metric.

The transport distance on land was increased and decreased by 50%, while the transport distance by sea was set to equal the distance from two other large Swedish port cities (Gothenburg on the west coast (700 km) and Luleå in the northern end of the Baltic Sea (2380 km)) to the storage facility. Since battery capacity remained the same, the entire increase was covered by LNG consumption. The diesel-powered truck used for the land transport was also exchanged to a battery electric powered truck.

The electricity source was changed from average Nordic consumption mix (93.2 g/kWh; Sandgren and Nilsson 2021) to Swedish mix (26 g/kWh; Sweco 2021) and marginal electricity (assumed to be coal-based) (750 g/kWh; Elforsk 2007).

Due to low data availability, the CO_2 losses throughout the handling steps were assumed to match those of CH_4 infrastructure, with values varying from 1.8% to 6% in conservative and more pessimistic scenarios, respectively (Rosa et al., 2021).

Due to the presence of the short lived but potent CH_4 in this system, the chosen climate metric applied to calculate the GWP may have a noticeable impact on the results. This was investigated by exchanging the time horizon of the chosen climate metric (GWP) from 100 years to 20 and 500 as defined in AR6 (IPCC, 2021). GWP20 adopts a shorter time horizon which highlights the short-term climate effects while GWP500 emphasise the long-term effects. Ecoinvent data were used to complete this analysis.

The different parameters were combined into a “best” and a “worst” case scenario, which represents the lower and upper boundaries of an interval of outcomes for the studied system.

The possible effects of CH_4 being a part of the stored gas was also evaluated. When storage of CH_4 slip was included, the choice of biogas upgrading technology has a decisive impact on the results. The amine scrubber that was used in the main scenario has a very low CH_4 slip and was compared to two other common upgrading technologies: membranes and pressure swing adsorption (PSA), based on data from Kvist and Aryal (2019).

3. Results

3.1. Primary energy demand

Total PED associated with the CCS system was 1450 MJ/tonne CO_2 captured and 0.056 MJ/MJ biomethane produced, which were attributed to the subsystems listed in Table 1. Liquefaction was clearly the most energy-intense step, accounting for 46% of total PED for the CCS system (Table 2). The two transport steps combined made up 38%. The PED at the storage site amounted to 15% of the total and that at the intermediate reloading and storage at port to only 2% of the PED for the CCS system. In total, the PED of the CCS system corresponded to just over 18% of the energy input required in the reference biogas production system.

The units used allowed the values to be converted to a percentage showing the energy penalty of the added CCS transport and storage chain compared with the amount of energy delivered as biomethane (Table 2). The residual percentage indicated the energy efficiency of the system, as shown in Fig. 2.

3.2. Global warming potential

The GHG emissions for the CCS system amounted to 0.10 tonne CO_2-eq/tonne CO_2 captured and 3.9 g CO_2-eq/MJ biomethane (Table 3).

Although liquefaction represented 45% of the energy used, it accounted for only 13% of the GHG emissions, since it used electricity generated from a high degree of renewable sources. This was also true for the processes at port and the storage site, contributing 0.02% and 4% of the total GWP, respectively. The two transportation steps had the largest climate impact, constituting over 82% of the total emissions, since they ran largely on fossil energy (LNG and diesel).

The GHG emissions of the CCS transport and storage chain relative to the amount CO_2 captured were 10% (Fig. 3). The residual percentage, i.e. the carbon efficiency of the system, was 90%. Relative to the amount

Table 2
Primary energy demand (PED) used by each of the five carbon capture and storage (CCS) subsystems, and the entire CCS system. Results were related to a reference biogas system using the results from Börjesson et al. (2016)(*) and reported for the two functional units per tonne CO_2 captured and MJ biomethane produced for the biogas system.

	PED (MJ/tonne CO_2 captured)	PED (MJ/MJ biomethane)
Biogas system*	8000	0.31
Liquefaction	660	0.026
Land transport	150	0.0059
Port	25	0.00097
Marine transport	400	0.016
Storage	210	0.0081
CCS total	1450	0.056

Table 3
Greenhouse gas (GHG) emissions from each of the five carbon capture and storage (CCS) subsystems, as well as the entire CCS system. Results were related to a reference biogas system using the results from Börjesson et al. (2016) (*) and reported for the two functional units per tonne CO_2 captured and MJ biomethane produced for the biogas system.

	GHG emissions (tonne CO_2-eq/ tonne CO_2 captured)	GHG emissions (tonne CO_2-eq/ MJ biomethane)
Biogas system*	0.48	$18.6*10^{-6}$
Liquefaction	0.0125	$0.48*10^{-6}$
Land transport	0.020	$0.79*10^{-6}$
Port	0.0002	$0.0085*10^{-6}$
Marine transport	0.062	$2.4*10^{-6}$
Storage	0.0043	$0.17*10^{-6}$
CCS total	0.10	$3.9*10^{-6}$

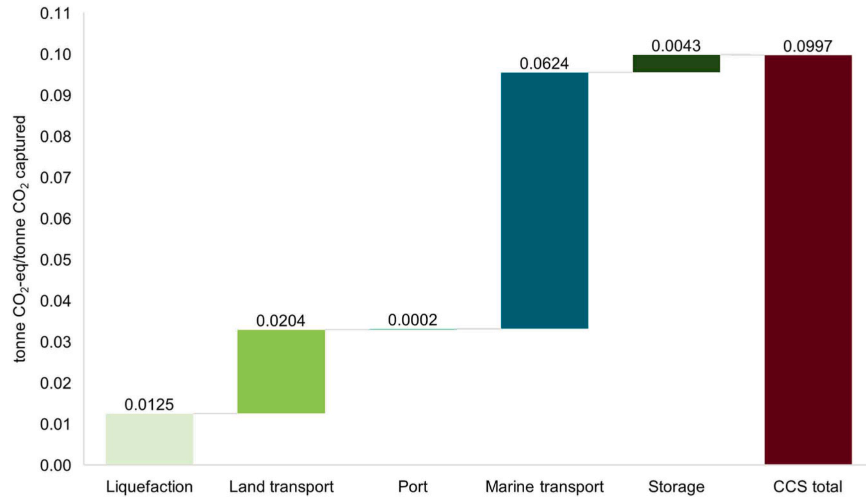

Fig. 3. Greenhouse gas (GHG) emissions of the carbon capture and storage (CCS) system relative to amount of CO_2 captured.

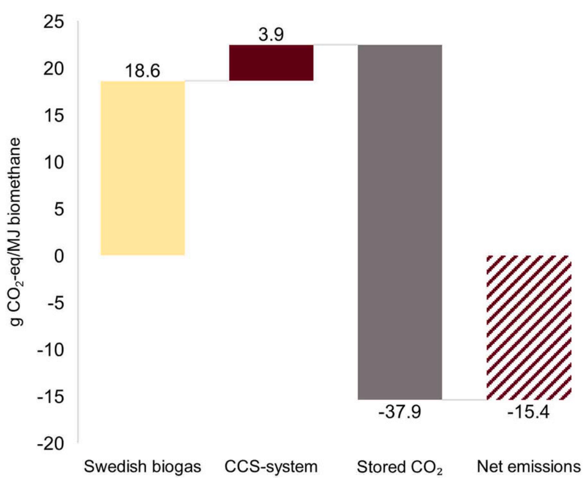

Fig. 4. Greenhouse gas emissions from the carbon capture and storage (CCS) scenario compared with greenhouse gas emissions from biomethane production and use as vehicle fuel (Swedish biogas) (based on Börjesson et al. 2016).

of biogas produced, the associated climate impact and the additional GHG emissions from the CCS system were outweighed by the stored CO_2, resulting in net-negative emissions (Fig. 4). Note that GHG emissions are expressed as grams instead of tonnes in Fig. 4, since this is a more common unit for assessing the climate impact of fuels. Since biogas systems are so heterogeneous in their operating conditions, a compilation of the results from selected LCAs on biogas can be found in the SM.

3.3. Sensitivity analysis

Table 4 shows a compilation of results from performed sensitivity analyses. Details to each case is given in the following sections and in the SM.

Table 4 shows the impact of changing the emissions factor for electricity from the Nordic mix used in the main scenario to that for Swedish mix and coal power. The biggest impact originated from the electricity demanding liquefaction. The energy penalty varies between around 4 and 10% and the GWP efficiency between 77% and 96% (Fig. 5).

Cumulative CO_2 leakage during transport and injection amounted to 3.5% (corresponding to 430 tonnes of CO_2) in the main scenario, based on the data available for each process. However, data availability, reliability and revision were considered low. The best available benchmark is probably methane infrastructure, which gives a probable range of 1.8–6% CO_2 leakage at the system level (Rosa et al., 2021). Using those upper and lower limit values corresponding to a CO_2 loss of 252 and 839 tonne CO_2/year, respectively. The amount of CO_2 that was stored changed from 13,644 tonnes CO_2/year to 13,817 and 13,226 (to be compared with the captured amount of 13,983 tonnes CO_2/year). The energy use was unaffected.

The results of the GWP analysis show a noticeable difference with the change in climate metric as short-lived GHGs are present in some of the studied subsystems; from 9.5% for GWP500 to 11% for GWP20. However, if we take into account the possibility of also storing some CH_4 that otherwise would have been released to the atmosphere together with the separated CO_2 in the upgrading process (negative bar in Fig. 6), this counters the impacts related to the rest of the CCS system (total height of positive bars in Fig. 6), making the total impact very similar no matter the climate metric applied (red circle in Fig. 6).

Table 4
Results of the sensitivity analyses. The comparison is to the main scenario which amounted to 1450 MJ/tonne CO_2-eq/tonne CO_2 captured and 0.10 tonne CO_2-eq/tonne CO_2 captured.

	Parameter change	PED change (%)	GWP change (%)
Increased land transport	+50%	+5%	+10%
Decreased land transport	-50%	-5%	-10%
Truck fuel change	Diesel → BEV	-6%	-8%
Decreased marine transport (Gothenburg port)	-60%	-16%	-38%
Increased marine transport (Luleå port)	+40%	+10%	+22%
Low carbon electricity	Swedish mix	0%	-10%
Fossil based electricity	Coal power	+38%	+93%
Climate metric time horizon decrease	GWP20	0%	+11%
Climate metric time horizon increase	GWP500	0%	-4%
"Best" case	Low carbon electricity BEV truck Short transport distance GWP20	-24%	-63%
"Worst" case	Fossil based electricity Diesel truck Long transport distance GWP500	+52%	+142%

Note: BEV (Battery Electric Vehicle).

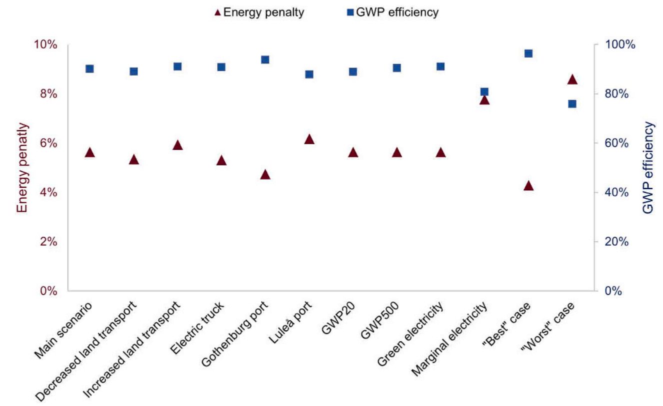

Fig. 5. Results of the sensitivity analyses for the two main parameters energy penalty (red triangle) - energy use of the CCS system relative the produced biogas - and GWP efficiency (blue square) - the net stored CO_2 after the greenhouse gas emissions from the CCS system have been subtracted. The "best" case scenario represents a combination of parameters that minimise the environmental impact, while the "worst" case represents a combination of parameters that increase the environmental footprint.

When CH_4 slip was included, an upgrading technology with a large CH_4 slip – i.e. more CH_4 to potentially be stored, showed a more beneficial outcome, to the point where it is the single biggest contributor to the overall climate efficiency (Fig. 7). As a guiding example, the benefits of avoided CH_4 emissions alone counteracts for the emissions from the CCS value chain at a CH_4 slip of 0.68% under the modelled circumstances.

4. Discussion

The CCS system generated additional emissions of 3.9 g CO_2-eq/MJ biomethane, but achieved substantial CO_2 storage, of −38 g CO_2-eq/MJ biomethane. This translates to a carbon efficiency of the CCS systems of over 90%, and implies that the breakeven emissions factor to achieve a net-zero biomethane product would be reached at +34 g CO_2-eq/MJ biomethane. When compared to the emissions factor of the biomethane fuel of 18.6 g CO_2-eq/MJ biomethane chosen for the reference system, adding CCS would result in a net emissions factor of −15.4 g CO_2-eq/MJ biomethane. As further reference, the emissions factor currently used for vehicle gas by the Swedish Energy Agency is 12.6 g CO_2-eq/MJ biomethane (Swedish Energy Agency, 2021), compared with this value the stored CO_2 would lead to a net-negative emissions of −23.5 g CO_2-eq/MJ biomethane. The additional PED of 5.6% for CCS could be considered a modest energy penalty for the delivered climate benefit. Energy demand is an important parameter not only for its associated GHG emissions, which have a decisive effect on the system's climate impact, but also as energy use itself need to be economized within a sustainable society. A significant share of the energy used in the CCS

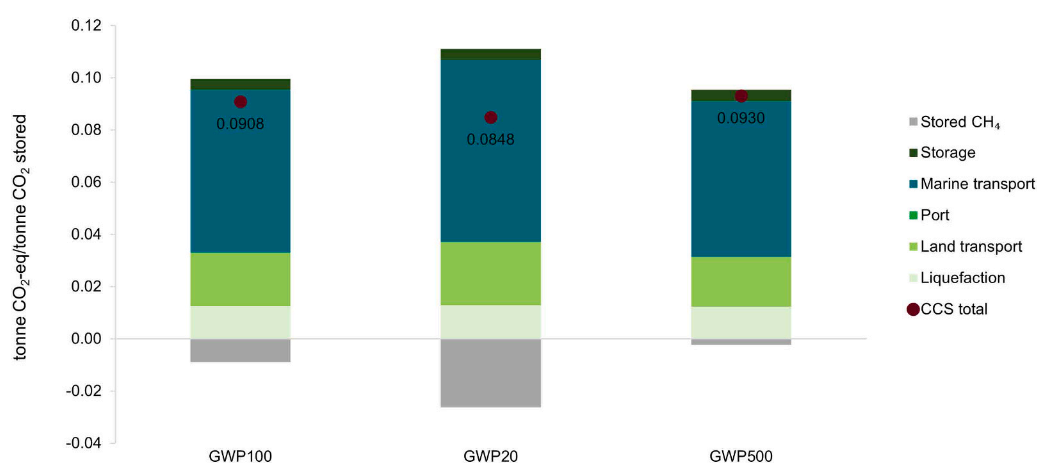

Fig. 6. Sensitivity analysis displaying the impact of a change in the chosen metric used to calculate the system's effect on the global warming potential (GWP) with respect to the functional unit tonnes CO_2 captured. The red marker denotes the sum of all bars.

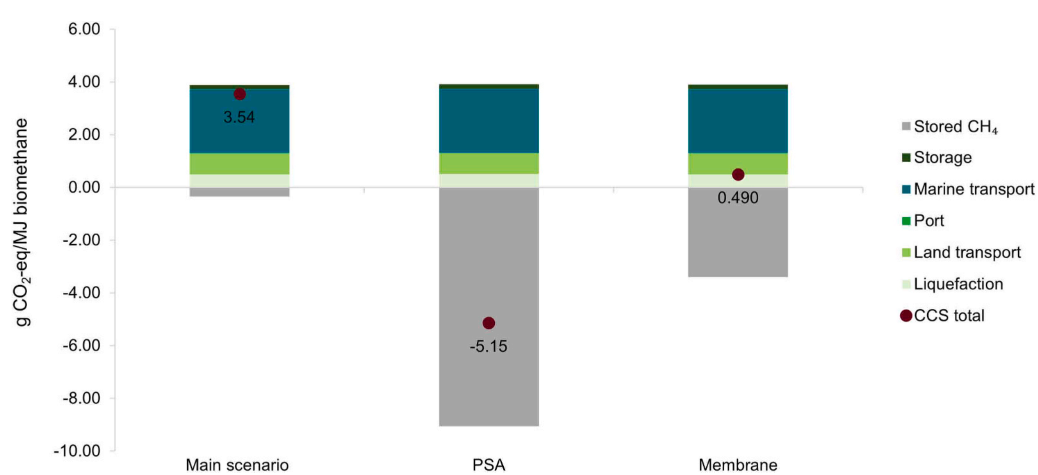

Fig. 7. Sensitivity analysis displaying the potential climate impact of CH_4 from biogas upgrading process depending on the upgrading technology used with respect to the functional unit MJ biomethane. An amine scrubber was assumed for the main scenario. The red marker denotes the sum of all bars.

system, mainly for transport, was fossil-based, which was the reason for transport distance and fuel type having large impacts on GWP. The share of fossil energy in future energy systems will likely decrease, improving the carbon efficiency of the CCS system even further. Nevertheless, even under current conditions, break-even transport distances exceed 9000 km by land or 27,000 km by ship – 45 and 15 times the distances analysed before the burden of the CCS system outweighs the benefits of removing CO_2 from the atmosphere.

The sensitivity analysis highlighted the importance of the electricity production. The share of renewables significantly influenced the overall GWP of CCS, as electricity was used throughout every step of the CCS value chain. While renewable electricity generation has shown a rapid expansion during the last decade, half of the global electricity supply remains fossil-based (IEA, 2025). Hence, from a systems perspective it can be questioned to what extent renewable electricity capacity can be considered available for non-essential uses such as CCS. With that said, electricity supply remains highly site and time dependent with varying renewable compositions.

Due to limited data on leakage of CO_2 throughout the value chain, this parameter was subjected to sensitivity analysis. However, because of the chosen functional unit and the fact that the biogenic CO_2 emissions are not accounted for, the CO_2 slip does not get represented in these results, but it lowers the amount of CO_2 that reach storage. Since GHG emissions from the CCS value chain are comparatively low relative to the amount of CO_2 captured, any leakage can have a large impact, potentially affecting the reliability and acceptance of CCS. In an increasingly decarbonised future, the relative impact of CO_2 slip may become substantial and warrants future attention.

Given the potent short-term climate impact of CH_4, one sensitivity analysis focused on the impact of the chosen climate metric. Applying a shorter time horizon (GWP20) increased the results by 11%, while a longer time horizon (GWP500) resulted in a 4% decrease. Interestingly, when potential co-storage of CH_4 slip from the biogas upgrading was included, this effect counteracted the impact of the metric time horizon and balanced overall GWP results.

Avoiding the 0.06% CH_4 slip from biogas upgrading would give an additional benefit of over 125 tonne CO_2-eq/year, corresponding to 0.0089 tonne CO_2-eq/tonne CO_2 captured. This equivalents almost 1% of the stored CO_2 or almost 9% of the total CCS value chain emissions. While the amine scrubber used in the main scenario has a very low CH_4 slip, other biogas upgrading technologies have higher slip rates, offering greater co-capture potential. Stored CH_4 slip could become the single biggest contributor to the overall climate efficiency: at slip-rates over 0.7%, the climate benefit from stored CH_4 would counteract the total CCS emissions leading to net-negative climate impact (calculated using GWP100). However, since presence of CH_4 affects the characteristics of the stored gas and reduces storage capacity (Blanco *et al.* 2014), we chose to not include this effect in our main results.

The conservative methodological approach - including current fossil transport fuels, realistic electricity mixes, CO_2 leakage, and infrastructure wear — aimed to avoid false positive results. Despite this, the CCS system demonstrated high energy and carbon efficiency. Nevertheless, the entire CCS value chain should be carried out with a minimum of CO_2 slip and performed in the most climate-friendly and energy-efficient manner, to achieve the highest total climate benefit possible and ensure high credibility of the CCS concept (Andersson et al., 2021).

Beyond the result presented in this study, there may be other important environmental impacts connected to the CCS value chain that warrants attention. These for example include effects on the ecosystems near storage facilities, acidification and aerosol formation from fossil fuel use, or off-site impacts raw material extraction and processing: which can involve hazardous chemicals and wastes, affect human health, and contribute to land use change and biodiversity loss. These potential impacts warrant further investigation and quantification in future studies.

Previous somewhat similar LCA studies of Norwegian combined heat-power (CHP and cement plants using the Aurora storage facility report emissions of 0.056 tonne CO_2-eq emitted/tonne CO_2 stored (Gassnova, 2019; Gassnova 2020b), i.e. around 30% lower than in this study. Comparison reveals both similarities and key differences. The system boundaries were largely comparable to those in this study. Their advantages included shorter marine transport, pipeline land transport (versus trucks), and lower electricity emissions factors. However, their analysis excluded CO_2 leakage and some infrastructure impacts that we included. Additionally, retrofitting their plants with carbon capture units increased energy use substantially — a penalty unnecessary at biogas facilities where upgrading infrastructure already exists, partially offsetting their transport and electricity advantages. Previous studies targeting the costs of GGR have attempted to optimise means of transport with respect to volume (e.g. Kjärstad et al., 2016), assess the feasibility of certain cases (e.g. Yang et al., 2020), compare the financial viability of different options per tonne CO_2 removed (e.g. Garcia et al., 2022) and identify factors affecting energy efficiency and the impact of scale (e.g. Han et al., 2015). A feasibility study has been performed on the two Norwegian plants, but some details have been redacted due to corporate secrecy (Gassnova, 2019). A best cost estimate for a similar system range around 100 €/tonne CO_2 stored (Andersson et al., 2021), although this risk to be rather optimistic compared with values reported by Löfblad et al. (2022) and DNV GL (2019). The capture process is deemed the most expensive, accounting for around half of system costs (Gassnova, 2019), which would give an existing biogas upgrading facility an advantage. The 100 €/tonne CO_2 stored would translate to around 2 SEK/kg biomethane if costs were fully passed to consumers without subsidies. Carbon pricing and greater willingness to pay for climate-neutral or -negative products could potentially justify the additional costs,

Deployment of bio-CCS at the studied plant size (100 GWh, 14,100 tonne CO_2/year) would yield annual net-negative emissions of 13,000 tonne CO_2-eq. The 2023 Swedish biomethane production of 1.5 TWh (2.3 TWh of biogas) (Energigas Sverige, 2025), represents a theoretical capture potential of around 130,000 tonnes of biogenic CO_2 from existing plants. There are planned projects corresponding to a doubled production capacity until 2030 (Energigas Sverige, 2025). Sweden's climate neutrality target for 2045 requires at least 85% reduced emissions (60.7 Mtonne CO_2-eq) compared with 1990 (71.4 Mtonne CO_2-eq) and no more than 15% (10.7 Mtonne CO_2-eq) complementary measures, such as GGRTs. Assuming half of these 15% (5.4 Mtonne CO_2) will be realised by geological storage of CO_2, our results of 90% carbon efficiency indicate that 5.8 Mtonne CO_2 must be captured yearly. With efficient technical and distribution solutions in place, biogas plants have the potential to meet around 10% of this yearly demand for negative emissions in Sweden to reach net-zero by 2045 (Andersson et al., 2021). Biogas systems offer sustainability advantages such as the opportunity to utilise biomass from waste streams as substrate (manure, food waste, sludge), which are less tightly linked to the negative environmental effects such as land use change, acidification, toxicity, decreased biodiversity or competition with food production that can be connected to high quality biomass harvested for energy purposes,. However, CH_4 slip throughout biogas production process warrants attention, and CH_4 removal or oxidation options could be an alternative or complement to CCS for further improved climate impact.

A plausible scenario for implementation of CCS in Sweden is that it will start as with retrofit on large emitters of biogenic CO_2 located close to shore, with large volumes and short transport distances as enabling factors (Swedish Energy Agency, 2010). First-moving actors would establish essential transport infrastructure and learn important lessons about efficient CO_2 transport over Sweden's relatively large distances, enabling future connection of smaller, more remote emitters, as suggested by Han et al. (2015). This could create network effects that substantially improve both cost and energy efficiency (Löfblad et al., 2022). However, CO_2 transport and storage networks remains a challenge from a technical, social and political perspective (Rosa et al., 2021). More research and feasibility studies are needed to identify efficient incentives and necessary measures to put this into practice. Storage within Swedish territory could be possible but will require additional investigation and substantial knowledge development before being realised (Löfblad et al., 2022).

To be able to meet the future projected global need for negative emissions amounting to billions of tonne CO_2 yearly, a variety of technological alternatives and concepts will be needed (Nemet et al., 2018). This study focused on CO_2 from biogas upgrading, but the concept extends to other applications such as ethanol production. The studied CCS value chain is meant to be detachable and scalable, making results generalisable within reasonable limits - we showed sensitivity to transport logistics and electricity source, but there might be other impactful factors such as the size of the plant and competition from carbon capture and utilisation (CCU). Meeting projected global needs for billions of tonnes yearly negative emissions requires diverse technological approaches. As negative carbon credits gain commercial value, pricing should reflect net climate benefits calculated through comprehensive LCA. Such in-depth climate impact assessments are crucial complements to technical and economic evaluations, identifying environmental hotspots, building stakeholder trust and support informed decision-making by scientists, policymakers and industry actors advancing bio-CCS implementation.

5. Conclusions

This assessment of adding a small-scale pre-combustion CCS system to an amine biogas upgrading unit demonstrated that biogas upgrading can function as a GGRT with high energy and carbon efficiency. The life cycle energy demand of the CCS value chain corresponded to just over 5.6% of the produced biogas energy content, with liquefaction being the most energy-demanding process at 45% of the overall energy demand. The climate benefit from CO_2 storage far exceeded all emissions from CO_2 transport and storage, yielding net-negative emissions of −34 g CO_2-eq/MJ biomethane. Assuming an emissions factor of 19 g/MJ vehicle gas in Sweden, introducing bio-CCS lowered the emissions to −15 g CO_2-eq/MJ biomethane - a potential advantage over other transport fuels.

The additional GHG emissions from the CCS systems were 0.10 tonne CO_2/tonne CO_2 captured, corresponding to a 90% carbon efficiency: 1.1 tonnes of CO_2 needed to be captured to store 1 net tonne of CO_2. Sensitivity analyses highlighted that the assumed share of renewable energy and electricity significantly impacted the results; a fossil intensive energy system could reduce the carbon efficiency down to 75%. Since availability of renewable energy is highly site- and time dependent, site-specific LCA should be performed to determine to what extent net-negative emissions can be delivered in each CCS case, as parameters such as the upgrading technology and transport system play an important role. Such awareness of the impacts related to CCS management is material to address hotspots and increase the efficiency and eco-credibility of CCS projects.

Biogas has a theoretical capacity to deliver around 10% of Sweden's 2045 negative emissions target, constituting a valuable contribution to permanently stored CO_2. With biogas production capacity expanding in many countries, the potential for small-scale CCS to deliver a relevant amount of negative GHG emissions in the future is worth continued attention. Large investments will be needed to establish a CO_2 transport system, and the lifetime of its infrastructure may result in certain lock-in effects. Hence, it is worth attempting to design it in a way that allows for industrial collaborations and enable connection of small-scale actors, ensuring tall available pathways for negative CO_2 emissions can be utilised.

CRediT authorship contribution statement

Emma Bromark: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Pernilla Tidåker:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Åke Nordberg:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Per-Anders Hansson:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Emma Bromark reports financial support was provided by Swedish Energy Agency. Pernilla Tidaker reports was provided by Swedish Energy Agency. Ake Nordberg reports was provided by Swedish Energy Agency. Per-Anders Hansson reports was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2026.109047.

References

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C.E., Scott, V., Gilfillan, S.M.V., Ogaya, X., Haszeldine, R.S., 2018. Estimating geological CO2 storage security to deliver on climate mitigation. Nat. Commun. 9 (1), 2201. https://doi.org/10.1038/s41467-018-04423-1.
Andersson, J., Tamm, D., Berg, K., 2021. Bio-CCS från biogasanläggningar. BioCCS biogas Plants. Res. Inst. Swed.
Bauer, F., Hulteberg, C., Persson, T., Tamm, D., 2013. Biogas upgrading - Review of commercial technologies. http://www.sgc.se/ckfinder/userfiles/files/SGC270.pdf.
Blanco, S.T., Rivas, C., Fernández, J., Artal, M., Velasco, I., 2012. Influence of methane in CO2 transport and storage for CCS technology. Environ. Sci. Technol. 46 (23), 13016–13023. https://doi.org/10.1021/es3037737.
Börjesson, P., Lantz, M., Andersson, J., Björnsson, L., Fredriksson Möller, B., Fröberg, M., Hanarp, P., Hulteberg, C., Iverfeldt, E., Lundgren, J., Röj, A., Svensson, H., Zinn, E., 2016Methane as vehicle fuel - a gate-to-wheel study (METDRIV).(2016:06)⟨https://f3centre.se/app/uploads/f3_2016-06_borjesson-et-al_final_170111-1.pdf [2022/03/25/11:45:35]⟩.
Carranza-Abaid, A., Wanderley, R.R., Knuutila, H.K., Jakobsen, J.P., 2021. Analysis and selection of optimal solvent-based technologies for biogas upgrading. Fuel 303, 121327. https://doi.org/10.1016/j.fuel.2021.121327.
Chart Industries (2018). Bulk CO2 Applications & Storage Systems. ⟨https://files.chartindustries.com/21111520_BulkCO2brochure_11x17.pdf⟩ ⟨[2022-06-02]⟩.
Chatzinikolaou, S., Ventikos, N., 2014. Assessing environmental impacts of ships from a life cycle perspective. Martech 2014 (Lisbon, Portugal).
Cordova, S.S., Gustafsson, M., Eklund, M., Svensson, N., 2022. Potential for the valorization of carbon dioxide from biogas production in Sweden. J. Clean. Prod. 370, 133498. https://doi.org/10.1016/j.jclepro.2022.133498.
Cruz, T.Td, Perrella Balestieri, J.A., de Toledo Silva, J.M., Vilanova, M.R.N., Oliveira, O. J., Ávila, I., 2021. Life cycle assessment of carbon capture and storage/utilization: from current state to future research directions and opportunities. Int. J. Greenh. Gas. Control 108, 103309. https://doi.org/10.1016/j.ijggc.2021.103309.
Dawood, B., Torre-Celeizabal, A., Pina-Vidal, C., Téllez, C., Rumayor, M., Garea, A., Casado-Coterillo, C., 2025. Life cycle assessment and multi-objective optimization of biogas upgrading using chitosan based composite membranes. J. Environ. Chem. Eng. 13 (5), 117688. https://doi.org/10.1016/j.jece.2025.117688.
Deng, H., Bielicki, J.M., Oppenheimer, M., Fitts, J.P., Peters, C.A., 2017. Leakage risks of geologic CO2 storage and the impacts on the global energy system and climate change mitigation. Clim. Change 144 (2), 151–163. https://doi.org/10.1007/s10584-017-2035-8.
Det Kongelige Olje- og Energidepartementet (2020). Langskip – fangst og lagring av CO2 [Longship – capture and storage of CO2]. (Meld. St. 33). ⟨https://www.regjeringen.no/contentassets/943cb244091d4b2fb3782f395d69b05b/nn-no/pdfs/stm20 1920200033000dddpdfs.pdf⟩.
DNV GL (2019). Potential for reduced costs for carbon capture, transport and storage value chains (CCS). ⟨https://ccsnorway.

com/app/uploads/sites/6/2020/07/Report-Cost-reduction-curves-for-CCS-Gassnova-version-2b-1.pdf [2022-11-21]⟩.
Elforsk (2007). Miljövärdering av el - med fokus på utsläpp av koldioxid [Environmental evaluation of electricity – with focus on emissions of carbon dioxide]. Stockholm. ⟨https://www.energiforetagen.se/globalassets/energiforetagen/det-erbjuder-vi/publikationer/miljovardering-av-el.pdf [2022-06-01]⟩.
Energigas Sverige (2025). Produktion av biogas och rötrester och dess användning år 2023 [Production of biogas and digestate and its use in the year 2024]. Stockholm. ⟨https://energigas.se/Media/mvwmqi3h/biogasstatistik-rapport_2024.pdf [2025-11-18]⟩.
Equinor (2019). EL001 Northern Lights - Receiving and permanent storage of CO2. ⟨https://northernlightsccs.com/wp-content/uploads/2021/03/RE-PM673-00011-02-Impact-Assessment.pdf [2021/05/01/]⟩.
Ecoinvent, 2025. *The ecoinvent database.* Version 3.9.1. https://www.ecoinvent.org/.
Fasihi, M., Efimova, O., Breyer, C., 2019. Techno-economic assessment of CO2 direct air capture plants. J. Clean. Prod. 224, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.
Feiz, R., Johansson, M., Lindkvist, E., Moestedt, J., Påledal, S.N., Ometto, F., 2022. The biogas yield, climate impact, energy balance, nutrient recovery, and resource cost of biogas production from household food waste—A comparison of multiple cases from Sweden. J. Clean. Prod. 378, 134536. https://doi.org/10.1016/j.jclepro.2022.134536.
Garcia, J.A., Villen-Guzman, M., Rodriguez-Maroto, J.M., Paz-Garcia, J.M., 2022. Technical analysis of CO2 capture pathways and technologies. J. Environ. Chem. Eng. 10 (5), 108470. https://doi.org/10.1016/j.jece.2022.108470.
Gassnova (2019). Full chain CO2 footprint. Porsgrunn. ⟨https://ccsnorway.com/app/uploads/sites/6/2020/07/CO2_footprint_feed_report-2.pdf [2021-10-16]⟩.
Gassnova (2020a). Demonstrasjon av fullskala CO2-håndtering [Demonstration of full scale CO2 management]. ⟨https://ccsnorway.com/app/uploads/sites/6/2020/10/Gassnovas-helkjederapport-redacted-version-som-publisert.pdf [2021-11-06]⟩.
Gassnova (2020b). Updated CO2 footprint calculations. Porsgrunn. ⟨https://gassnova.no/app/uploads/sites/6/2020/11/Updated-CO2-footprint-calculations.pdf [2021-10-19]⟩.
Goglio, P., Williams, A.G., Balta-Ozkan, N., Harris, N.R.P., Williamson, P., Huisingh, D., Zhang, Z., Tavoni, M., 2020. Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. J. Clean. Prod. 244, 118896. https://doi.org/10.1016/j.jclepro.2019.118896.
Golmakani, A., Nabavi, S.A., Manović, V., 2021. Production of negative-emission biomethane by twin double-bed pressure swing adsorption with tail gas sequestration. Chem. Eng. J. 408, 127312. https://doi.org/10.1016/j.cej.2020.127312.
Han, C., Zahid, U., An, J., Kim, K., Kim, C., 2015. CO2 transport: design considerations and project outlook. Curr. Opin. Chem. Eng. 10, 42–48. https://doi.org/10.1016/j.coche.2015.08.001.
Hayat, M.A., Alhadhrami, K., Elshurafa, A.M., 2024. Which bioenergy with carbon capture and storage (BECCS) pathways can provide net-negative emissions? Int. J. Greenh. Gas. Control 135, 104164. https://doi.org/10.1016/j.ijggc.2024.104164.
Hilaire, J., Minx, J.C., Callaghan, M.W., Edmonds, J., Luderer, G., Nemet, G.F., Rogelj, J., Del Mar Zamora, M., 2019. Negative emissions and international climate goals—learning from and about mitigation scenarios. Clim. Change 157 (2), 189–219. https://doi.org/10.1007/s10584-019-02516-4.
IEA (2025). Electricity 2025. Internation energy agency, Paris ⟨https://www.iea.org/reports/electricity-2025⟩.
IGC Engineering (n.d.). Carbon Dioxide Pressure Vessels and Storage Tanks. ⟨https://igc-pressure-vessels.co.uk/carbon-dioxide-pressure-vessels/ [2022/03/10/]⟩.
Iordan, C., Lausselet, C., Cherubini, F., 2016. Life-cycle assessment of a biogas power plant with application of different climate metrics and inclusion of near-term climate forcers. J. Environ. Manag. 184, 517–527. https://doi.org/10.1016/j.jenvman.2016.10.030.
IPCC (2018). Global Warming of 1.5 °C -special report. ⟨https://www.ipcc.ch/sr15/files/104/sr15.html [2021/03/10/]⟩.
IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896.
Jackson, S., Brodal, E., 2018. A comparison of the energy consumption for CO2 compression process alternatives. IOP Conf. Series Earth Environ. Sci. 167, 012031. https://doi.org/10.1088/1755-1315/167/1/012031.
Johansson, F., Kjärstad, J., 2019. Avskiljning, transport och lagring av koldioxid i Sverige - Behov av forskning och demonstration [Separation, transport and storage of carbon dioxide in Sweden – Need for research and demonstration]. (ISBN: 978-91-88041-20-3). Chalmers. [2022-05-03].
Kameyama, M., Hiraoka, K., Sakurai, A., Naruse, T. & Tauchi, H. (2014). Development of LCA software for ships and LCI Analysis based on actual shipbuilding and operation. I: Institute, N.M.R. (red.). Tokyo.
Kjärstad, J., Skagestad, R., Eldrup, N.H., Johnsson, F., 2016. Ship transport—A low cost and low risk CO2 transport option in the Nordic countries. Int. J. Greenh. Gas. Control 54, 168–184. https://doi.org/10.1016/j.ijggc.2016.08.024.
Kvist, T., Aryal, N., 2019. Methane loss from commercially operating biogas upgrading plants. Waste Manag. 87, 295–300. https://doi.org/10.1016/j.wasman.2019.02.023.
Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sustain. Energy Rev. 39, 426–443. https://doi.org/10.1016/j.rser.2014.07.093.
Li, H., Tan, Y., Ditaranto, M., Yan, J., Yu, Z., 2017. Capturing CO2 from biogas plants. Energy Procedia 114, 6030–6035. https://doi.org/10.1016/j.egypro.2017.03.1738.
Löfblad, E., Gode, J., Kjärstad, J., Grubbström, C., Holm, J., Romson, Å., Steen, L., 2022. Samv. Kring infrastruktur F. öR. Transp. och lagring Av. koldioxid Collab. Infrastruct. Transp. Storage Carbon Dioxide(2022:838). Energiforsk.
Ming, T., Richter, Rd, Dietrich Oeste, F., Tulip, R., Caillol, S., 2021. A nature-based negative emissions technology able to remove atmospheric methane and other greenhouse gases. Atmos. Pollut. Res. 12 (5), 101035. https://doi.org/10.1016/j.apr.2021.02.017.
Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, Wd.O., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., Dominguez, Md.M.Z., 2018. Negative emissions—Part 1: research landscape and synthesis. Environ. Res. Lett. 13 (6). https://doi.org/10.1088/1748-9326/aabf9b.
Nemet, G.F., Callaghan, M.W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W.F., Minx, J.C., Rogers, S., Smith, P., 2018. Negative emissions—Part 3: innovation and upscaling. Environ. Res. Lett. 13 (6). https://doi.org/10.1088/1748-9326/aabff4.
Ng, W.Y., Low, C.X., Putra, Z.A., Aviso, K.B., Promentilla, M.A.B., Tan, R.R., 2020. Ranking negative emissions technologies under uncertainty. Heliyon 6 (12), e05730. https://doi.org/10.1016/j.heliyon.2020.e05730.
Poblete, I.B.S., Araujo, Od.Q.F., de Medeiros, J.L., 2020. Dynamic analysis of sustainable biogas-combined-cycle plant: time-varying demand and bioenergy with carbon capture and storage. Renew. Sustain. Energy Rev. 131. https://doi.org/10.1016/j.rser.2020.109997.
Reinert, C., Deutz, S., Minten, H., Dörpinghaus, L., von Pfingsten, S., Baumgärtner, N., Bardow, A., 2021. Environmental impacts of the future German energy system from integrated energy systems optimization and dynamic life cycle assessment. Comput. Chem. Eng. 153, 107406. https://doi.org/10.1016/j.compchemeng.2021.107406.
Rosa, L., Sanchez, D.L., Mazzotti, M., 2021. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy Environ. Sci. 14 (5), 3086–3097. https://doi.org/10.1039/D1EE00642H.
Sandgren, A. & Nilsson, J. (2021). Emissionsfaktor för nordisk elmix med hänsyn till import och export - Utredning av lämplig systemgräns för elmix samt beräkning av det nordiska elsystemets klimatpåverkan. miljöinstitutet, I.S. ⟨https://www.ivl.se/download/18.556fc7e17c75c84933f392/1635759400558/FULLTEXT01.pdf [2022-08-01]⟩.
Scheutz, C., Fredenslund, A.M., 2019. Total methane emission rates and losses from 23 biogas plants. Waste Manag. 97, 38–46. https://doi.org/10.1016/j.wasman.2019.07.029.
SOU (2020). Vägen till en klimatpositiv framtid [The road to a climate positive future]. (SOU 2020:4). Statens offentliga utredningar. Stockholm, Sweden. ⟨https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2020/01/sou-20204/ [2021-09-04]⟩.
Stripple, H. (2001). Life Cycle Assessment of Road - A Pilot Study for Inventory Analysis. miljöinstitutet, I.S. ⟨https://www.ivl.se/download/18.34244ba71728fcb3f3f57f/1591704221839/B1210E.pdf⟩ [2022-06-01].
Sweco (2021). Carbon intensity and primary energy factors. (300031634). Energimyndigheten.
Swedish E.P.A. (2025). Situation update for the Climate leap [Lägesbeskrivning för Klimatklivet]. Swedish environmental protection agency [Naturvårdsverket]. ⟨https://www.naturvardsverket.se/4975d1/globalassets/amnen/klimatomstallning/klimatklivet/dokument/klimatklivets-lagesbeskrivning-2025.pdf⟩ [2025-06-01].
Swedish energy agency (2020). Produktion och användning av biogas och rötrester år 2019 [Production of biogas and digestate and its use in the year 2019]. (ER 2020:25). Energimyndigheten, Eskilstuna. ⟨https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=179401⟩.
Swedish energy agency (2021). Drivmedel 2020 [Fuel 2020]. (2021:29). Energimyndigheten, Eskilstuna. ⟨https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=203063⟩.
Swedish Energy Agency (2010). Systemstudie av möjligheter att etablera en infrastruktur för CCS i Östersjöregionen [System study of possibilities to establish an infrastructure in the Baltic Sea region]. (ER 2010:36). Energimyndigheten, Eskilstuna. ⟨https://energimyndigheten.a-w2m.se/FolderContents.mvc/Download?ResourceId=104304 [2022-08-29]⟩.
Terlouw, T., Bauer, C., Rosa, L., Mazzotti, M., 2021. Life cycle assessment of carbon dioxide removal technologies: a critical review. Energy Environ. Sci. 14 (4), 1701–1721. https://doi.org/10.1039/D0EE03757E.
Trunzo, G., Moretti, L., D'Andrea, A., 2019. Life cycle analysis of road construction and use. Sustainability 11 (2), 377. ⟨https://www.mdpi.com/2071-1050/11/2/377⟩.
Wolff, S., Seidenfus, M., Gordon, K., Álvarez, S., Kalt, S., Lienkamp, M., 2020. Scalable life-cycle inventory for heavy-duty vehicle production. Sustainability 12 (13), 5396. ⟨https://www.mdpi.com/2071-1050/12/13/5396⟩.
Yang, M., Baral, N.R., Anastasopoulou, A., Breunig, H.M., Scown, C.D., 2020. Cost and life-cycle greenhouse gas implications of integrating biogas upgrading and carbon capture technologies in cellulosic biorefineries. Environ. Sci. Technol. 54 (20), 12810–12819. https://doi.org/10.1021/acs.est.0c02816.
Zahid, U., An, J., Lee, U., Choi, S.P., Han, C., 2014. Techno-economic assessment of CO2 liquefaction for ship transportation. Greenhouse Gases Sci. Technol. 4 (6), 734–749. https://doi.org/10.1002/ghg.1439.