



OPEN Reduced life cycle climate impact from manure through catalytic methane conversion and carbon dioxide removal

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Agri-food systems constitute around one-third of global greenhouse gas (GHG) emissions, with roughly half consisting of non-CO₂ GHGs, mainly methane (CH₄) and nitrous oxide (N₂O). Methods and technologies to mitigate non-CO₂ GHGs are currently limited, which is a reason for agriculture being categorised as a hard-to-abate sector. This study examines mitigation of GHG emissions from manure storage headspace through oxidation of CH₄ emissions at low concentrations, using a thermal catalytic process with and without subsequent CO₂ capture and storage (CCS). The technology is studied using a combination of process modelling and life cycle assessment at four CH₄ concentrations: 300, 1000, 3000 and 10,000 ppmv. The primary energy demand and net climate effect were evaluated, reaching a net climate effect of +0.10, -0.77, -0.91 and -0.97 g CO₂-eq emitted/g CO₂ mitigated, respectively. The wide range of results is mainly influenced by the process energy demand being strongly correlated to the CH₄ concentration. The sensitivity analysis shows that a net negative climate effect can also be achieved at 300 ppmv with access to low emission energy sources. Coupling CCS worsens the net climate effect of the system at all studied CH₄ concentrations, mainly due to the additional energy demand for CO₂ separation.

Keywords GGR, CH₄, Methane emissions, LCA, Manure management, Climate change

Abbreviations

CE	Climate effect
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CH ₄	Methane
CF	Carbon footprint
CO ₂	Carbon dioxide
ED	Energy demand
GGR	Greenhouse gas removal
GGRT	Greenhouse gas removal technology
GHG	Greenhouse gas
GWP	Global warming potential
kJ	Kilo Joule (10 ³ joule)
LCA	Life cycle assessment
MJ	Mega Joule (10 ⁶ joule)
PED	Primary energy demand

The increase in greenhouse gas (GHG) emissions and climate scenario modelling shows the need for rapidly regressing GHG emissions through the parallel deployment of mitigation efforts and negative emissions across all of sectors¹. However, some sectors are regarded as more challenging to handle than others. The GHG emissions from the agricultural sector are considered hard-to-abate, as they are predominantly not tied to energy use

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but rather originate from animals, soils and manure; thus, a renewable energy transition will not impact these emissions². The global climate impact from agri-food systems amounted to 16 Gt carbon dioxide equivalents (CO₂-eq) in 2022, with over half caused by non-CO₂ GHGs, mainly methane (CH₄) and nitrous oxide (N₂O)³. The low concentrations (typically < 1%-vol) and dispersed nature of the emissions make them difficult to quantify, target and reduce^{4,5}. This indicates a need for different types of mitigation strategies for GHG emissions in agriculture and that a future net-zero or net-negative emissions balance would require residual emissions being offset through greenhouse gas removal (GGR)⁶. GGR can be achieved through natural (biological) processes as well as engineered (technical) systems, i.e. greenhouse gas removal technologies (GGRTs)⁷. A rather versatile portfolio of GGRTs has been presented, with the majority involving carbon dioxide removal (CDR)⁸. However, second only to CO₂, CH₄ is such a potent of a GHG that it contributes to 25% of total radiative forcing (RF), despite its atmospheric concentration being only 0.5% that of CO₂⁹. Due to its high RF and short atmospheric residence time (approximately 12 years), rapid reductions in CH₄ emissions have great potential to impact global warming in the short term¹⁰. Despite there being a strong case for CH₄ mitigation, it remains poorly covered in climate policy, although it has received increased attention in recent years¹¹.

A strategy to evade the warming effect of a high GWP gas such as CH₄ is to convert it into a lower GWP gas, such as CO₂⁸. Such research has been put forward, with suggested applications both for the fossil fuel industry¹² and ambient air e.g.^{13–15}, although these are at a low technological readiness level¹⁶. CH₄ gradually oxidizes in the atmosphere over time, but this reaction can be initiated by, for example, introducing a catalyst and/or energy addition via light, heat or electricity¹⁷. For example, de Richter et al.¹⁵ used photocatalysts to convert CH₄ from ambient air, a technology that could be applied to mitigate methane from concentrated sources. Ming et al.¹⁴ discussed several technologies to remove methane from atmosphere, such as enhancing hydroxyl radicals, generation of chlorine atoms, methanotrophic bacteria in bioreactors. CH₄ removal from ambient air would require large air flows due to the low concentration¹⁸. There are published studies that focus mainly on the catalyst development^{19–21} for treating low-concentration methane emissions but less on the process technology or assessed using a wider systems perspective. Sirigina et al.²² proposed process concepts based on thermal-catalytic oxidation of methane at low concentrations, which forms the basis for this study.

Over half of the global CH₄ emissions originates from agrifood systems²³. The scientific focus of climate intervention in the agricultural sector has so far been on CH₄ emissions management approaches rather than removal measures. None of the previously mentioned studies^{12–23} have evaluated agricultural applications. Many CH₄ emissions arise from large poorly constrained areas, such as organic soils, rice fields and wetlands^{4,24}. Since the higher the concentration of CH₄, the easier it is to get the CH₄ conversion reaction running²², it is preferable to identify a CH₄ point source to increase process efficiency and decrease component size²⁵. Possible alternatives of concentrated emission sources include manure storage or stables for ruminants²⁶. Livestock cause considerable CH₄ emissions originating from enteric fermentation (~ 70%) and manure (~ 30%)²³. GHG emissions from manure is the second largest emission source from farms²³. During manure storage, organic matter in the manure starts to decompose, forming CO₂ under aerobic conditions and CH₄ through anaerobic reactions²⁷. The rate of emissions depends on a number of factors, such as organic matter, temperature, moisture and pH²⁸, and a future warmer climate would increase CH₄ emissions from manure²⁹. Manure degradation can be partially regulated by lowering the pH of the manure through cooling, increasing acidity or covering the source^{29–31}. The manure could also be subjected to anaerobic digestion, which allows the CH₄ to form under controlled circumstances where it can be collected and utilised for its energy content³². Despite this being an efficient utilisation of the waste and lowered climate impact, only around 5% of manure is digested in Sweden, one barrier being the high investment cost of farm-based biogas plants³³. A potential approach that has not yet been explored is to treat the air from the manure storage space on-site by oxidising the CH₄ in a reactor containing a catalytic material to facilitate the reaction, as was recently proposed by Sirigina, et al.²². The approach of this system is to convert the CH₄ as soon as it is emitted to avoid its warming effect, and the conditions allows adaption to the CH₄ concentrations that are typical to agricultural sources. The resulting CO₂ from the oxidation reaction is biogenic in nature, which can be captured and stored. The most common technologies to capture CO₂ are chemical absorption and adsorption³⁴. Geological storage is necessary to achieve long-term removal of the CO₂ from the atmosphere³⁵.

To achieve sustainable and credible GGR, the applied technologies must result in a net negative emission balance over the system's lifecycle and long-term storage reliability of the removed emissions³⁶. There is a growing number of studies of CDR technologies which emphasise the importance of the life cycle assessment (LCA) methodology to evaluate its effectiveness in delivering negative emissions, suggesting clear variance in effectiveness across technologies (see e.g. review by Rueda, et al.¹). However, the life-cycle perspective of GGR through the conversion of CH₄ emissions emerging from biogenic sources is currently in its infancy with only one scientific publication, on photocatalytic oxidation of CH₄³⁷. There is also a need for further discussion about scenarios where GGR targeting CH₄ emissions can be considered as a greenhouse gas removal or mitigation strategy. This study aims to contribute with an evaluation of thermal catalytic oxidation as an option for reducing CH₄ emitted from manure storage using a life cycle perspective. The objective of the study was to determine the energy demand and climate efficiency of the proposed technology. Furthermore, the impact of releasing the exhaust gas to the atmosphere after the conversion process was compared with subsequent capture and storage of the CO₂ from the exhaust gas. The study attempted to identify energy and climate related hotspots in the process to provide guidance for future system development.

Methodology

This study investigated a process technology for thermal catalytic treatment of the CH₄ emitted from manure storage and subsequent CO₂ capture and storage (CCS). The approach was to compare a reference state of conventional unabated manure storage emissions to a scenario where the manure storage space is integrated with the suggested technology:

- Scenario A: *CH₄-conversion*. GHG emissions from manure storage headspace is treated through catalytic CH₄ oxidation and the exhaust gas is released into the atmosphere.
- Scenario B: *Co-removal*. GHG emissions from manure storage headspace is treated through catalytic CH₄ oxidation followed by capture and storage of the CO₂ in the outlet gas.

The scenarios are explained in greater detail below. The study was performed through a combination of process modelling in Aspen Plus V12 and LCA. Both the LCA model and the process model relied largely on generic literature data and are not meant to represent a specific installation or determine an optimal system of production, but rather to provide a representative example based on currently available data.

Life cycle assessment

The study covered each process step involved, from manure storage to the suggested catalytic treatment until the exhaust gas is released or treated for CO₂ capture for storage after the process. Processes occurring upstream of manure storage were excluded as they remain unaffected throughout the scenarios. The system boundary considered was cradle-to-grave, meaning the study included emissions from the entire life cycle of the technical appliances, including the necessary energy and raw materials, transport and processing, manufacturing of machinery, infrastructure and facilities, as well as its end of life. The life cycle inventory (LCI) was established through data collection from the literature and by utilizing the process parameters obtained from process models developed in Aspen (Sect. 2.3), with the resulting data used for the life cycle impact assessment. LCI data on a European level was primarily used and, if the corresponding data was not available, on a global level. As a final option, country-specific LCI datasets were used. The data was compiled over the three life cycle phases: manufacturing (raw material extraction and processing), operation (plant in operation), and end of life (material waste management). The climate impact and primary energy demand (PED) for the raw material for the process components manufacturing and catalyst was based on data from Ecoinvent v. 3.9.1. End of life for the materials required were included based on Ecoinvent³⁸ data.

The functional unit provides a quantitative measure of the function(s) of the assessed process and serves as a basis for comparison³⁹. For GGRTs, a functional unit that reflects the function of lowered global warming is encouraged, allowing comparison between different GGR options³⁶. Therefore, we used the functional unit (FU) 'grams (g) of CO₂-equivalents (CO₂-eq) mitigated'. The resulting impacts from the LCA is related to the functional unit in accordance with Eq. (1):

$$\text{impact score} = \frac{\text{enviromental impact}}{FU} \quad (1)$$

The impact categories considered are primary energy demand (PED) in kilojoules (kJ) (Eq. 2) and net climate effect (CE), defined as g CO₂-eq emitted relative to the CO₂-eq mitigated (Eq. 3):

$$PED = ED * PEF \quad (2)$$

$$\text{net CE} = \frac{e_{\text{emitted}} - e_{\text{mitigated}}}{e_{\text{mitigated}}} \quad (3)$$

ED denotes energy demand, PEF the primary energy factor and *e* GHG emissions in g CO₂-eq. By this definition, a negative value of the net CE denotes lower system emissions than mitigated emission, whereas a positive value of the net CE is to be interpreted as the system causing more GHG emissions than is being mitigated. As the GHGs emitted from manure are of biological origin, their removal would be categorized as negative emissions, provided that the total removal of GHG emissions is larger than the total GHG emissions emitted to the atmosphere by the processes required for GGR³⁶. Compared to the reference state, oxidising CH₄ as soon as it is emitted will help eliminate the large RF which is otherwise exerted during its residence time in the atmosphere. This was shown as an arithmetically negative contribution to the net CE, although the carbon atom is still present in the atmosphere in the CH₄ conversion case. However, the term mitigated was chosen as the assumption that we are in fact removing or mitigating emissions needs a broader system level discussion, which is outside the scope of this article.

GWP100 was used as the conversion metric to assess climate impact from GHG emissions as is standard practice in LCA. However, with CH₄ being such a central component of this study, the metric choice was subjected to sensitivity analysis to highlight its implications, by replacing GWP100 with GWP20 and GWP500. GWP values as defined in AR6 were used⁴⁰. To allow this, disaggregated GHG emission data was used when possible.

The energy used for operation was solely in the form of electricity. The electricity source was assumed to be a European mix with an emission factor of 293 g CO₂-eq/kWh⁴¹ and a primary energy factor of 2.3⁴². This was subjected to sensitivity analysis, exchanging the electricity source for natural gas power with 436 g CO₂-eq/kWh⁴³ and a primary energy factor of 2.0, and for a more renewable mix represented by the Nordic consumption mix (approximately 50% hydropower, 20% nuclear power, 15% wind and solar power and 15% combined heat and power) with 93.2 g CO₂-eq/kWh⁴⁴ and primary energy factor of 1.7⁴⁵. Data was chosen to cover life-cycle emissions from electricity generation.

System description

Livestock slurry was assumed to be stored on a farm in covered manure storage with a capacity of 5000 m³, sufficient for manure from around 200 dairy cows including a grazing period of 3 months⁴⁶. The manure was stored for up to 9 months before being spread on nearby fields as fertilizer. Biological processes degrading the

organic matter in the manure form emissions of gases and heat. Based on IPCC guideline data⁴⁷ for the yearly average CH₄ emissions, the CH₄ emission rate from the manure was determined to be 0.390 mg of CH₄ (10.5 mg CO₂-eq) per second. In the reference state, the GHG emissions were released to the atmosphere without any intervention. For this analysis we chose to model four different concentrations of CH₄ (300, 1000, 3000, and 10,000 ppmv), representing conditions which cause low to high CH₄ emissions (see Table S1 for context). This was achieved by adjusting the dilution of CH₄ in four different airflows (6890, 2067, 689 and 207 m³/h), respectively. This interval gives information on how the emissions rate relates to the size of the process plant and covers a relevant range of operating conditions. We further assume the share of aerobic vs. anaerobic degradation of organic matter in the manure storage was such that the GHG emissions consisted of CO₂ and CH₄ on a 40:60 molar% basis based on Grant, et al.⁴⁸. The CO₂ originating from the manure degeneration (0.71 g/s) entered the process alongside the CO₂ in ambient air, which was set to 417 ppmv. Details can be found in the Supplementary material (SM), Tables S3 and S4.

Scenario A: CH₄ conversion

In scenario A, the airflow from the covered manure storage headspace was actively ventilated and directed to a catalytic oxidizer where CH₄ was oxidised to CO₂ before release into the atmosphere. Different CH₄ concentrations were achieved by diluting the CH₄ emissions through varying airflow.

Scenario B: co-removal

Once the CH₄ had been oxidized, following an identical route as in Scenario A, the residual gas flow entered a carbon capture unit to separate the CO₂ from the rest of the air. Due to the degradation processes in manure forming CO₂, its concentrations change, to match the amount of CH₄, creating a 40:60 mix. The CO₂ flows are described in the SM (Fig. S1 & Table S2). The separated CO₂ was liquefied and transported to and injected at a geological storage site. According to a previous work on transport and storage for relevant conditions, the captured CO₂ would require 1.5 GJ/tonne CO₂ stored and cause 0.10 tonne CO₂-eq emissions/tonne CO₂ to be stored⁴⁹.

Process description and modelling

Modelling of the CH₄ conversion unit and co-removal via solid sorbent-based adsorption followed the same methodology as presented in Sirigina, et al.²², with some modifications made to fit the application of the present study. The chosen CH₄ concentrations and corresponding gas flows were given as input data (see SM for details). The model output consisted of stream flow rates (Tables S5–S8), energy demand for each process step (Table S11), as well as the capacity and size of the required equipment (Tables S12–S16). The flow sheet for the methane conversion process is shown in Fig. 1 and Fig. S12a in the SM. The outlet stream from the manure storage was directed into the process using a blower. A dehumidifier reduced the inlet moisture content in the stream. The stream was then preheated using the thermal energy of the product stream from the reactor. An electric heater increased the temperature before entering the reactor. The exhaust stream was cooled down after leaving the reactor. For 300 and 1000 ppmv CH₄, a solid sorbent based vacuum temperature swing adsorption (VTSA)-based process was considered for CO₂ capture.

For the cases with a 3000 and 10,000 ppmv CH₄ concentration, a monoethanolamine (MEA) based absorption process was modelled in Aspen Plus and integrated to the CH₄ conversion unit (Tables S17, S18). Process schematics for co-removal based on adsorption (co-removal) and co-removal based on MEA absorption are shown in the SM (Fig. S12b and c).

The Aspen Process Economic Analyser (APEA) integrated in Aspen Plus was used to estimate the installed weight of the equipment. The weight of all the equipment except the reactor was obtained from APEA. The methodology for sizing the reactor and of heat transfer coefficients (Tables S9 & S10) used in dimensioning the heat exchangers are presented in the SM.

The plant size was inversely related to the CH₄ concentration, as a low concentration entails a larger volume of air being treated to remove the same total amount of CH₄. Stainless steel 304 was considered as the default material for all the heat exchangers and the reactor in the CH₄ conversion unit. Other installations were assumed to consist of 90% steel and 10% concrete as a best estimate. Plant lifetime was set to 20 years.

The catalyst used for CH₄ oxidation is 6.5% Pd/Al₂O₃, and a conversion rate of 95% was considered for the analysis. The catalyst amount required for the conversion was estimated based on the kinetic equation provided in Alyani and Smith⁵⁰. For the conversion rate to be even higher, the catalyst amount would increase exponentially. The right amount of catalyst for each CH₄ concentration was calculated based on reaction kinetics to match the amount of CH₄ emitted. The lifetime of the catalyst was set to 10 years, meaning it is exchanged once during the technical lifetime of the plant. The studied catalyst shows reversible inhibition in the presence of water⁵⁰; hence a dehumidifier is needed. It is plausible that a considerable share of ammonia will dissolve in the condensate from the dehumidifier. However, the effects on the process of remaining ammonia are currently unknown and therefore are not considered. Based on the design conditions assumed in the study, other gases, such as N₂O, were assumed to have passed through the system without undergoing any reaction⁵¹. We assumed no gas slip occurred within the treatment process since all the components are closed components in the system. An inlet temperature of 330 °C was considered for the catalytic conversion of methane^{22,50}. At 300 ppmv, a separate heater was necessary to reach the required reaction temperature, while at the higher CH₄ concentrations, the excess heat from the oxidised CH₄ was enough to sustain the reaction. It was necessary to cool the gas stream after the reaction regardless of whether it was exhausted or if CO₂ was captured.

The choice of CO₂ capture system was based on energy demand estimated by Kiani et al.⁵² and Sabatino et al.⁵³. The chemical absorption system using MEA has higher energy demand at very low concentrations of CO₂ when compared to the solid sorbent-based capture technology. Therefore, solid sorbent-based technology was

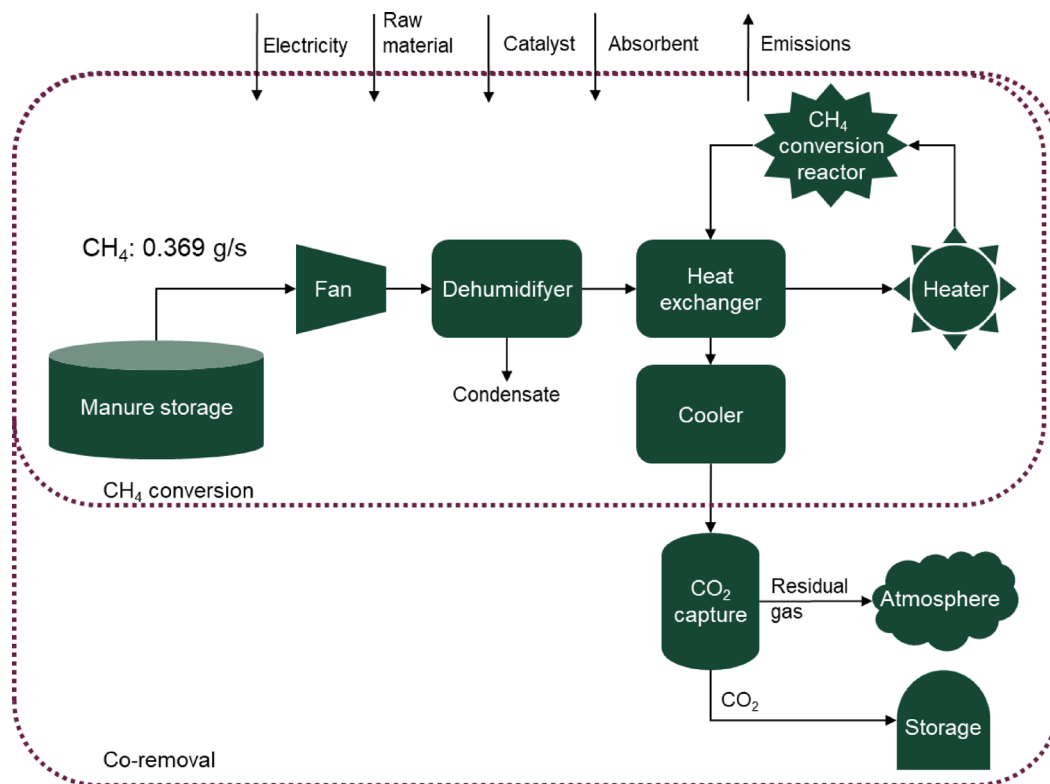


Fig. 1. System sketch illustrating the scenarios covered in the study.

considered for the 300 and 1000 ppmv cases, while the MEA based chemical absorption CO₂ capture technology was considered for 3000 ppmv and 10,000 ppmv cases.

A solid sorbent (APDES-NFC; 3-aminopropylmethyldiethoxysilane - functionalized nanofibrillated cellulose adsorbent) VTSA process was used for the CO₂ capture at the low CH₄ concentrations (300 and 1000 ppmv CH₄). The energy demand for CO₂ capture through adsorption (excluding the blower) was set to 11.04 GJ/tonne CO₂⁵³. A process based on APDES-NFC was considered due to its similarity with the sorbent used by Climeworks. The case with the maximum productivity was considered and the resulting sorbent requirement was linearly scaled down for the capture of CO₂, corresponding to the amount in the stream from CH₄ conversion unit. The regeneration temperature was 110 °C, capture efficiency was 80% and PED was 2.83 GJ/tonne CO₂ based on Sabatino et al.⁵³. Heat integration was not possible at 300 and 1000 ppmv due to the low quality of waste heat stream from the CH₄ conversion unit. The manufacturing for this case was assumed to equal the DAC plant described by Terlouw, et al.⁵⁴ and scaled linearly to match the capture capacity of our system. For 3000 ppmv and 10,000 ppmv CH₄ concentrations, a MEA based absorption process was modelled in Aspen Plus and integrated to CH₄ conversion unit. Heat integration was modelled by using excess heat from the CH₄ reactor for the regeneration of the absorbent. Process schematics for co-removal based on adsorption (co-removal) and co-removal based on MEA absorption are shown in Fig. S12b and c. The regeneration temperature was ~ 120 °C. The capture efficiency was ~ 89% for the case with 10,000 ppmv CH₄ concentration, while the capture efficiency was ~ 83% for the case with 3000 ppmv CH₄ concentration. It was found from the model that approximately 1.5 kg MEA was required as makeup per tonne of CO₂ capture for the case with 10,000 ppmv CH₄ concentration, while 1.95 kg MEA was required per tonne of CO₂ captured for the case with 3000 ppmv of CH₄ concentration. The amount of MEA required for makeup in our models was similar to the value (1.5 kg) reported in literature⁵⁵. The environmental impact for MEA was obtained from Ecoinvent³⁸. The CO₂ capture plant sizing for the MEA absorbent process was done using the Aspen Process economic analyser in the same way as with other installations.

Results

The output from the process modelling constituted a part of the LCI and was part of the life cycle PED and CE. Additional results such as specific results from the process model in Aspen can be found in the Supplementary material. As defined in 2.1, a negative net CE denotes lower system emissions than mitigated emissions, whereas a positive net CE is to be interpreted as the system causing more GHG emissions than were being mitigated per functional unit.

Scenario A: CH₄ conversion

The CE for oxidising CH₄ at the four different concentrations is shown in Fig. 2, displaying the positive and negative climate contribution as well as the net value represented by the difference between the two. The CE was

clearly non-linear with an improving net-effect with increasing CH_4 concentrations. A total amount of 0.37 g CH_4 /s (10.3 g CO_2 -eq) was oxidised, and 0.019 g CH_4 /s (0.54 g CO_2 -eq) exited with the waste gas, corresponding to the 95% conversion capacity of the catalyst. In accordance with the definition of the functional unit, this oxidised amount equals -1.0 g CO_2 -eq.

The additional GHG emissions were divided into emissions originating from the manufacturing and those from the operations phase. The results for the end-of-life phase were too low to be clearly displayed in any graphic and were therefore included in the manufacturing phase. The emissions from the operations phase made the predominant contribution (98%, 96%, 93% and 83% at a 300, 1000, 3000 and 10,000 ppmv CH_4 concentration, respectively). However, as the absolute additional emissions decreased for higher CH_4 concentrations, the relative impact of the plant manufacturing increased, corresponding to 2%, 4%, 7% and 17%, respectively (Fig. S2 in the SM). The GHG emissions from the operation consist of direct emissions from the process, and indirect emissions from the energy demand. The direct emissions are what is left in the exhaust. These are counted as climate neutral due to their biological origin and the fact that in the reference case, they would all have reached the atmosphere. However, they impact the results via the functional unit, which is made up by the mitigated emissions. The indirect emissions depend on the energy source used to power the process.

The total PED was 31, 6.3, 2.3 and 0.77 kJ/g CO_2 -eq mitigated from the low to high CH_4 concentrations, respectively. The energy required for operation made up a significant share of the total PED (Fig. S2 in SM). In absolute numbers, it decreased with increasing CH_4 concentration. Lower concentrations of CH_4 led to larger volumes of air being treated to mitigate a given quantity of CO_2 -eq, hence the PED for pressure loss, dehumidifying and heating the air increase. At all four CH_4 concentrations, the blower constitutes the largest share of the PED for operation, followed by the dehumidifier (Fig. S3 in SM).

The manufacturing of the dehumidifier was associated with high PED and CE. In the 10,000 ppmv case, this amounted to almost 60% of the PED and 50% of the CE (Fig. S5 in SM). The palladium for the catalyst used to initiate the CH_4 oxidation asserted a high climate impact, and at the lowest concentration, which requires the largest catalyst amount, this constituted almost 65% of the overall climate effect from manufacturing. The recuperator was also demanding to manufacture (Fig. S5 in SM). However, as CH_4 concentrations increased so does the heat discharge from the oxidation process, meaning the size of the recuperator could be significantly decreased. At the lowest concentrations, additional heat was required to reach a high enough temperature for oxidation to initiate, but at 1000 ppmv CH_4 and above, the heat transfer in the recuperator is sufficient to sustain the reaction.

Scenario B: co-removal

From a life cycle perspective, climate efficiency was worsened when CCS was added (Table 1). This is mainly due to the much higher GWP of CH_4 but also due to the additional process steps required for CCS, which slightly increase the PED and cause additional GHG emissions (Figs. S4 & S8 in SM). When summarizing the effects of the oxidized CH_4 with the captured CO_2 , the mitigation equals 12.9, 11.7, 11.5 and 11.4 g CO_2 -eq/s from the lowest to highest CH_4 concentrations, respectively. In accordance with the definition of the functional unit, this oxidised amount equals -1.0 g CO_2 -eq.

The PED increased due to the added capture unit, mainly due to the energy required for the regeneration of the sorbent. The energy demand from operating CO_2 capture alone was higher than CH_4 conversion in the cases with medium and high CH_4 concentrations.

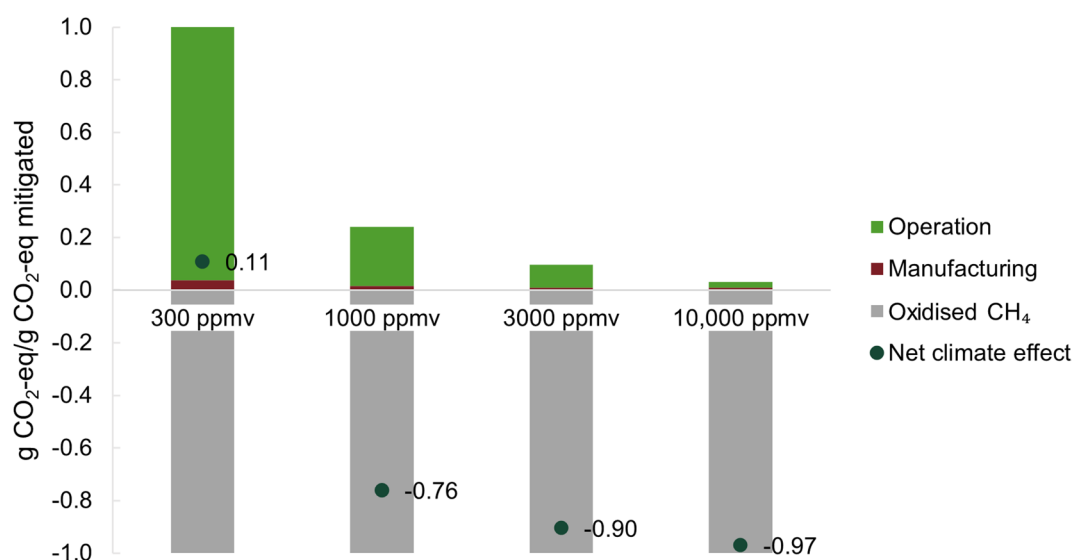


Fig. 2. The climate effect of processes necessary for oxidising CH_4 as well as the net effect. The study is designed to remove an equivalent amount of CH_4 in each scenario but at different concentrations, hence the grey bar has the same value for all four studied scenarios.

CH ₄ concentration (ppmv)	300	1000	3000	10,000
Net climate effect (CH ₄ conversion)	+0.11	-0.76	-0.90	-0.97
Manufacturing (CCS)	+0.0057	+0.013	+0.0083	+0.016
Operation (CCS)	+0.011	+0.13	+0.057	+0.00057
Transport and storage (CCS)	+0.015	+0.011	+0.0097	+0.0092
Stored CO ₂	-0.21	-0.15	-0.13	-0.13
Net climate effect (co-removal)	+0.14	-0.62	-0.83	-0.94
Change in GWP (absolute)	+0.073	+0.18	+0.15	+0.10
Change in GWP (relative)	+65%	+24%	+17%	+11%
Change in PED (relative)	+2%	+51%	+82%	+59%

Table 1. Changes in climate effect (g CO₂-eq emitted/g CO₂-eq removed) and PED for co-removal compared to CH₄ conversion.

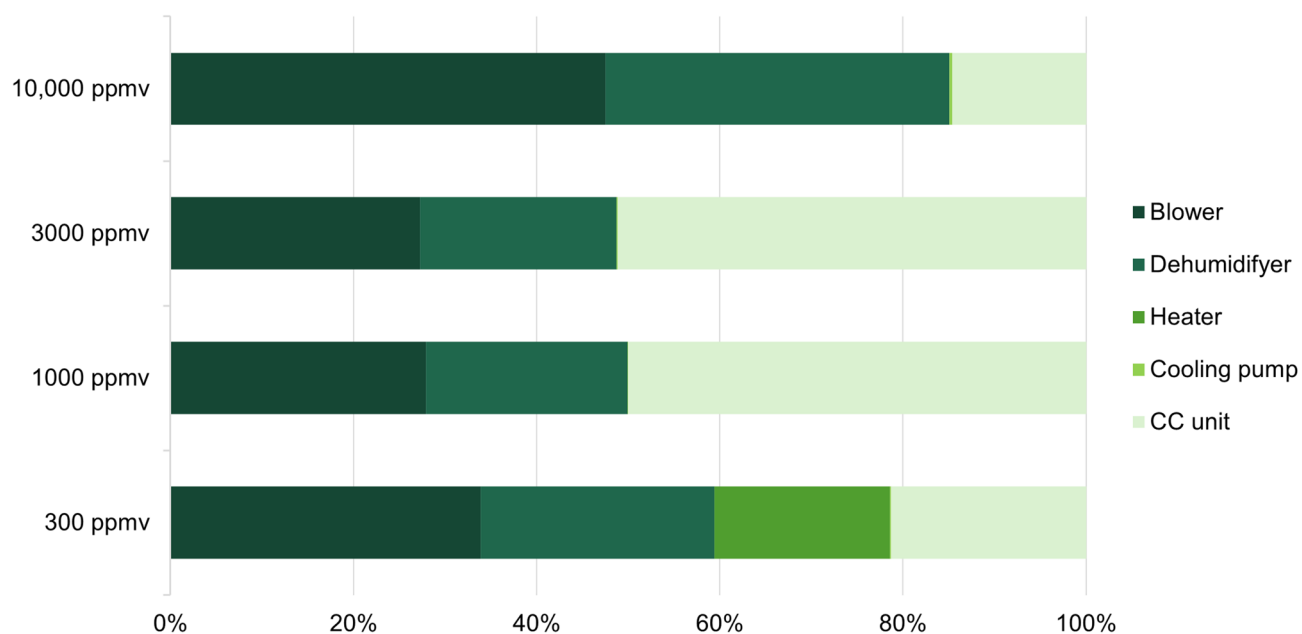


Fig. 3. The share of primary energy demand when operating the CH₄ oxidation and CO₂ capture processes at the four studied CH₄ concentrations, divided between the energy using components.

The CO₂ capture process required additional energy use, which was especially visible for the medium concentrations (Fig. 3). The PED for the CO₂ capture process was highly dependent of the concentration of both CH₄ and CO₂. At the highest CH₄ concentration, the energy generated from the CH₄ oxidation reaction could be utilized in the amine regeneration, lowering the need for additional heat.

The manufacturing of the CO₂ capture components added a considerable contribution to the overall manufacturing emissions, around 40% for all three cases (Fig. S6 in SM).

Sensitivity analysis

The following results are for the sensitivity analyses performed for the CH₄ conversion scenario. Results for sensitivity analyses for the co-removal scenario can be found in the SM (Figs. S9 and S11).

Energy source

In a sensitivity analysis, the impact of using different emission factors and PEFs for electricity was evaluated. The European mix used in the main scenario was exchanged for natural gas power and a Nordic consumption mix. A comparison shows this had a determining effect on the net CE for the low CH₄ concentration (Fig. 4), while the impact is more modest for the higher CH₄ concentration.

The primary energy factor differs between the different electricity sources, which affects the PED. For the natural gas, this leads to a PED decrease of between 8.0 and 11%; for the Nordic mix, the PED decrease was between 23 and 25%.

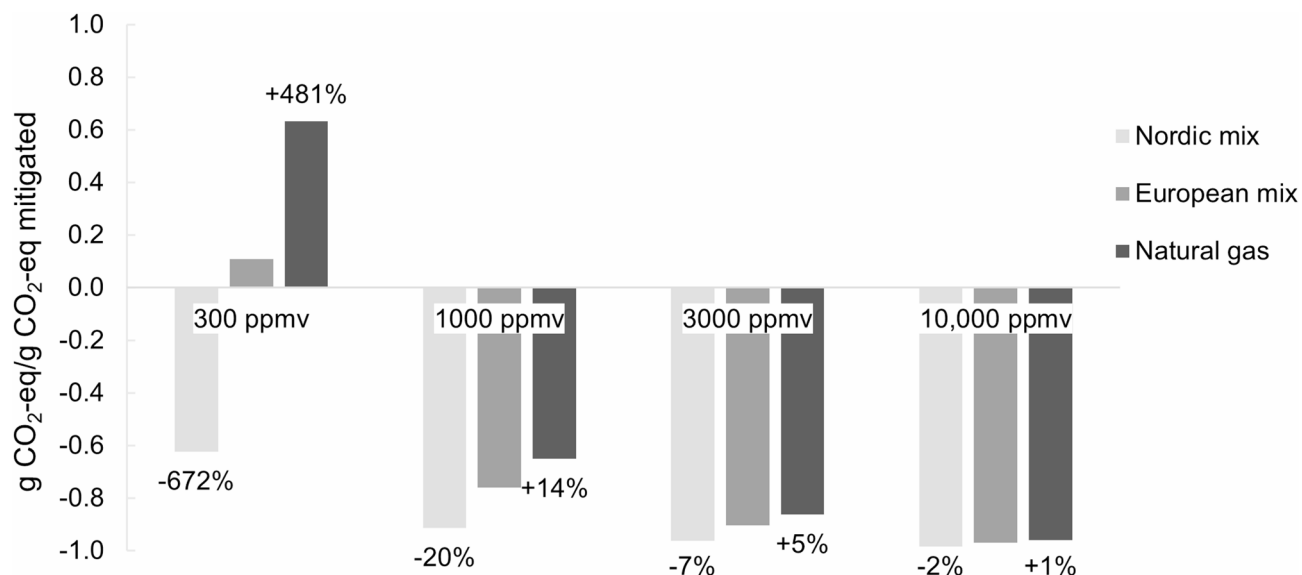


Fig. 4. Sensitivity analysis for the impact of emissions factor for electricity on the net climate effect for CH₄ conversion at the four studied CH₄ concentrations. The data labels show the relative increase/decrease compared to the main scenario (European mix).

Climate metrics

A sensitivity analysis for the impact of the choice of climate metric was evaluated, highlighting GWP20 and GWP500 in comparison to the main case which uses GWP100 (Fig. 5). The shorter the chosen time horizon for the metric, the better the system performance appears. At the low CH₄ concentration, the system net CE varies greatly depending on the metric used. For the medium and high CH₄ concentrations, the impact is visible but more modest.

The GWP reduction for the process was shared by CH₄ and CO₂. With the use of the different metric time horizons, the relative contribution of each gas varied (Fig. 6).

The climate metric affects the functional unit, which in turn affects the results for PED. In these two cases, the change would be a 66% decrease in PED per g CO₂-eq mitigated for GWP20, and a 275% increase for GWP500.

Through a combined analysis of electricity emissions factor and climate metric, an interval of the CE of the technology under different conditions and assumptions can be identified (Figs. S10 and S11).

Discussion

The results confirmed that the CH₄ concentration was the most influential factor for the net CE of the system. It was inversely proportional to the energy demand for operation due to the large volumes of air being treated per gain in reduced climate impact at low concentrations of CH₄ (i.e. the relation between the number of molecules of H₂O to remove and N₂ molecules to heat compared to CH₄ oxidised). The net CE was positive (Fig. 2) at the lowest CH₄ concentration modelled in this study (300 ppmv), i.e. the CH₄ conversion process contributed to global warming from a life cycle perspective much due to the GHG emissions from operation, outweighing the gain from the oxidised CH₄. However, a sensitivity analysis highlighted the importance of increasing the share of renewable energy sources, as switching to a renewable electricity mix (modelled as the current consumption mix of the Nordic countries) improved the net GWP more than 6 times compared to the European mix (Fig. 4). This resulted in a net negative CE also for the lowest CH₄ concentration. The impact of the electricity mix was especially clear at the low CH₄ concentration due to its high energy demand. For CH₄ concentrations from 1000 to 10,000 ppmv, a net-negative CE could be reached even with natural gas-powered electricity, although at worsened net CE. A higher share of renewables also lowered the PED as these energy sources have lower primary energy factors than fossil energy sources.

To evaluate and compare the climate impact of emitting or mitigating GHGs, a conversion metric must be chosen. The GWP100 is the most widespread metric used in both policy and science, although it has long been criticised for not fairly representing the actual temperature response, especially underestimating short term effects caused by, for example, CH₄ e.g. in^{6,56,57}. The sensitivity analysis of the climate metric (Fig. 5) illustrates how a shorter time horizon weights the impact of CH₄ mitigation more than a longer time horizon. GWP20 emphasises the impact of mitigating the short-term effects of CH₄, resulting in net-negative CE for all three concentrations, both with and without CO₂ capture. GWP500 instead put more emphasis on the long-term impact of CO₂, giving a clear lowering of the net CE compared to the GWP100 results.

Due to the strong warming effect of CH₄ compared to CO₂, no matter the metric used in this study, avoiding the impact of CH₄ played a decisive role compared to the benefits of also capturing the subsequent CO₂, ranging from around 50% of the total climate benefit attributed to CH₄ and 50% from CO₂ for GWP500 to 92% for CH₄ and 8% for CO₂ for GWP20 (Fig. 6). No matter the concentration and metric, the net CE decreased when

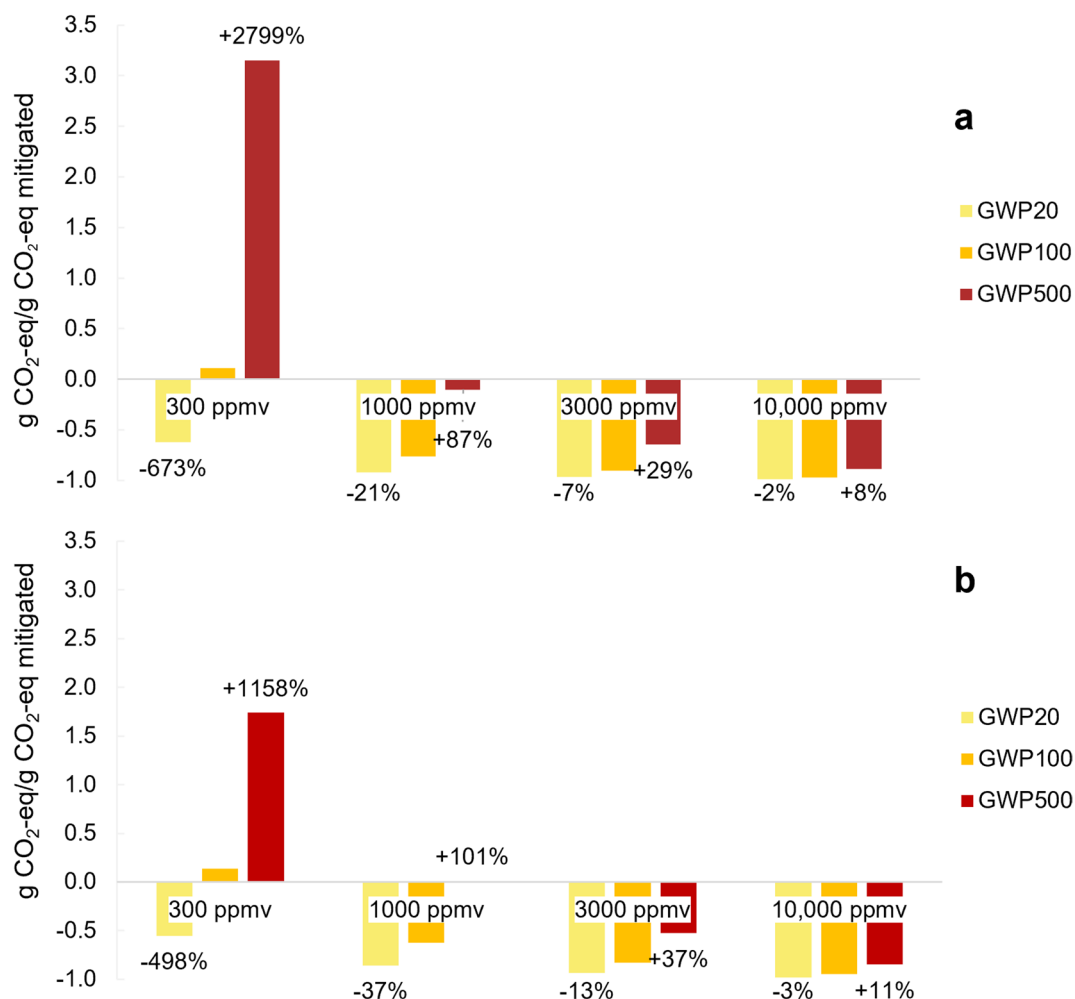


Fig. 5. Sensitivity analysis highlighting the choice of metric on the net climate effect for CH₄ oxidation at the four modelled CH₄ concentrations. The data labels show the relative increase/decrease compared to the main scenario (GWP100). CH₄ conversion (**a**) and co-removal (**b**).

CO₂ capture was introduced due to the additional energy (Table 1) and material demand compared to sole CH₄ oxidation. However, depending on the studied timescale, the prioritisation between CH₄ and CO₂ could differ, as targeting CH₄ emissions could deliver significant short-term effects. From a longer time perspective, however, the accumulation of CO₂ in the atmosphere is what will largely determine the level the mean global temperature will reach and remain at due to its longer residence time⁵⁸.

The study identified the blower, the dehumidifier and the catalyst demand as important hotspots for both energy demand and CE (Fig. 3). Since the process energy had such a major impact on the overall result, especially at low concentrations, technological improvements could have a substantial effect on overall performance and feasibility. Energy demand for the blower can be reduced by minimizing pressure drops throughout the process. The development of a less water-inhibited catalyst material with a lower carbon footprint would improve the system CE directly at the manufacturing stage (Figs. S6 & S7 in SM) and indirectly by reducing or eliminating the need for the energy demanding dehumidification step. Palladium minerals are rare and have wide uses, from catalysts to jewellery, electronics and fuel cells. Hence, like with other metals important for the green transition, there are risks such as rising prices and tightened supply in the future⁵⁹. Furthermore, a lower minimum temperature difference in the recuperator could reduce the energy demand, although this would increase the heat transfer area of the recuperator. As part of the PED for operation consists of thermal energy, it may be possible to connect a secondary renewable energy source or waste heat to improve the net CE. All these aspects are especially pronounced at low CH₄ concentrations due to the high energy and raw material demand per CO₂-eq mitigated.

For manure storage, the CH₄ emissions at each moment in time vary based on a number of factors. As this is expected to impact the operation of the machinery as well as system efficiency and subsequent energy use, we chose to conduct this study as a snapshot of a moment in time with static conditions, with the four studied concentrations covering a large interval of conditions. This approach was an attempt to decrease complexity and be able to perform initial evaluation and information gathering on the most important parameters affecting strategies for design and operation of this novel system. Under practical operating conditions, manure level,

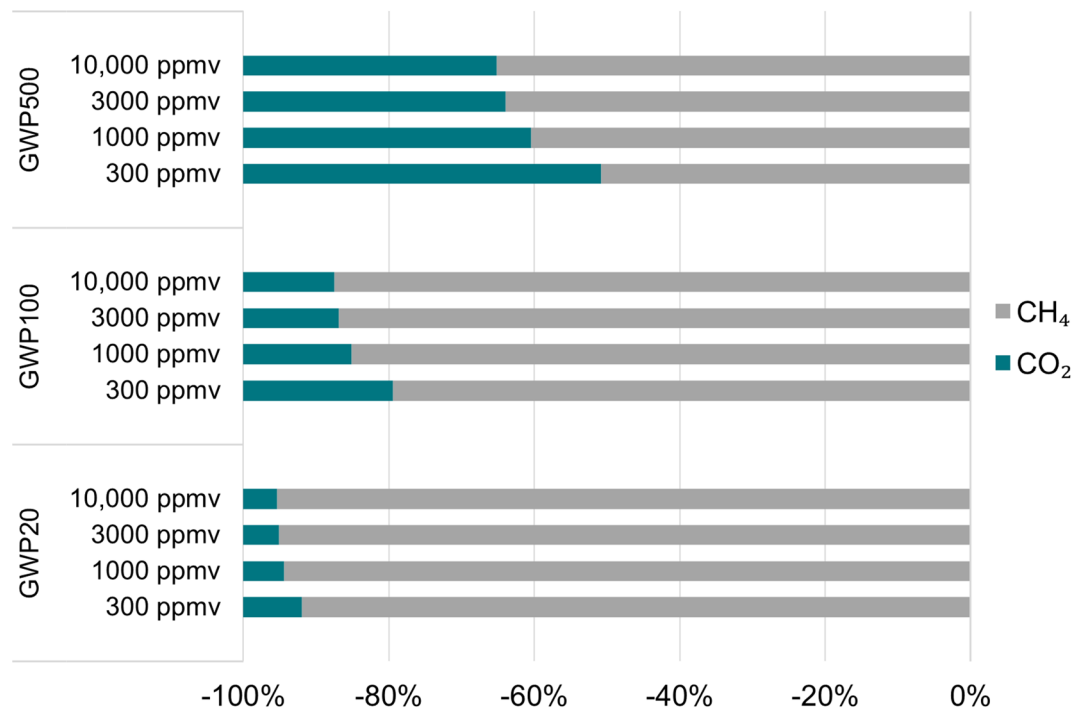


Fig. 6. The achieved climate benefit of the co-removal is shared by CO₂ and CH₄. The figure shows the relative contribution of each gas at the four CH₄ concentrations modelled using different climate metrics.

outdoor temperature and energy source would have a decisive impact on the net CE. The rate of CH₄ emitted is closely linked to the storage temperature, and the relatively large energy demand for operation constituted a noticeable impact on the net CE. Therefore, one could expect that this type of system would deliver the largest climate benefits if implemented in parts of the world with a warm climate and a substantial renewable electricity supply, and on farms with large herds of livestock and effective manure collection systems. The larger the share of manure collected, the greater the climate benefit that could be achieved for the investment per animal. It is also vital that the entire value chain required for CH₄ oxidation and CO₂ capture and storage can be carried out with a minimum of GHG slip and performed in a climate friendly and energy efficient manner to reach the highest possible total climate benefit and maintain high credibility for the GGR concept.

This study evaluated the technology from the perspectives of PED and CE. However, other types of environmental impacts may also be relevant. The MEA used for CO₂ capture is toxic and acidic, posing risks to organisms and the local environment⁶⁰. CO₂ capture and exhaust cooling also require water, which can increase freshwater consumption. On the positive side, the technology may reduce NH₃ emissions, as part of the ammonia dissolves in the condensate from the dehumidifier. This may help mitigate e.g. acidification, aerosol formation and odour. Indirect environmental effects may also occur elsewhere or over time — for example, from aluminium and palladium mining, which can involve hazardous chemicals, affect human health, and contribute to land use change and biodiversity loss. These potential impacts warrant further investigation and quantification in future studies.

Considering the promising net CE presented in this study, it seems reasonable to continue exploring technologies for the conversion of CH₄ with and without subsequent CO₂ capture to analyse its prospects for implementation under different conditions, such as scale, location and CH₄ concentration. Some relevant research topics for future studies could be investigating practical constraints on the equipment and materials, techno-economic analysis, and experimentation to confirm modelling results. There are also options to increase system efficiency and increased systems integration through, for example, carbon capture and utilisation. In the future, more detailed case studies that examine feasibility under certain conditions with more case specific and time-dynamic data for a particular application should be used, whether it be manure storage or some other unabated CH₄ emissions source.

The low CH₄ concentrations analysed in this study could allow for the targeting of emission sources where GGR has not been considered previously, such as the agrifood sector, which accounts for over half of overall CH₄ emissions. There is currently no technology to completely eliminate non-CO₂ GHG emissions from agriculture, and improvements in carbon efficiency and emission reduction measures risk being partly counteracted by the increased primary production demand necessary for feeding an increasing world population⁶¹. The burden on reduced GHG emissions in other sectors would increase unless unabated agricultural emissions could be sequestered or compensated for through additional GGR. Further research on ways to reduce global warming via CH₄ could improve the technology used and identify the most promising areas of implementation to maximise efficiency.

Conclusions

This study presents a thermal catalytic technology capable of delivering climate mitigation by oxidising low-concentration CH₄ emissions, below the point of ignition, with and without subsequent CO₂ capture and storage. The results showed that the PED was highly dependent on the CH₄ concentration. At 300 ppmv CH₄, the process yielded a slightly positive net climate effect, but achieved a net-negative climate effect at CH₄ concentrations of 1000 ppmv and above. The prominent impact of the process energy demand rendered the energy source decisive. When the assumed European electricity mix was replaced with a lower-emission Nordic mix, a net-negative climate effect was reached at all four studied CH₄ concentrations. Changing the climate metrics from GWP100 to GWP20 also led to net-negative results across all concentrations, as it emphasises the short-term warming impact of CH₄. At CH₄ concentrations above 3000 ppmv, a lower energy demand in combination with the increasing feasibility of utilising excess heat from the CH₄ conversion process enabled net-negative effects even with natural gas operation, and regardless of the climate metric. Nonetheless, using a low emissions energy and a high energy efficiency is key to maximise the benefit and credibility of the technology avoid wasting limited renewable energy resources on GGR.

Adding CO₂ co-removal and storage worsened the net climate effect at all concentrations due to increased PED and the dominant short-term impact of CH₄ conversion. Targeting the most concentrated CH₄ emission sources possible is thus the most energy efficient approach. However, system improvements- such as reducing pressure drops in the blower and dehumidifier and developing more durable, low-footprint catalysts- could further increase energy efficiency. Such developments would increase the system efficiency to reach net-negative climate effect at even lower CH₄ concentrations, thus allowing catalytic conversion of CH₄ to target and efficiently abate a wider range of CH₄ emission sources.

Data availability

Supplementary material associated with this article can be found in the online version.

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References

1. Rueda, O., Mogollón, J. M., Tukker, A. & Scherer, L. Negative-emissions technology portfolios to Meet the 1.5°C target. *Glob. Environ. Change*. **67**, 102238. <https://doi.org/10.1016/j.gloenvcha.2021.102238> (2021).
2. Lund, J. F., Markusson, N., Carton, W. & Buck, H. J. Net zero and the unexplored politics of residual emissions. *Energy Res. Social Sci.* **98**, 103035. <https://doi.org/10.1016/j.erss.2023.103035> (2023).
3. FAO. FAOSTAT: Emission totals. (2024).
4. Gálfaik, M., Olofsson, G., Crill, P. & Bastviken, D. Making methane visible. *Nat. Clim. Change*. **6**, 426–430. <https://doi.org/10.1038/nclimate2877> (2016).
5. Abernethy, S., Kessler, M. I. & Jackson, R. B. Assessing the potential benefits of methane oxidation technologies using a concentration-based framework. *Environ. Res. Lett.* **18**, 094064. <https://doi.org/10.1088/1748-9326/acf603> (2023).
6. Brazzola, N., Wohland, J., Patt, A. & Correction Offsetting unabated agricultural emissions with CO₂ removal to achieve ambitious climate targets. *PLOS ONE*. **16**, e0259548. <https://doi.org/10.1371/journal.pone.0259548> (2021).
7. Minx, J. C. et al. Negative emissions—Part 1: research landscape and synthesis. *Environ. Res. Lett.* **13** <https://doi.org/10.1088/1748-9326/aabf9b> (2018).
8. Goglio, P. et al. 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> (2020).
9. Jackson, R. B. et al. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environ. Res. Lett.* **15**, 071002. <https://doi.org/10.1088/1748-9326/ab9ed2> (2020).
10. Dreyfus, G. B., Xu, Y., Shindell, D. T., Zaelke, D. & Ramanathan, V. Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming. *Proc. Natl. Acad. Sci.* **119** (e2123536119). <https://doi.org/10.1073/pnas.2123536119> (2022).
11. Olczak, M., Piebalgs, A. & Balcombe, P. A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness. *One Earth*. **6**, 519–535. <https://doi.org/10.1016/j.oneear.2023.04.009> (2023).
12. Karacan, C. Ö. et al. Mitigating climate change by abating coal mine methane: A critical review of status and opportunities. *Int. J. Coal Geol.* **295**, 104623. <https://doi.org/10.1016/j.coal.2024.104623> (2024).
13. Wang, Y. et al. Atmospheric removal of methane by enhancing the natural hydroxyl radical sink. *Greenh. Gases Sci. Technol.* **12**, 784–795. <https://doi.org/10.1002/ghg.2191> (2022).
14. Ming, T., Richter, R., Oeste, D., Tulip, F., Caillol, S. & R. A nature-based negative emissions technology able to remove atmospheric methane and other greenhouse gases. *Atmospheric Pollution Res.* **12**, 101035. <https://doi.org/10.1016/j.apr.2021.02.017> (2021).
15. de_Richter, R., Ming, T., Davies, P., Liu, W. & Caillol, S. Removal of non-CO₂ greenhouse gases by large-scale atmospheric solar photocatalysis. *Prog. Energy Combust. Sci.* **60**, 68–96. <https://doi.org/10.1016/j.pecs.2017.01.001> (2017).
16. Ming, T. et al. Perspectives on removal of atmospheric methane. *Adv. Appl. Energy*. **5**, 100085. <https://doi.org/10.1016/j.adapen.2022.100085> (2022).
17. Meng, X. et al. Direct methane conversion under mild condition by Thermo-, Electro-, or photocatalysis. *Chem* **5**, 2296–2325. <https://doi.org/10.1016/j.chempr.2019.05.008> (2019).
18. Lackner, K. S. Practical constraints on atmospheric methane removal. *Nat. Sustain.* **3**, 357–357. <https://doi.org/10.1038/s41893-020-0496-7> (2020).
19. Duan, H. et al. Catalytic combustion of methane over noble metal catalysts. *ACS Catal.* **14**, 17972–17992. <https://doi.org/10.1021/acscatal.4c05650> (2024).
20. Feng, X. et al. Progress and key challenges in catalytic combustion of lean methane. *J. Energy Chem.* **75**, 173–215. <https://doi.org/10.1016/j.jechem.2022.08.001> (2022).
21. Zhang, X. et al. Progress and challenges of spinel materials for catalytic combustion of methane. *Fuel* **379**, 133090. <https://doi.org/10.1016/j.fuel.2024.133090> (2025).
22. Sirigina, D. S. S., Goel, A. & Nazir, S. M. Process concepts and analysis for co-removing methane and carbon dioxide from the atmosphere. *Sci. Rep.* **13**, 17290. <https://doi.org/10.1038/s41598-023-44582-w> (2023).
23. FAO. Greenhouse gas emissions from agrifood systems 2000–2020. Report No. No. 50. (2022).

24. Lan, X., Nisbet, E. G., Dlugokencky, E. J. & Michel, S. E. What do we know about the global methane budget? Results from four decades of atmospheric CH₄ observations and the way forward. *Philosophical Trans. Royal Soc. A: Math. Phys. Eng. Sci.* **379**, 20200440. <https://doi.org/10.1098/rsta.2020.0440> (2021).
25. Jackson, R. B. et al. Atmospheric methane removal: a research agenda. *Philosophical Trans. Royal Soc. A: Math. Phys. Eng. Sci.* **379**, 20200454. <https://doi.org/10.1098/rsta.2020.0454> (2021).
26. Stolaroff, J. K. et al. Review of methane mitigation technologies with application to rapid release of methane from the Arctic. *Environ. Sci. Technol.* **46**, 6455–6469. <https://doi.org/10.1021/es204686w> (2012).
27. Im, S., Petersen, S. O., Lee, D. & Kim, D. H. Effects of storage temperature on CH₄ emissions from cattle manure and subsequent biogas production potential. *Waste Manage.* **101**, 35–43. <https://doi.org/10.1016/j.wasman.2019.09.036> (2020).
28. Rodhe, L. K. K., Abubaker, J., Ascue, J., Pell, M. & Nordberg, Å. Greenhouse gas emissions from pig slurry during storage and after field application in Northern European conditions. *Biosyst. Eng.* **113**, 379–394. <https://doi.org/10.1016/j.biosystemseng.2012.09.010> (2012).
29. Smith, P., Reay, D. & Smith, J. Agricultural methane emissions and the potential for mitigation. *Philosophical Trans. Royal Soc. A: Math. Phys. Eng. Sci.* **379**, 20200451. <https://doi.org/10.1098/rsta.2020.0451> (2021).
30. Im, S., Mostafa, A. & Kim, D. H. Use of citric acid for reducing CH₄ and H₂S emissions during storage of pig slurry and increasing biogas production: Lab- and pilot-scale test, and assessment. *Sci. Total Environ.* **753**, 142080. <https://doi.org/10.1016/j.scitotenv.2020.142080> (2021).
31. Gerber, P. J. et al. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. *Animal* **7**, 220–234. <https://doi.org/10.1017/S1751731113000876> (2013).
32. Ericsson, N., Nordberg, Å. & Berglund, M. Biogas plant management decision support – A temperature and time-dependent dynamic methane emission model for digestate storages. *Bioresource Technol. Rep.* **11**, 100454. <https://doi.org/10.1016/j.biteb.2020.100454> (2020).
33. Mundra, I. & Lockley, A. Emergent methane mitigation and removal approaches: A review. *Atmospheric Environment: X*. **21**, 100223. <https://doi.org/10.1016/j.aeaoa.2023.100223> (2024).
34. Godin, J., Liu, W., Ren, S. & Xu, C. C. Advances in recovery and utilization of carbon dioxide: A brief review. *J. Environ. Chem. Eng.* **9**, 105644. <https://doi.org/10.1016/j.jece.2021.105644> (2021).
35. Fasihi, M., Efimova, O. & Breyer, C. 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> (2019).
36. Terlouw, T., Bauer, C., Rosa, L. & Mazzotti, M. Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy Environ. Sci.* **14**, 1701–1721. <https://doi.org/10.1039/D0EE03757E> (2021).
37. Johannisson, J. & Hiete, M. Exploring the photocatalytic total oxidation of methane through the lens of a prospective LCA. *Atmospheric Environment: X*. **16**, 100190. <https://doi.org/10.1016/j.aeaoa.2022.100190> (2022).
38. Ecoinvent (ed). (ed ecoQuery) (2025).
39. Deutz, S. & Bardow, A. Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption. *Nat. Energy*. **6**, 203–213. <https://doi.org/10.1038/s41560-020-00771-9> (2021).
40. IPCC. Assessment report 6. Chap. 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. (2021).
41. Bastos, J. L. V., Muntean, E., Duerr, M., Kona, M. & Bertoldi, A. Paolo. (European commission, Joint Research Centre (JEC), 2020).
42. Cogen Europe, E. U. Primary energy factor for electricity: key to ensure well-informed choices, achieve real energy savings and reduce consumer energy bills. (2017).
43. Quaschnig, V. *Specific Carbon Dioxide Emissions of Various Fuels* https://www.volker-quaschnig.de/datserv/CO2-spez/index_e.php (2022).
44. Sandgren, A. & Nilsson, J. Emissionsfaktor för Nordisk Elmix med hänsyn till import och export - Utredning av lämplig systemgräns för Elmix Samt beräkning av Det Nordiska elsystemets klimatpåverkan. [eng: *emission factors for nordic electricity mix with import and export taken into account*] (2021).
45. Sweco Carbon intensity and primary energy factors. (2021).
46. Andersson, E. et al. Rekommendationer för gödsling och Kalkning 2025 [eng: *recommendations for fertilization and liming 2025*]. *Rep. No JO*. **24**, 10 (2025). (Jönköping, Sverige).
47. IPCC. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 10: Emissions from Livestock and Manure Management. (2019).
48. Grant, R. H., Boehm, M. T. & Bogan, B. W. Methane and carbon dioxide emissions from manure storage facilities at two free-stall dairies. *Agric. For. Meteorol.* **213**, 102–113. <https://doi.org/10.1016/j.agrformet.2015.06.008> (2015).
49. Bromark, E., Tidåker, P., Nordberg, Å. & Hansson, P. A. To what extent can small-scale bio-CCS from biogas upgrading contribute with net-negative emissions? <https://doi.org/10.2139/ssrn.5544365> (2025).
50. Alyani, M. & Smith, K. J. Kinetic analysis of the inhibition of CH₄ oxidation by H₂O on PdO/Al₂O₃ and CeO₂/PdO/Al₂O₃ catalysts. *Ind. Eng. Chem. Res.* **55**, 8309–8318. <https://doi.org/10.1021/acs.iecr.6b01881> (2016).
51. Campo, M. C. et al. Carbon dioxide removal for methane upgrade by a VSA process using an improved 13X zeolite. *Fuel Process. Technol.* **143**, 185–194. <https://doi.org/10.1016/j.fuproc.2015.11.024> (2016).
52. Kiani, A., Jiang, K. & Feron, P. Techno-economic assessment for CO₂ capture from air using a conventional liquid-based absorption process. *Front. Energy Res.* **8** 2020 (2020).
53. Sabatino, F. et al. A comparative energy and costs assessment and optimization for direct air capture technologies. *Joule* **5**, 2047–2076. <https://doi.org/10.1016/j.joule.2021.05.023> (2021).
54. Terlouw, T., Treyer, K., Bauer, C. & Mazzotti, M. Life cycle assessment of direct air carbon capture and storage with Low-Carbon energy sources. *Environ. Sci. Technol.* **55**, 11397–11411. <https://doi.org/10.1021/acs.est.1c03263> (2021).
55. Abanades, J. C., Rubin, E. S. & Anthony, E. J. Sorbent cost and performance in CO₂ capture systems. *Ind. Eng. Chem. Res.* **43**, 3462–3466. <https://doi.org/10.1021/ie049962v> (2004).
56. Cain, M. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *Npj Clim. Atmospheric Sci.* **2**, 29. <https://doi.org/10.1038/s41612-019-0086-4> (2019).
57. Nisbet, E. G. et al. Very strong atmospheric methane growth in the 4 years 2014–2017: implications for the Paris agreement. *Glob. Biogeochem. Cycles*. **33**, 318–342. <https://doi.org/10.1029/2018GB006009> (2019).
58. Allen, M. R. et al. Net zero: Science, Origins, and implications. *Annu. Rev. Environ. Resour.* **47**, 849–887. <https://doi.org/10.1146/aannurev-environ-112320-105050> (2022).
59. Andersen, E. V. et al. The vulnerability of shifting towards a greener world: the impact of the eu's green transition on material demand. *Sustainable Horizons*. **10**, 100087. <https://doi.org/10.1016/j.horiz.2023.100087> (2024).
60. Karl, M., Wright, R. F., Berglen, T. F. & Denby, B. Worst case scenario study to assess the environmental impact of amine emissions from a CO₂ capture plant. *Int. J. Greenhouse Gas Control*. **5**, 439–447. <https://doi.org/10.1016/j.ijggc.2010.11.001> (2011).
61. Tanzer, J. & Hermann, L. *Sustainable and Circular Management of Resources and Waste towards a Green Deal*. (eds Majeti Narasimha Vara Prasad and Marzena Smol) 285–296 (Elsevier, 2023).

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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