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Environmental performance of biomethanation based on life cycle assessment

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ABSTRACT

Climate change has recently had a significant impact on the environment, necessitating a shift from fossil-based to renewable energy sources. A promising long-term storage solution for renewable energy is the production of hydrogen through electrolysis, known as green hydrogen. This hydrogen can be utilized in Power-to-X applications, such as power-to-gas, where captured CO_2 is used for methanation with hydrogen. Employing biomethane in place of natural gas in the transportation sector can significantly reduce greenhouse gas emissions. There is a research gap in the absence of comprehensive LCA studies comparing in-situ and ex-situ biomethanation processes with traditional biogas upgrading methods. The aim of the study is to evaluates the environmental performance of using hydrogen in in-situ and ex-situ biomethanation to increase methane content in biogas for heavy-duty vehicles, comparing these methods with traditional membrane separation upgrading. Through LCA, the climate change impact shows a 52 % reduction in emissions for membrane separation compared to fossil-based scenarios. Ex-situ biomethanation results in a 44%–54 % reduction, while in-situ biomethanation achieves 43%–53 %, depending on the electricity source for hydrogen production. Acidification and marine eutrophication impacts are higher in alternatives using grid electricity, while freshwater eutrophication stems from solar-powered hydrogen electrolysis. These findings underscore the importance of integrating renewable energy sources and advanced biogas upgrading techniques to achieve significant environmental benefits. The novelty of this research lies in its comprehensive LCA comparing traditional and innovative biogas upgrading technologies, providing valuable insights for future energy and environmental strategies.

1. Introduction

Climate change has recently had a significant impact on the environment. The most known impacts international and domestic effects include irregular weather patterns, retreating global ice sheets, and rising sea levels [1]. Annually, around 34 billion tons of carbon dioxide equivalence greenhouse gases are emitted from burning fossil fuels to generate electricity globally [2]. One way to address this problem is by switching from fossil-based energy to renewable energy [3]. Renewable energy sources, such as wind and solar, are inherently fluctuating, necessitating energy storage solutions to mitigate supply fluctuations and enhance grid flexibility [4].

A promising long-term storage solution for renewable energy is the production of hydrogen through electrolysis, known as green hydrogen, which has a much smaller climate impact compared to conventional hydrogen production [5]. This stored hydrogen can be used in Power-to-X applications to produce various synthetic fuels, including synthetic natural gas, synthetic methanol, synthetic ammonia, and other synthetic chemicals [6]. In these applications, one option is power-to-gas, where captured CO_2 from various sources can be used for methanation with hydrogen [7]. Power-to-gas can provide large-scale and long-term energy storage, especially as the share of renewable energy in the system increases [8]. Renewable gases, such as biomethane or synthetic methane, play an important role in achieving net-zero greenhouse gas emission in EU by 2050, utilizing the existing natural gas infrastructure [9]. The Gas for Climate 2050 report states that approximately 141 billion cubic meters of biomethane will be available

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Nomenclature

AD	Anaerobic digestion
AEL	Alkaline electrolyser
CH_4	Methane
CO_2	Carbon dioxide
Eq	Equivalence
EU	European Union
GWh	Gigawatt hour
GWP	Global warming potential
H_2	Hydrogen
K	Potassium
LCA	Life cycle assessment
LHV	Lower heating value
N	Nitrogen
N_2O	Nitrogen peroxide
NO_x	Nitrogen oxide
P	Phosphorus
PEM	Polymer electrolyte membrane
SR	Sensitivity ratio

by 2050 [10]. Methanation can be achieved through two methods: chemical methanation and biological methanation.

Anaerobic digestion (AD) is a process that uses microorganisms to convert organic compounds into biogas. Biogas usually contains 35–40 % CO_2, 60–65 % CH_4, and 1–5% impurities. Biogas is a one possible feedstock for biomethanation process [11]. Biogas can be upgraded by increasing the methane content through the removal of CO_2 using water scrubbing, membrane upgrading, pressure swing adsorption, amine scrubbing, cryogenic separation, and other technologies [12]. It is possible to achieve 99 % methane purity from membrane separation technology [13]. LCA studies have been done on traditional upgrading method which shows that using upgraded biogas have better environmental performance compared to combustion of natural gas [14,15].

Microorganisms act as catalysts for biomethanation where hydrogen and carbon dioxide present in biogas are converted to methane [16]. It can be achieved by using a separate reactor (ex-situ), or by adding hydrogen directly to the AD reactor (in-situ). Study by Elyasi et al. (2021) [11], shows that biomethanation with hydrogen has better environmental performance than water scrubbing. Previous study has examined the LCA of biogas with carbon capture and storage (CCS) and carbon capture and utilization (CCU). The study highlights the separation of CO_2 using different technologies, such as amine scrubbing and water scrubbing. It also explores the utilization of CO2 by selling it to various companies or using it for the ex-situ methanation process [17].

Earlier research has focused on comparing the environmental impacts of various CO_2 separation methods and the ex-situ biomethanation of biogas. However, the research gap lies in the lack of comprehensive LCA studies that directly compare in-situ and ex-situ biomethanation processes with conventional biogas upgrading technologies. The novelty of this study lies in performing LCA on both in-situ and ex-situ biomethanation and comparing them with conventional biogas upgrading. The aim is to quantify the environmental performance of utilizing hydrogen either in in-situ or ex-situ biomethanation to increase the methane content of biogas for use in heavy-duty vehicles and to compare this performance with traditional membrane separation upgrading technology.

2. Materials and methods

In this study, evaluation of the environmental performance of both in-situ and ex-situ biomethanation through the implementation of the Life Cycle Assessment (LCA) method is conducted. LCA is a systematic method used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle (ISO standard 14044–14044:2006) from all the stages of a product's life, from raw material extraction through materials processing, manufacturing, distribution and disposal [18,19]. This approach ensures a comparable and reliable assessment of the environmental impact of biomethanation processes.

The LCA performed in this study is on SPHERA's LCA for Expert software, version 10.8.0.14. The inventory in the LCA for Expert software includes data from the database covering the period from 1992 to 2024. The selected life cycle impact assessment (LCIA) method used is ReCiPe 2016 midpoint (H). The inventory database for GABI can be found in supplementary material (SM) under background systems sheet (table 6.1) and is also available on Sphera website [20].

2.1. Goal and scope

The goal of this study is to compare the environmental performance of biomethanation of biogas with both in-situ and ex-situ biomethanation and compare the performance with membrane upgrading and with the base case where biogas is used in Combined Heat and Power (CHP). The LCA employed in this study focuses on the cradle-to-grave perspective, encompassing the entire biomethanation production process till the end-use phase of biomethane in vehicles.

In LCA, the outcome of each product system is measured and quantified using a functional unit, which allows for the comparison of different scenarios. The selected functional unit for this study is the output product of waste treatment and methane, produced electricity and heat and used N, P and K fertilizer as shown in Table 1. The functional unit in this study is defined such that the same amount of waste treatment, heat, electricity, methane, and nutrients are the outcomes for all scenarios to ensure a fair comparison.

The investigated impact categories in this study are climate change, acidification, and eutrophication (both fresh water and marine). The selection of these impact categories was made because climate change is an important category for showing the global impact of releasing greenhouse gases. The acidification impact category was selected due to the inclusion of fuel combustion in the scenarios, especially in trucks utilizing methane-containing gases. The eutrophication impact category is vital for demonstrating the impacts of spreading nutrients on fields in

Table 1
Functional unit.

Mass flows (S0, S1, S2, S3)		
Input feedstock	33 400	t/a
Output digestate		
N	242 000	kg/a
P	27 261	kg/a
K	61 000	kg/a
Incineration of reject waste (S0, S1, S2, S3)		
Mass	33 400	t/a
Electricity	1 144 000	MJ/a
Heat	13 000 000	MJ/a
CHP (S0)		
Biogas	4 195 000	Kg
Electricity	46 900 000	MJ/a
Heat	134 000 000	MJ/a
Additional energy (S1, S2, S3)		
Grid electricity	46 900 000	MJ/a
Biomass district heat	134 000 000	MJ/a
Methane used in trucks (S0, S1, S2, S3)		
Natural gas (S0)	124 000 000	MJ/a
Biomethane (S0)	0	MJ/a
Natural gas (S1)	42 000 000	MJ/a
Biomethane (S1)	82 000 000	MJ/a
Natural gas (S2)	0	MJ/a
Biomethane (S2)	124 000 000	MJ/a
Natural gas (S3)	4 000 000	MJ/a
Biomethane (S3)	120 000 000	MJ/a

the form of mineral fertilizers and digestate. To assess the long-term climate impacts, global warming potentials (GWP100) is considered.

2.2. System boundary

The studied system boundary is shown in Fig. 1. Waste collection is excluded from the system boundary. However, the initial stage of waste transfer from collection points to the biogas plant is considered within the system boundary. The studied system begins with the transport of waste to the plant for pretreatment, where rejected waste is utilized to produce heat and electricity in a waste-to-energy plant. The remaining waste then undergoes anaerobic digestion to produce biogas. Subsequently, the system boundary includes the biomethanation process (in-situ or ex-situ) or membrane upgrading and ends with the utilization of the end-products. This study includes a baseline scenario and three distinct scenarios. The baseline scenario includes the use of fossil natural gas in trucks, pretreatment of waste to produce heat and electricity, an AD reactor to produce biogas that will be incinerated in a CHP plant to produce heat and electricity, and digestate including N, P, and K nutrients used on field (S0). The second scenario includes upgrading of biogas by membrane separation technology to produce biomethane instead of combustion of biogas in CHP to be used in vehicles (S1). The third scenario encompasses ex-situ biomethanation (S2) achieved by treating biogas with hydrogen in a separate reactor to produce biomethane to be used in vehicles. The fourth scenario (S3) involves in-situ biomethanation, achieved by directly introducing hydrogen into the AD reactor to produce biomethane to be used in vehicles.

The selection of key concepts for these technologies (S1, S2, and S3) is based on comprehensive review of existing studies, ensuring a strong foundation for this research. The selection of membrane separation as upgrading technology has been derived from previous research [21,22] and primary data from company. In-situ biomethanation was selected as it has been shown to improve overall biomethane productivity compared to conventional upgrading methods [23–25]. Ex-situ biomethanation was included as well due to research that highlights a higher CO_2 conversion rate leading to increased biomethane production compared to in-situ biomethanation [26,27]. Previous research also emphasizes the important role of renewable electricity for the environmental performance of hydrogen production [5] and subsequent biomethanation [21]. The greater the share of renewable electricity, the lower the climate change impact of the biomethanation process [21]. Therefore, beside grid electricity, solar and wind power are used in the scenarios for hydrogen production.

By integrating these concepts, this study aims to provide a holistic perspective that bridges existing knowledge gaps and advances the understanding of conventional methods and newly emerging approaches for biogas upgrading. The decision to employ biomethane in place of natural gas in transportation sector originates from its ability to significantly reduce greenhouse gas emissions, as research conducted by Uusitalo et al. (2014) [28]. Biomethane is primarily utilized in heavy-duty vehicles rather than passenger cars due to the anticipated widespread electrification of most passenger vehicles. However, heavy-duty vehicles are not expected to transition to electric models due to existing traffic laws [29]. The potential for electrifying these

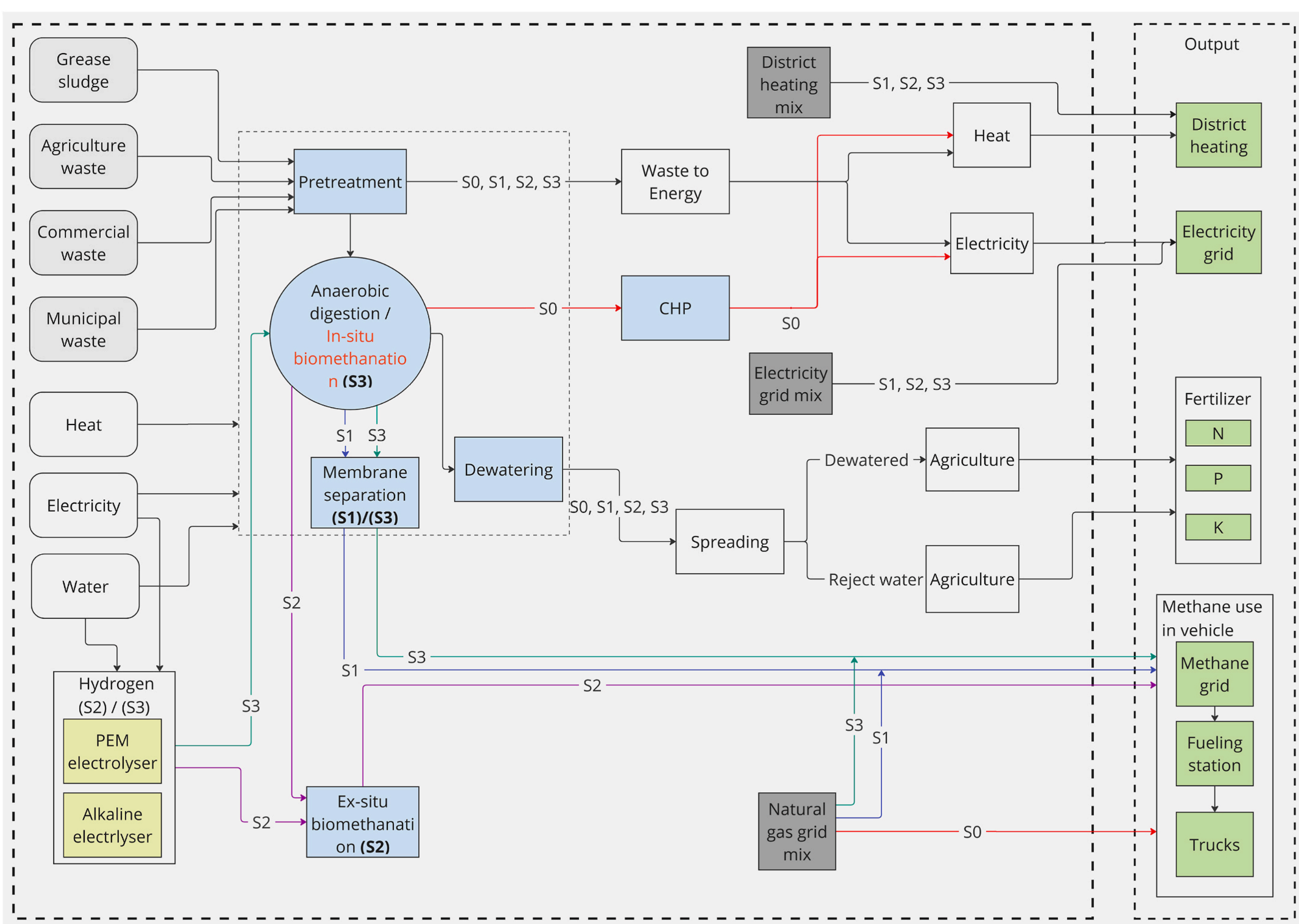

Fig. 1. The system boundary including the investigated scenarios base line (S0), membrane upgrading (S1), ex-situ biomethanation (S2) and in-situ biomethanation (S3).

heavy-duty vehicles remains limited, especially in Finland, even with advancements in battery capacity [30]. The Statista report of 2022 highlights a significant 50 % decline in new natural gas-based passenger cars in Finland between 2020 and 2021 [31] and hence this directs the study's focus solely toward heavy-duty vehicles.

Moreover, another study by Uusitalo et al. (2013) highlights the benefits of utilizing biogas or upgraded biogas within the transportation sector. This can be achieved either by directly using biogas in engines or by employing biogas in CHP plants to generate electricity for use in electric cars, resulting in the most substantial reduction of greenhouse gas emissions in the transportation sector [32,33]. The study by Lee et al. (2021) shows the advantages of using biomethane compared to compressed natural gas used in vehicles [34].

Furthermore, recent developments, such as the closure of the natural gas pipeline between Russia and Finland and the destruction of the Baltic Connector gas pipeline, which is now repaired and linking Finland and Estonia, have resulted in a significant reduction (almost halving) of natural gas consumption in Finland in 2022 [35–37]. This situation underscores the advantages of utilizing biomethane as a substitute for natural gas in the transportation sector.

The ex-situ and in-situ scenarios require hydrogen, which was assumed to be produced via electrolysis utilizing either polymer electrolyte membrane (PEM) electrolyser or alkaline (AEL) electrolyser. Three distinct electricity provision options were outlined for the electrolysis. The first option involves sourcing 100 % of the required electricity from wind energy harnessed in Finland. The second option involves utilizing 100 % electricity from solar energy generated within Finland. The third options entails utilizing the electricity from the 2022 Finnish electricity grid.

Biogas production relies on a combination of energy sources. To power the process, electricity is drawn from the Finnish electricity grid mix. For the heat needed within the plant, heat is generated by incinerating the needed part of biogas in a boiler. Additionally, the water required for the AD plant is sourced from the Finnish municipality water supply system. The digestate is assumed to be spread onto agricultural fields using a diesel tractor, allowing it to serve as a fertilizer to meet the demand for nitrogen, potassium, and phosphorus nutrients [38] as shown in Fig. 1. Moreover, the system boundary accounts for fugitive emissions caused by leaks and flaring of biogas in the biogas plant as shown in Table 2. The detailed values can be seen in supplementary material (SM).

To ensure an accurate comparison of the environmental impact of the studied scenarios, a system expansion approach with additional production approach has been used. This approach allows for fair comparison of the scenarios that have differences in the output of the multiple products. For instance, the input of hydrogen for ex-situ biomethanation (S2) exceeds that for in-situ biomethanation (S3) due to higher conversion rate of CO_2 to CH_4 in ex-situ biomethanation compared to in-situ biomethantion and is absent for membrane separation (S1), leading to different outcomes of biomethane for each scenario. Therefore, to ensure a fair comparison, additional natural gas is supplied in scenarios S1 and S3 to make sure that the same amount of methane for vehicle use is available from all scenarios [39]. Similarly, in scenario S0, where biogas is combusted to produce heat and electricity, additional heat and electricity are supplied to scenarios S1, S2, and S3 to ensure the same amount of heat and electricity in all scenarios.

Table 2
Transport distance and capacity of incoming waste.

Feedstock	Capacity (t/a)	Transport distance (km)
Commercial Biowaste	10 200	62
Municipal Biowaste	10 200	41
Grease sludge	11 500	36
Solid carbohydrate residues (agriculture)	1500	44

2.3. Life cycle inventory analysis

During the life cycle inventory (LCI) analysis phase, all material and energy flows within and across the boundaries of the examined product system are thoroughly quantified. It is important to note that the LCA procedure and standards (ISO standard 14040–14044:2006) utilized in this study are consistent with those employed in a previous article on hydrogen production LCA, authored by Patel et al. (2024) [40].

In this particular study, initial data for the waste to biogas process was sourced from Gasum company, while data for ex situ biomethanation was collected from Biogas Clean company. As for in situ biomethanation, relevant data was collected through an extensive literature review. For Finnish electricity grid mix, data was collected from Statics Finland [41,42]. For additional support, secondary data was acquired from the LCA for expert database. In cases where the LCA for expert database lacked the required information, data was extracted from reputable scientific literature.

Gasum's biogas plant in Lohja is located in Munkkaa waste management center, Finland. The plant was commissioned in January 2021. Lohja biogas plant process an annual total of 60 000 tonnes of biowaste and produces around 40 GWh of biogas for transportation. Plant also produce 50 000 tonnes of organic fertilizer annually [43]. The Lohja plant uses membrane upgrading technology for biogas upgrading, which separates CO_2 from biogas and releases it into the air.

The transport distance and the capacity of incoming waste data can be seen in Table 2. It shows the distance of incoming waste to the plant and the total mass of waste. Additionally, the heat, electricity, and water requirements for the plant are based on Lohja plant data as shown in Table 3 and the other valuable data from Lohja plant that was used in this study can be seen in Table 3. The other inventory data used in this study, such as background processes, utilized trucks, spreading of digestate, emissions from trucks, and all the other data, can be found in the SM.

2.4. Normalisation

Normalisation is an optional step used to compare and relate category indicators to reference indicator information. There are difficulties associated with comparing and ranking the scenarios different impact categories and the magnitude of the impacts compared with one another, so normalisation is applied to help compare different category indicators with common reference system [44–46]. In this study, the reference indicator information used includes the Finland category indicator and the EU-27 category indicator. The reference indicator information for Finland and EU-27 can be found in SM under normalisation excel sheet (table 7.1)

Table 3
Data from Lohja plant used in this study.

Parameter	Value	Unit
AD heat need	4000	MWh/a
Electricity need	3200	MWh/a
Water consumption	3000	m3/a
Active carbon use	16 000	kg/a
Biogas production	4 447 530	kg/a
Flaring	3	%
CH_4 in biogas	64	%
CO_2 in biogas	35	%
Spreading	2.35	l_{diesel}/t
LHV biogas	23	MJ/kg
LHV LFG	18	MJ/kg
LHV Methane	50	MJ/kg
Emission of biogas combustion, N_2O	0.005	g/MJ
Emission of biogas combustion, CH_4	0.004	g/MJ
Emission of biogas combustion, NO_x	0.02	g/MJ

The normalisation impact for a specific impact category (N_i) can be calculated as $N_i = S_i/R_i$ [46], where i is the impact category, N_i is normalised impact for a specific impact category, S_i is the characterised impact of the impact category i of the system under study, and R_i is the estimated environmental impact of the reference region.

2.5. Sensitivity analysis

The results of LCA can be affected by various modelling assumptions and decisions, particularly concerning the parameter values used This is especially the case related to the parameters for the processes that do not exist at the moment in the studied case plant. Consequently, it is imperative to employ sensitivity analysis to evaluate the impact of model's assumptions and decisions on the LCA result. In this study, perturbation analysis was utilized to identify the impacts of parameter variations on the overall net outcome. Perturbation analysis shows the most sensitive parameters based on the sensitivity ratio (SR) which can be determined by the following equation: $SR = \frac{\frac{\Delta result}{intial\ result}}{\frac{\Delta parameter}{intial\ parameter}}$ [47].

Heijungs and Kleijn (2001) suggested that parameters SR values greater than 0.8 are considered important because they have a significant impact on the outcome of LCA. If the SR value exceeds 1.0, it indicates that the parameter is particularly crucial. On the other hand, if the SR value is less than 0.2, the parameter has minimal influence on the overall results [48]. The same method was applied in the study by Patel et al. (2024) [40].

3. Results and discussion

The LCIA results, along with the normalised results and sensitivity analysis, are presented. The findings are also discussed in detail alongside the result.

3.1. Life cycle impact assessment results

The LCIA results of the climate change impact category for the membrane separation, in-situ, and ex-situ biological methanation from different scenarios of hydrogen production comparing with baseline fossil based natural gas is shown in Fig. 2. The results are illustrated using only the alkaline electrolyzer. The results are shown as specific emission in Fig. 2. The detailed result of annual and the specific emission results can be found in the SM under results sheet (Tables 4.1 and 4.5 respectively).

The result shows that the scenario including membrane separation S1 results in a 52 % reduction in emissions compared to baseline scenario S0. The case of ex-situ biomethanation scenario S2 demonstrates emission reductions ranging from 44 % to 54 % compared to the baseline scenario S0, depending on the source of electricity for hydrogen production. Similarly, in-situ biomethanation S3, emission reductions range from 43 % to 53 % compared to the baseline scenario S0, depending on the source of electricity for hydrogen production. Using a PEM electrolyzer for hydrogen production results in a 0.3 % greater impact on overall outcomes compared to an alkaline electrolyzer. The highest emissions in the grid electricity mix come from electricity from hard coal followed by waste, and then by hydropower.

The highest emissions in scenarios S1, S2, and S3 come from the use phase of the fertilizer. This is because, in this study, when nitrogen is used as a fertilizer and spread on agricultural fields, 3 % of that nitrogen is converted to nitrous oxide (laughing gas) and is emitted into the air. This assumption of nitrous oxide emission is based on previous studies, such as Smith et al. (2004), Bouwman et al. (2002), Rees et al. (2002) [49] [50] [51] [52]. If the assumption is made that 1 % of nitrogen becomes nitrous oxide, then the fertilizer end-use result will drop by 60 % from the current result.

The second highest emissions for scenario S1, S2 and S3, after the use phase of the fertilizer, come from the incineration of reject waste from pretreatment. The incineration emissions of reject waste are around 1358 kg CO_2eq per ton of reject waste. This is because the composition of reject waste consists of 50 % plastic, 30 % municipal solid waste, and 20 % biodegradable waste. Based on IPCC inventory report, every ton of residual municipal waste incineration emits 1000 kgCO_2eq [53]. According to Jeswani et al. (2021), every one ton of mixed plastic waste incineration produces 1700 kgCO_2eq emission [54].

Fig. 3 illustrates the results of acidification for scenarios S0, S1, S2, and S3. The results show that the baseline scenario has a lower acidification impact than the alternatives, if the alternatives use grid mix electricity. It is evident from Fig. 3 that in all scenarios, the highest SO_2 equivalence emissions occur from the provision of heat and electricity in scenarios S1, S2, and S3. The second highest emissions come from the electricity used to produce hydrogen, depending on whether the electricity is sourced from the grid or renewable sources. In both scenarios

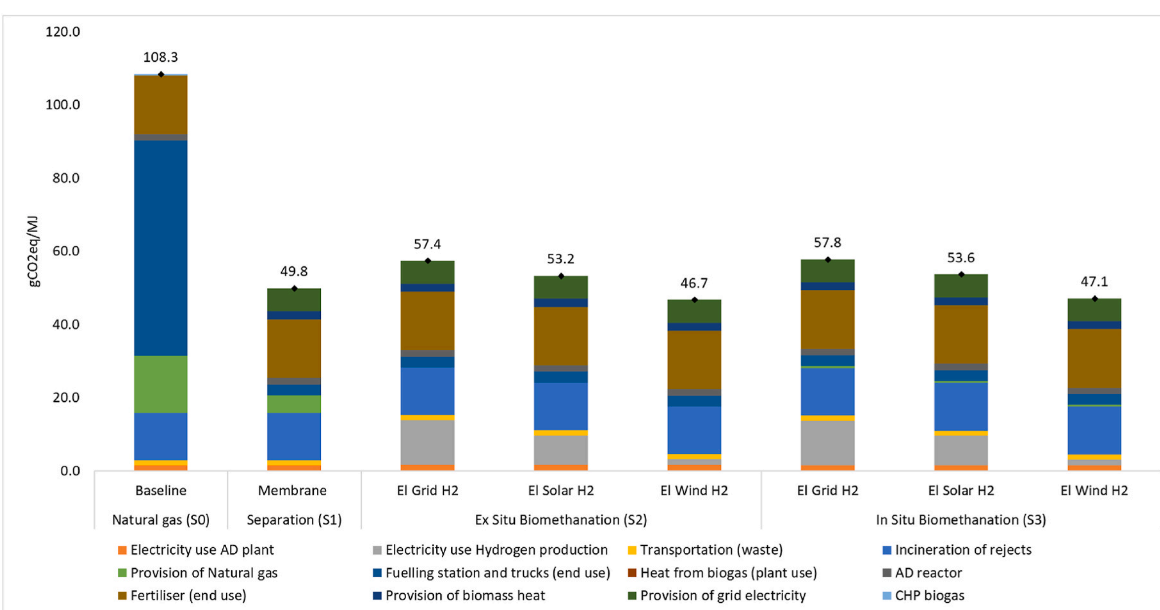

Fig. 2. LCIA results for climate change impact category.

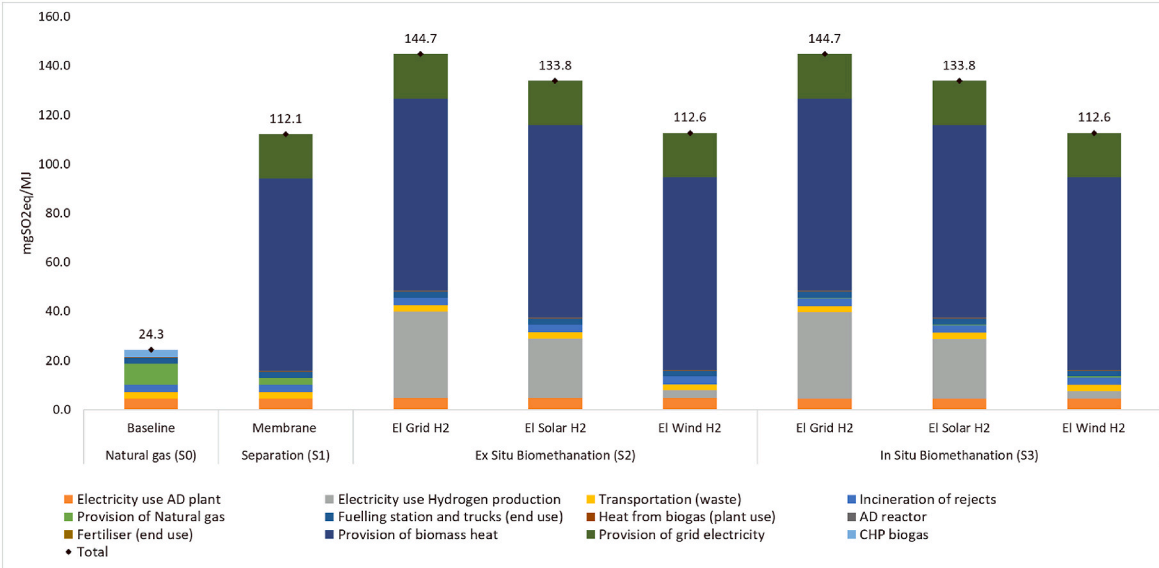

Fig. 3. LCIA results for acidification impact category.

S2 and S3, the difference is around 22 % when hydrogen is produced using electricity from the grid compared to wind electricity, as shown in Fig. 3. The second highest SO_2 equivalence emissions happens when methane (natural gas or biomethane) is used in the trucks. It is due to the fact that NO_2 emission occur during the combustion of methane in vehicles. The annual and the specific emission result of acidification can be found in SM under result sheet (Tables 4.2 and 4.6 respectively).

Eutrophication results are calculated for two different impact categories: freshwater eutrophication and marine eutrophication. Fig. 4 illustrates freshwater eutrophication, with the major impact coming from hydrogen production via electrolysis, where electricity is sourced from the solar energy. The high impact is due to the production phase of solar panels. While water consumption remains consistent across all scenarios for the electrolysis process, variations in results are attributable to the use of fossil-based electricity within the electricity grid mix. Fig. 5 shows the marine eutrophication results, illustrating that the highest impact comes from scenarios where the electricity grid mix is used to produce hydrogen. These emissions are attributed to the use of fossil-based electricity within the grid mix. On the other hand, the baseline scenario S0 has the lowest impact compared to S1, S2, and S3 due to the absence of hydrogen consumption and electricity use, resulting in less energy use. The annual and the specific emission result for freshwater and marine eutrophication can be found in SM under results sheet (Table 4.3, 4.4. 4.7 and 4.8 respectively).

Additionally, using biomethane in transportation, especially for heavy-duty vehicles and maritime transport, can significantly reduce greenhouse gas emissions and aid in the decarbonization of these sectors. Studies like the one by Sulewski et al. (2023) and Pavičić et al. (2022) highlight the potential of biomethane to replace natural gas in various applications, promoting the development of sustainable energy systems across different regions [55,56].

3.2. Normalised results

Figs. 6 and 7 show the normalised results of the annual environmental impacts of the studied scenarios compared with the annual

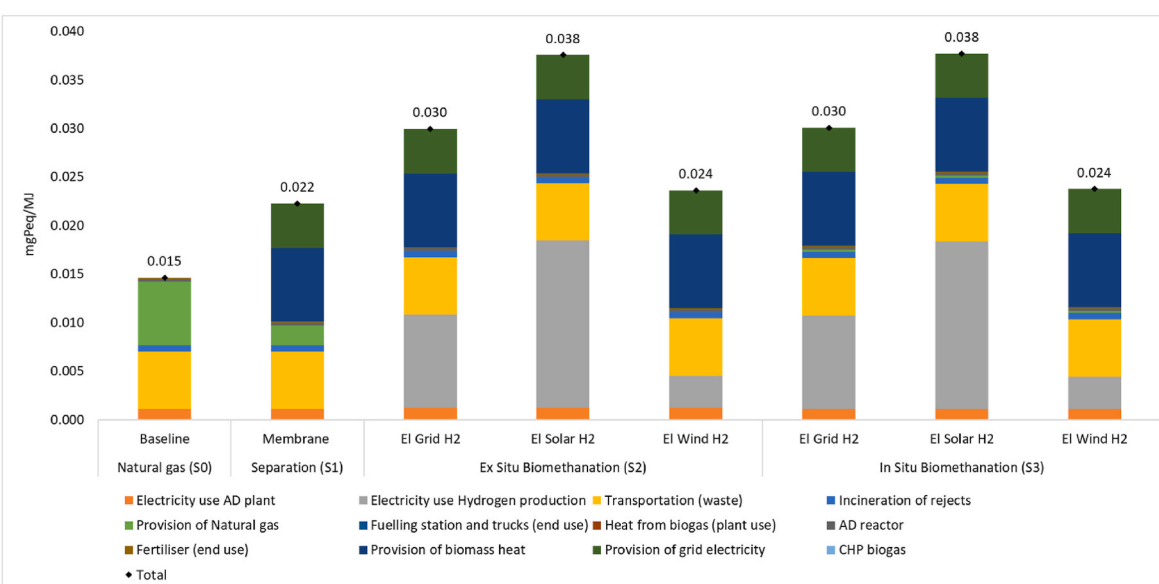

Fig. 4. LCIA results for freshwater eutrophication impact category.

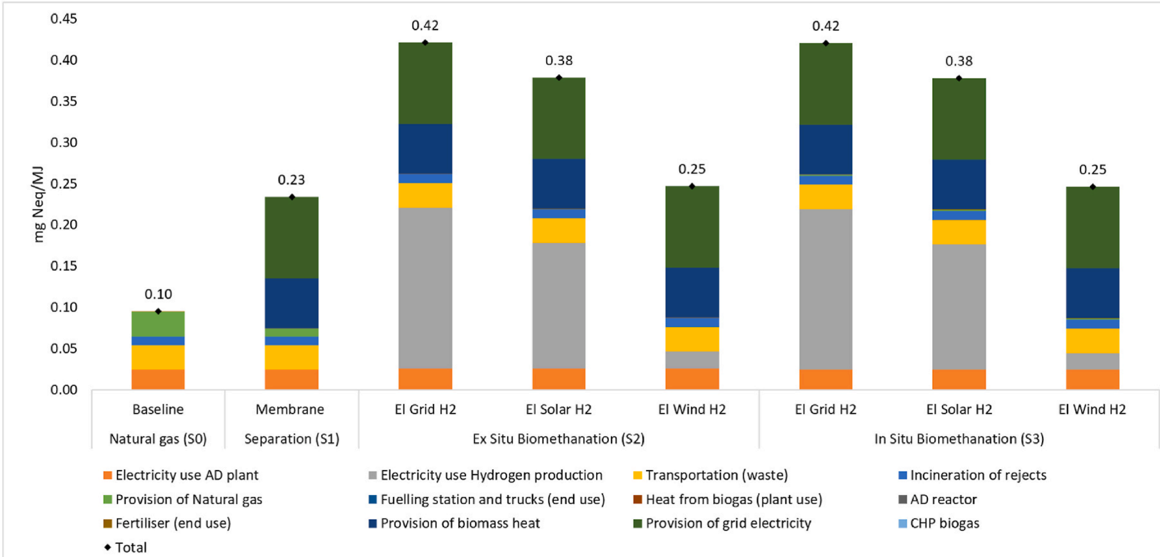

Fig. 5. LCIA results for marine eutrophication impact category.

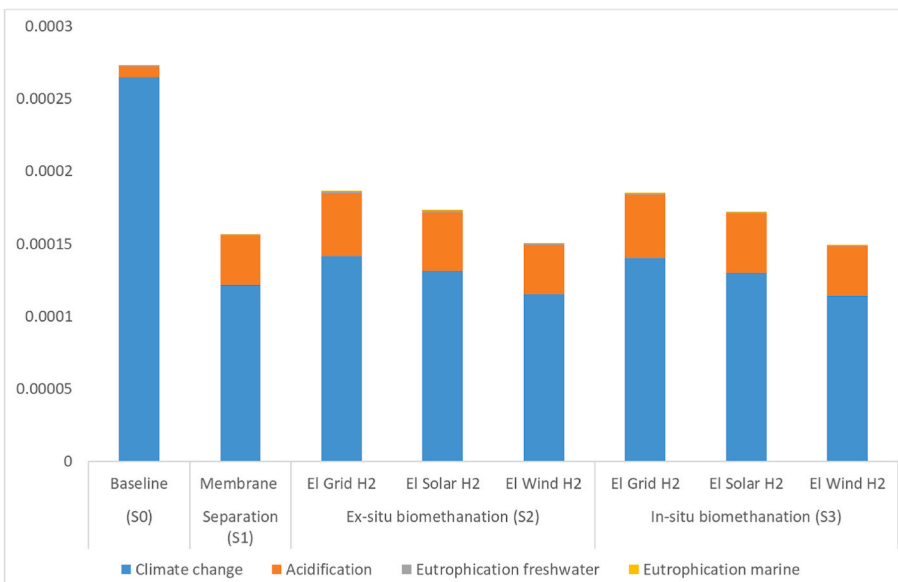

Fig. 6. Normalised result of the studied scenarios compared with Finnish standard values.

Finnish environmental impacts and the annual EU-27 environmental impacts, respectively. The change in relation to the annual emissions of Finland and the EU-27 is more significant in climate change than in acidification and eutrophication. The baseline scenario has the lowest eutrophication impact compared to the other scenarios. The acidification impacts are almost the same across all scenarios for Finnish and EU-27.

3.3. Sensitivity analysis

Table 4 shows the SR values for all the scenarios for climate change impact category where electricity source is from grid mix for all the scenarios. It is evident from the table that the SR values for all the parameters are below 0.8. There is not a single parameter that stands out from the conducted sensitivity analysis. The SR value which are above 0.2 are highlighted in Table 4. It can be seen from Table 4 that the N_2O emission in the fertilizer spreading is the most sensitive parameter to the results. The electricity used for hydrogen production, if coming from the electricity grid mix, is moderate sensitive parameter to the results. Moreover, the share of the rejects from the pretreatment process of incoming waste is moderately sensitive to the results. Additionally, the share of the plastic, where the mass of plastics is incinerated, is sensitive to the results. This sensitivity is because the share of plastic incineration has the high emission compared to other waste incineration. Furthermore, the wet digestate output parameter in the AD reactor is moderately sensitive. More digestate means less biogas and more emissions from drying and spreading the digestate on agricultural fields and hence could be more sensitive based on the different case study.

The SR value for all the scenarios for the acidification impact category can be found in SM under Sensitivity sheet (Table 5.2). It can be seen from the table that the SR values for all the parameters are below 0.8 and hence there is not a single parameter that would stand out. The parameter with an SR value higher than 0.2 is highlighted. The highest SR value for the acidification impact category comes from hydrogen production, where the electricity used for hydrogen production comes from the electricity grid mix (SR = 0.72), followed by heating efficiency

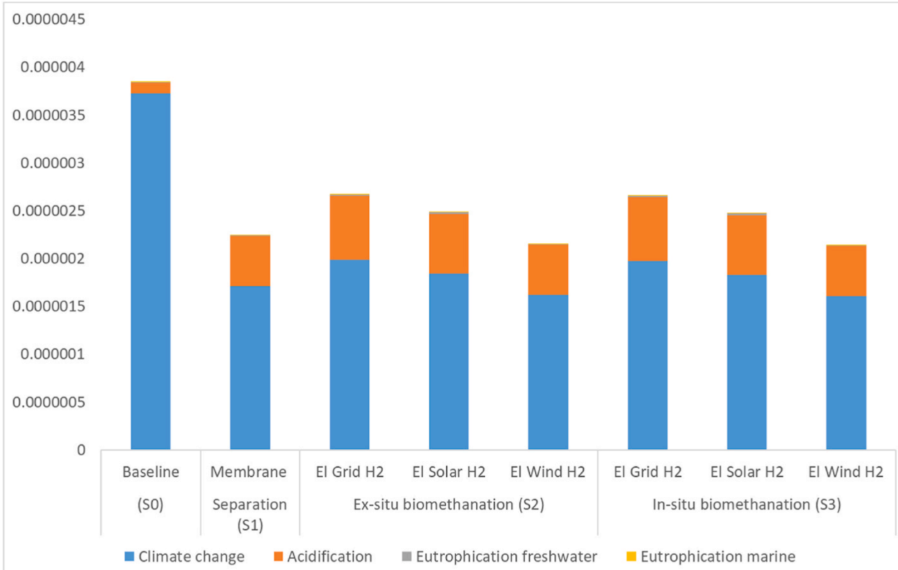

Fig. 7. Normalised result of the studied scenarios compared with EU-27 standard values.

Table 4
Sensitivity ratio for scenario S0, S1, S2 and S3 for climate change impact category.

Sensitivity Ratio (SR)				
Parameters	Baseline (S0)	Membrane separation (S1)	Ex-situ biomethanation (S2)	In-situ biomethanation (S3)
AD plant				
Electricity use	0.08	0.04	0.03	0.03
Share of dry digestate	0.03	0.02	0.02	0.02
Share of wet digestate	0.36	0.36	0.31	0.30
Methane slip from AD reactor	0.03	0.03	0.03	0.03
Share of rejects	0.33	0.32	0.27	0.26
Incineration of rejects				
Electricity efficiency	0.04	0.04	0.02	0.02
Heat efficiency	0.07	0.07	0.05	0.05
Share of biowaste	0.02	0.01	0.01	0.01
Share of municipal solid waste	0.00	0.00	0.00	0.00
Share of plastic waste	0.22	0.22	0.18	0.18
Hydrogen production				
Electricity consumed	0.00	0.00	0.25	0.24
Waste heat	0.00	0.00	0.01	0.01
Oxygen	0.00	0.00	0.05	0.05
Fuelling station and trucks end use				
Methane leak from fuelling station	0.00	0.03	0.02	0.02
Fertilizer (end use)				
Emission of N_2O from field	0.40	0.39	0.33	0.32

of waste incineration (SR = 0.35).

The SR values for all scenarios in the freshwater eutrophication and marine eutrophication impact categories can be found in the SM, under the Sensitivity sheet (Tables 5.3 and 5.4, respectively). The SR values for all parameters are below 0.8, indicating that no single parameter stands out. Table 5.3 in the SM shows that for freshwater eutrophication, hydrogen production, when electricity from the grid is used, has a relatively high impact on the model (SR = 0.50). Although this parameter is not critical, it significantly influences the model. Table 5.4 shows that for marine eutrophication, the high impact on the model comes from the heat efficiency of incineration of rejects (SR = 0.15).

4. Conclusion

The transition from fossil-based energy to renewable energy sources is crucial in mitigating climate change impacts. The LCA in this study focuses on comparing the environmental performance of biogas use for CHP production and traditional biogas upgrading method with in-situ and ex-situ biomethanation processes, utilizing hydrogen to enhance biogas methane content, and comparing with fossil based natural gas.

The climate change results indicate substantial emission reductions across all scenarios when compared to the baseline scenario (S0). The membrane separation scenario (S1) achieves a 52 % reduction in emissions. Both ex-situ (S2) and in-situ (S3) biomethanation processes show emission reductions ranging from 44 % to 54 % and 43 %–53 %, respectively, depending on the electricity source for hydrogen production. The difference in emissions between using PEM or AEL electrolyzers in the biomethanation process is minimal, with PEM electrolyzers resulting in approximately 0.3 % higher emissions.

From climate change point of view the analysis highlights that the highest emissions in scenario S1, S2 and S3 arise from the fertilizer use phase, primarily due to nitrous oxide emissions from nitrogen application. Reducing the assumed nitrous oxide emission factor from 3 % to 1 % significantly decreases the fertilizer use phase emissions. The second highest emission comes from the incineration of reject waste, attributed to its composition, with substantial contributions from plastic waste. If biogenic CO_2 emissions are taken into account, all the scenarios will have a 35–40 % higher impact than current emissions because of the CO_2 released during combustion of biogas in CHP and biomethane in vehicles and from the membrane separation.

In terms of acidification potential, the highest emissions come from the provision of heat, followed by provision of electricity in scenarios S1, S2, and S3. The source of electricity (grid vs. renewable) plays a crucial role, with renewable electricity significantly lowering emissions for hydrogen production compared to hydrogen production via electricity grid mix. In baseline scenario the highest emission comes from the provision of natural gas.

Eutrophication results, encompassing both freshwater and marine categories, show that the highest emissions come from hydrogen production via electrolysis, particularly when solar electricity used in the case of freshwater eutrophication and grid electricity is used in case of marine eutrophication in scenario S1, S2 and S3. The provision of heat and electricity in scenarios S1, S2, and S3 also have the largest share of acidification impact. The baseline scenario S0 has the lowest impact due to the absence of hydrogen production and the provision of heat and electricity consumption. The relevance of the results has been verified by comparison with previous research [57–61], which falls within the same range for biogas, fossil-based natural gas, and biomethane in the climate change category. In-situ biomethanation is a very new technology, and there have been limited studies conducted on it.

Normalisation results show that the highest impact comes from climate change, followed by acidification, across all scenarios for both EU-27 and Finnish standard values of annual emissions.

Overall, the study demonstrates that membrane separation, in-situ, and ex-situ biomethanation processes offer superior climate change performance compared to the fossil-based baseline scenario, but lower acidification, freshwater and marine eutrophication compared to the fossil-based baseline scenario. Scenarios S2 and S3 will have better environmental performance when hydrogen production and plant electricity use rely solely on wind energy. It is not clear whether biomethanation performs better in terms of environmental performance compared to membrane separation of CO_2 (traditional biogas upgrading). In this comparison, the impacts of electricity production and consumption are crucial. These findings underscore the importance of integrating renewable energy sources and advanced biogas upgrading techniques to achieve significant environmental benefits. The novelty of this research lies in its comprehensive LCA comparing traditional and innovative biogas upgrading technologies, providing valuable insights for future energy and environmental strategies.

CRediT authorship contribution statement

Gulam Husain Patel: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Mika Horttanainen:** Supervision. **Marika Kokko:** Supervision. **Hulya Civelek Yörüklü:** Validation. **Jouni Havukainen:** Supervision, Software.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT (GPT-4), an advanced AI model developed by OpenAI in order to improve the readability and language of the manuscript. After using this service, the author reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.135244.

Data availability

No data was used for the research described in the article.

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