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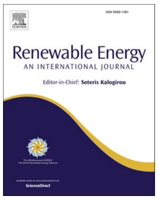

Environmental impact assessment of the production of biomethane from landfill biogas and its use as vehicle fuel

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ABSTRACT

Biogas and biomethane are expected to play an increasing role in the short-term future of the energy market. It is imperative to identify alternative sources of these gases and minimize the utilization of those derived from fossil sources. One such source is biogas obtained from landfill gas, which can be subsequently upgraded to produce biomethane. This can then be used to replace the fossil natural gas for both energy generation and vehicle use. This paper employs the Life-Cycle Assessment methodology to analyze the environmental impact of the production of biomethane derived from landfill biogas. The objective was to identify the unit processes that have the greatest environmental impact. These processes were CO_2 removal, which contributed 84 % to the impact category of 'global warming', and the second stage of biogas compression, which contributed 37 % to the impact category of 'fossil resources scarcity'. Based on these results, we propose recommendations to reduce the environmental impact of both processes. Furthermore, an analysis was conducted on the use of biomethane as a vehicle fuel, which revealed that it has the potential to reduce the environmental impact of driving both light and heavy-duty vehicles in comparison with the use of diesel and petrol.

1. Introduction

The current global energy crisis is resulting in significant and long-lasting changes that may speed the transition to a more secure and sustainable energy system [1]. The strongest tremors have been felt in the natural gas, coal, and power markets, but there has also been major volatility in the oil markets. Energy markets remain incredibly susceptible due to persistent geopolitical and economic worries, and the crisis serves as a warning of the brittleness and unreliability of the present global energy system. All this demands an immediate adjustment, and the transformation of the global energy system is projected to heavily rely on biogas and biomethane [2–4].

Biogas is produced during the anaerobic digestion of organic material in an oxygen-free environment. The methane content of biogas typically ranges from 45 % to 75 % by volume depending on the type of feedstock and the biogas obtention technique, with most of the remainder being CO_2, and traces of other gases such as ammonia, carbon monoxide, halogenated hydrocarbons, hydrogen sulfide, nitrogen, siloxanes, and water vapor [5–9].

Biogas can be utilized straight to produce electricity and/or heat or can be upgraded to biomethane by removing CO_2 and other impurities [10,11]. Due to its properties like those of fossil natural gas, biomethane can be used in distribution infrastructure or end-user equipment of natural gas, and as a transport fuel in natural gas vehicles [12].

Currently, more than 50 % of the global production of biogas is located in Europe (215 TWh), while 25 % of biogas is produced in China (87 TWh). The remaining biogas is produced primarily in the United States and India. Two-thirds of Europe's biogas plant capacity are in Germany and Denmark. The primary feedstock utilized to facilitate the expansion of Germany's biogas sector was energy crops. However, recent policy shifts have favored the utilization of agricultural residues, sequence crops, animal manure, and the biogas that may be captured from landfills.

The generation of biomethane through the utilization of biogas upgrading techniques has recently emerged as a subject of considerable interest [13]. Indeed, biomethane production from biogas increased by

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20 % in 2022 respect to 2021. Biomethane can be used both for energy production and vehicle fuel [14]. The strength and design of measures intended to decarbonize gas supplies in various regions of the world will greatly impact the potential for future growth in this sector. The primary challenges for producing biomethane are the removal of carbon dioxide and contaminants (such as hydrogen sulfide and siloxanes) from biogas. There are several technologies for converting biogas to biomethane, with amine scrubbing and pressure swing adsorption the two with the lowest environmental impact, energy consumption and CH_4 emissions. Water scrubbing proved to be more cost-effective for small-size plants, while potassium carbonate scrubbing present higher biomethane obtention values than other techniques for large-size plants [15]. Indeed, the production of biomethane from landfill gas has been proven to be technically and economically viable in specific circumstances [16].

The conventional production of natural gas is associated with a high environmental impact [17]. For instance, 16 % of total energy-related CO_2 emissions in Europe can be attributed to leaks from gas pipelines and processing facilities, as well as to the intentional venting or flaring of unwanted natural gas at production sites (IEA, 2021). In addition, landfill gas emissions that are not captured have a considerable environmental impact [18]. Consequently, it is anticipated that the production of biomethane from landfill gas and its subsequent utilization as an energy source or in vehicles will have a more favorable environmental impact than alternatives derived from fossil sources.

A common method for evaluating the environmental impacts of processes over the course of their whole life cycle is Life-Cycle Assessment (LCA) [19–21]. For instance, Alengebawy et al. [22] used a comparative LCA to assess three biogas use scenarios and concluded that the upgrading scenario reduced emissions in 8 out of the 10 impact categories that were examined.

Collet et al. [23] conducted an LCA of biomethane production using three different production methods: upgrading biogas produced by anaerobic digestion of water sludge, methanation of carbon dioxide available from biogas upgrading, and finally, methanation of carbon dioxide without prior separation (still contained in biogas). Additionally, Xu et al. [24] examined the energy use and environmental effects of a biomethane facility that used pressurized water scrubbing, monoethanolamine aqueous scrubbing, and ionic liquid scrubbing as upgrading methods. Following the same approach, Leonzio [25] conducted an LCA to compare upgrading units supplied with various chemical solvents. Ferreira et al. [26] examined the LCA of using biomethane in different applications, as fuel for cooking and for light and heavy-duty vehicles, under Brazilian framework circumstances without considering the effects of upgrading and other intermediary phases in the supply chain. Ardolino et al. [27] assessed the environmental viability of the anaerobic treatment of separately collected organic municipal solid waste components to produce biogas, which is subsequently upgraded to biomethane for use in the road transport sector. Results showed that the creation of energy is always more polluting than the production of biomethane for road transportation.

However, to the best of the authors' knowledge, there are not studies that specifically addressed the life-cycle environmental impacts of the production of biomethane from landfill biogas and its utilization in vehicles. In this study, we analyze a real case study of the first biomethane plant of Andalusia (Spain), which is located in the province of Granada. This plant utilizes landfill gas as its primary source for biomethane production, which is expected to provide environmental benefits and contribute to the region's strategy to mitigate climate change and promote sustainability. This study serves to illustrate how renewable gas (or biomethane) generated from waste can contribute to meeting the objectives defined by European regulations in terms of the decarbonization of transport and the enhancement of air quality. Furthermore, this plant serves as a model for replication in other landfills in Spain and beyond. The biomethane plant contributes to the circular economy by using the gases generated in landfills, which would otherwise be emitted into the atmosphere. The LCA of this plant provides novel knowledge in this sector, given that 74 % of the biogas produced in Europe originates from agricultural waste, manure and energy crops.

In this context, this study presents an LCA of the upgrading processes of landfill biogas to biomethane. We also compared different fossil fuels and renewable biomethane fuel produced, exploring their use as vehicle fuel in two different vehicles This article presents an inventory of relevant energy and material inputs, an assessment of the potential environmental impacts associated with the identified inputs and outputs, and an interpretation of the results to facilitate the drawing of conclusions and recommendations that will enable informed decisions to be made to minimize the environmental impacts of the process under study.

2. Methodology

The standards that define the LCA methodology, followed in this article, are the Standard "UNE-EN ISO 14040:2006. Environmental management. Life cycle analysis. Principles and reference framework"; and "Standard UNE-EN ISO 14044:2006/A1:2018. Environmental management. Life cycle assessment. Requirements and guidelines". The first one defines the methodology to carry out an LCA of a product or system, based on the following phases: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation. The second one is used as a complement to the UNE-EN ISO 14040:2006 and provides requirements and guidelines.

A variety of software tools, libraries and impact assessment methodologies are employed within the context of LCA. The differences between them are attributable to their respective mathematical and statistical calculations, modelling choices, and the impact categories that they include. In this study, the SimaPro 9.4.0.1 PhD software (PRé Sustainability B.V.) was employed. Most of the data to build the LCI were collected from a real plant already in operation. For the background data, the library chosen was 'ecoinvent 3 allocation at point of substitution (APOS) - unit (U)'. The 'allocation' model is an attributional model that allows the identification of critical points in the life cycle. The methodologies used for the LCIA phase were ReCiPe 2016 midpoint (H) V1.03/World (2010) H and ReCiPe 2016 endpoint (H) V1.03/World (2010) H/A. These methodologies encompass a wide range of impact categories, including both midpoint and endpoint perspectives. While the midpoint perspective provides more detailed information about the environmental impacts caused, the endpoint perspective considers how the areas of protection are affected by these impacts. Finally, the interpretation of the results was carried out to identify the main variables, the most relevant impact categories and most impactful unit processes. Furthermore, our results were compared against those obtained by similar studies and final recommendations were given. We also applied this methodology to compare the use phase of biomethane as a vehicle fuel with the use of conventional fuel.

3. Life-Cycle Assessment of the production of biomethane from landfill biogas

3.1. Goal and scope

The objective of this LCA is to analyze the conversion of the biogas emitted during the decomposition of organic matter in a solid urban waste landfill, which would otherwise be emitted to the atmosphere, into biomethane suitable for use as fuel. The purpose of this process is twofold: reduce the environmental impact caused by the emission of landfill biogas and reduce the need for fossil fuels in vehicles. The biogas generated at the landfill goes through a purification process and is transformed into biomethane. A schematic diagram of the biomethane production process from landfill biogas and the boundaries of the system modelled is shown in Fig. 1.

The geographical scope, where the biomethane plant is located, is Spain. The system studied corresponds to the biomethane production from landfill biogas, i.e. a gate-to-gate analysis. The processes included

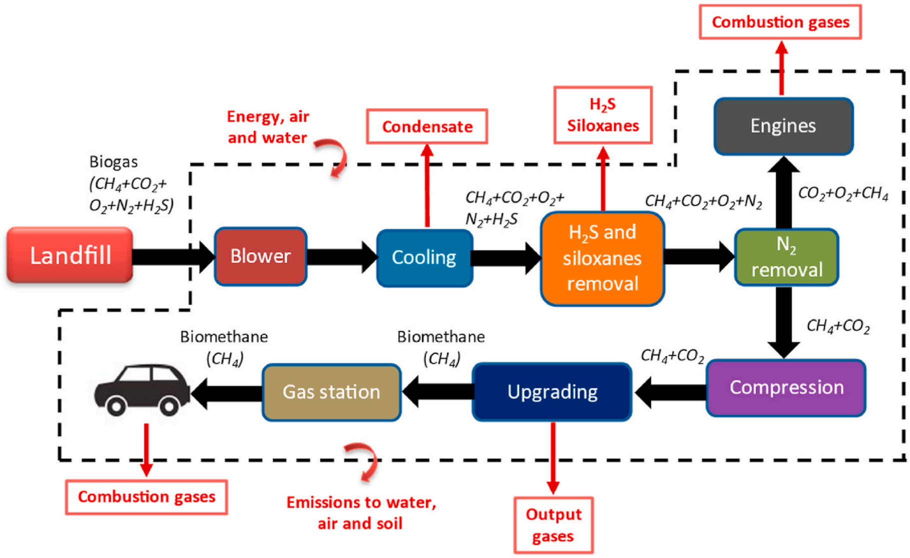

Fig. 1. Block flow diagram and system boundaries.

within the boundaries of the defined system are those between the biogas feeding to the plant, up to the storage of the produced biomethane in the gas station. In addition, Section 4 analyses the use of the biomethane as vehicle fuel. The functional unit chosen is the production of 1 Nm^3 of biomethane.

This plant is divided into three main stages, as described below. The values for each input and output are listed in Section 3.2.

- Pre-treatment stage: the biogas from the municipal solid waste landfill is fed to the plant via a blower. The gas then passes through a cooling unit, whose function is to remove water from the biogas. The water flow generated is called 'condensate'. Next, the water-free biogas passes through a hydrogen sulfide and siloxane removal unit.
- Enrichment stage: the biogas from the previous stage is treated to remove mainly CO_2, O_2 and N_2 using VPSA (Vacuum Pressure Swing Adsorption) technology. This technology allows obtaining a biomethane with more than 96 % of CH_4. At this stage, a gas with a low-methane content is generated as a by-product, which can be used to feed cogeneration engines and produce electrical and thermal energy for the plant's partial self-sufficiency. In addition, because of the removal of CO_2 from the biogas, a gas stream rich in the desorbed CO_2 is generated (namely off-gas), which is emitted to the atmosphere. However, a CO_2 recovery and purification unit could be implemented for use in food and industrial applications. This scenario will be described in Section 3.4.2.
- Biomethane compression and storage stage: the biomethane obtained is compressed ('compression 2'), upgraded and stored at 7.5 bar to bring it to conditions suitable for use as a fuel.

During the stage of biomethane use, biomethane is supplied by a gas station for use as a vehicle fuel in a light-duty vehicle and in a heavy-duty vehicle. The pressure of biomethane in the gas station is 230 bar. It is projected that the biomethane that is not consumed in the vehicles will be injected into the natural gas network.

The management of the by-products and waste generated in the process is included within the system boundaries. The by-product generated is a gas with a low methane content, which is used to power combustion engines for electricity production. The wastes generated in the process are described in Section 1 of Supplementary Information.

The production process is assumed to be at steady state. Therefore, the impacts associated with the maintenance, start-up and shut-down stages of the plant are not included in the study. The construction of the plant and the gas plant itself is not included either. Other excluded processes include municipal solid waste management, landfill management and machinery use. A more complete description of these excluded processes can be found in Section 1 of the Supplementary Information.

Some of the points above are not considered since this would mean including a municipal solid waste treatment plant in the study, which is out of the system boundaries of the biomethane production process. Therefore, the landfill biogas enters the system free of environmental impact, following a burden-free approach, like in other LCA studies of waste management (e.g. Garcia-Garcia and Rahimifard [28]). The goal of this study does not include an environmental impact comparison between this process and conventional landfilling (i.e. the waste management option that this process substitutes), nor a comparison with the production of conventional vehicle fuel. However, a later section (Section 4) compares the environmental impact of the use of biomethane as fuel with that of conventional vehicle fuel.

3.2. *Inventory analysis*

The inputs and outputs of the unit processes are identified and quantified in this section. The inputs comprise material and energy flows from natural or human origin. The outputs comprise emissions to air, discharges into water and spills on the soil produced during the process. All inputs and outputs in LCI are referred to the functional unit selected.

The data to model the process were collected from a real plant already in operation in the province of Granada (Spain), from bibliographic sources on similar studies that analyze the processes to produce biomethane, and from the ecoinvent 3 database (APOS, U), prioritizing processes defined for Spain or Europe.

Table 1 show the data corresponding to the flow of the main process streams and their composition.

Fig. 2 presents a simplified block diagram that illustrates the

Table 1
Flow rate and composition of input and output streams.

Parameter	Biogas	Biomethane	CH_4-rich gas	Off-Gas
Flow rate, Nm^3/h	500	221.7	89.2	189.1
CH_4, %	51.5	96.7	37.0	4.6
CO_2, %	38.9	0.2	27.5	89.7
O_2, %	1.0	0.15	3.3	0.8
N_2, %	8.9	3.0	32.1	4.9
H_2S, ppm	350	<1	<1	<1
Water, mg/L	17.2	2	–	–

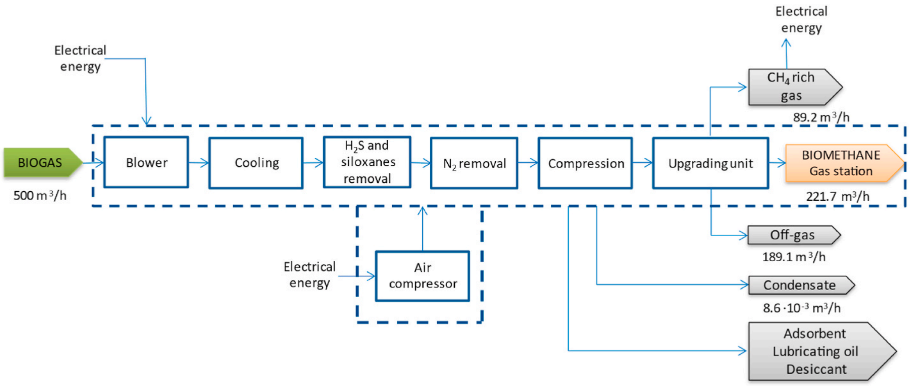

Fig. 2. Simplified block diagram of the process.

principal inputs and outputs within the system. There are three main flows within the system under study: the CH_4-rich gas that is used to fuel cogeneration engines; the CO_2-rich gas that is currently being emitted into the atmosphere; and the biomethane that is produced in the upgrading process. In later sections, we provide recommendations to avoid the emission of the CO_2-rich gas into the atmosphere.

Tables 2 and 3 show the material and energy inputs and outputs of the system, referring to 1 Nm^3 of biomethane generated and setting a utilization capacity of 60 %. Some basic equipment has been grouped together when their consumption is very small, so the total power is included as the sum of the power of such equipment.

3.3. *Impact analysis*

This section presents the results obtained from the LCA of the biomethane production plant by using the ReCiPe 2016 midpoint (H) V1.03/World (2010) H and ReCiPe 2016 endpoint (H) V1.03/World (2010) H/A methodologies.

3.3.1. *Midpoint results*

Table 4 shows the results obtained for each midpoint indicator, while Fig. 3A shows the characterized results in terms of percentage of damage caused by each unit process under each impact category. The most remarkable result is the contribution of the “CO_2 removal” stage with more than 80 % of total impact on the global warming impact category. This is caused by the direct emission of the CO_2-rich exhaust gas into the atmosphere. For the rest of the categories, the largest contributors are the water removal and compression 2 stages, with proportional contributions between 30 and 40 % of the total impact, due to the use of energy-intensive equipment.

Normalized results (Fig. 3B) show the environmental impact categories that contribute the most to the overall environmental impact of the system. The highest values are obtained from human carcinogenic toxicity, marine ecotoxicity, global warming and terrestrial ecotoxicity (4,62E-04, 2,58E-04, 2,56E-04 and 2,41E-04, respectively). The remaining environmental impact categories contribute only a minimal amount to the overall environmental impact of the system.

Table 2
Material inputs and outputs of the system.

Stream	Value
Biogas, Nm^3	2.255
Biomethane, Nm^3	1.000
CH_4-rich gas, Nm^3	0.402
Off-Gas, Nm^3	0.853
Condensates, L	0.0388
Adsorbent (Activated carbon) - H_2S unit, kg	0.00752
Adsorbent (Activated carbon) - siloxanes unit, kg	0.000251
Biomethane desiccant, kg	0.000376
Compressor and pump lubricating oil, L	0.000175

Table 3
Electrical consumption of the main equipment of the system.

Equipment	Electrical consumption, kWh
Blower	0.0541
Biogas compressor (compressor 2)	0.298
Biogas cooler	0.135
Air compressor (compressor 1)	0.0406
Ventilation 1	0.0046
Ventilation 2	0.0046
Heat exchanger	0.0076
Blower	0.0647
Pump 1	0.0444
Pump 2	0.0276
Pump 3	0.0276
Pump 4	0.0276
Pump 5	0.0276
Other ancillary equipment	0.0246
Gas station	0.0094

Table 4
Characterization results for each midpoint indicator.

Environmental impact category	Unit	Value
Global warming (1)	kg CO_2 eq	2.04484398
Stratospheric ozone depletion (2)	kg CFC11 eq	1.9596E-07
Ionizing radiation (3)	kBq Co-60 eq	0.01060456
Ozone formation, Human health (4)	kg NOx eq	0.00106033
Fine particulate matter formation (5)	kg PM2.5 eq	0.00076382
Ozone formation, Terrestrial ecosystems (6)	kg NOx eq	0.0010676
Terrestrial acidification (7)	kg SO_2 eq	0.00193824
Freshwater eutrophication (8)	kg P eq	1.6718E-05
Marine eutrophication (9)	kg N eq	1.2391E-06
Terrestrial ecotoxicity (10)	kg 1,4-DCB	0.2500783
Freshwater ecotoxicity (11)	kg 1,4-DCB	6.3597E-05
Marine ecotoxicity (12)	kg 1,4-DCB	0.00026645
Human carcinogenic toxicity (13)	kg 1,4-DCB	0.00127912
Human non-carcinogenic toxicity (14)	kg 1,4-DCB	0.00934451
Land use (15)	m^{2}a crop eq	0.00761089
Mineral resource scarcity (16)	kg Cu eq	0.00046314
Fossil resource scarcity (17)	kg oil eq	0.08293374
Water consumption (18)	m^3	0.00243798

3.3.2. *Endpoint results*

The endpoint results, by using the ReCiPe 2016 endpoint H/A v1.03 method, are shown in Table 5. The contribution of each unit process to each environmental impact category is shown in Fig. 4.

The environmental impact of the global warming categories is mostly caused by the CO_2-removal stage (84 % to the overall impact), as with the midpoint method. In the other categories, the impact is more evenly distributed between the water removal stages and the second

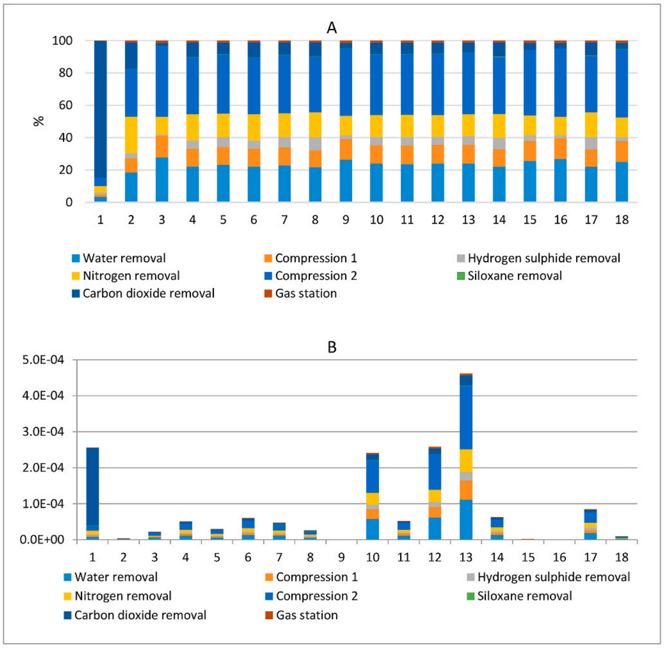

Fig. 3. Midpoint results. A) Contribution of the different unit processes for each midpoint indicator; B) Normalized results. The numbers in x-axis represents each of the impact categories defined in Table 4.

Table 5
Characterization results for each endpoint indicator.

Environmental impact category	Unit	Value
Global warming, Human health (1)	DALY	1.8976E-06
Global warming, Terrestrial ecosystems (2)	species.yr	5.7257E-09
Global warming, Freshwater ecosystems (3)	species.yr	1.5643E-13
Stratospheric ozone depletion (4)	DALY	1.0402E-10
Ionizing radiation (5)	DALY	9.0101E-11
Ozone formation, Human health (6)	DALY	9.6491E-10
Fine particulate matter formation (7)	DALY	4.7983E-07
Ozone formation, Terrestrial ecosystems (8)	species.yr	1.3772E-10
Terrestrial acidification (9)	species.yr	4.1089E-10
Freshwater eutrophication (10)	species.yr	1.1196E-11
Marine eutrophication (11)	species.yr	2.1063E-15
Terrestrial ecotoxicity (12)	species.yr	2.8515E-12
Freshwater ecotoxicity (13)	species.yr	4.4133E-14
Marine ecotoxicity (14)	species.yr	2.7993E-14
Human carcinogenic toxicity (15)	DALY	4.2471E-09
Human non-carcinogenic toxicity (16)	DALY	2.13E-09
Land use (17)	species.yr	6.7501E-11
Mineral resource scarcity (18)	USD2013	0.00010701
Fossil resource scarcity (19)	USD2013	0.01702918
Water consumption, Human health (20)	DALY	5.2191E-09
Water consumption, Terrestrial ecosystems (21)	species.yr	2.0245E-11
Water consumption, Aquatic ecosystems (22)	species.yr	1.7093E-15

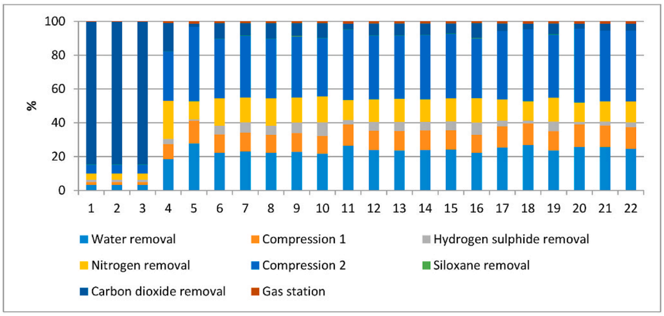

Fig. 4. Proportional contribution of the different unit processes for each endpoint indicator. The numbers in X axis represents each of the impact categories defined in Table 5.

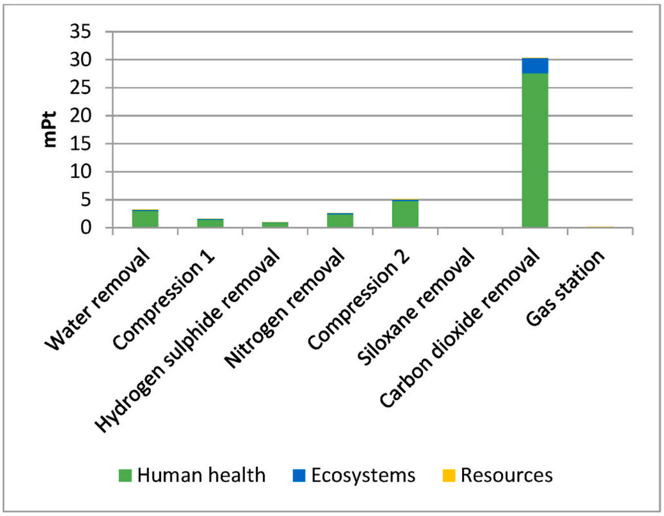

Fig. 5. Overall environmental impact produced by the different unit processes in each area of protection.

compression stage, as with the midpoint method. For instance, for fossil resources scarcity, the process with the greatest environmental impact is the second compression stage (37 % of the total impact), as the biogas compressor has a high energy consumption from fossil resources. For this impact category, electricity consumption contributes 83 % of the total impact in the unit processes, while activated carbon consumption accounts for the remaining 17 %. However, as the consumption of both resources is distributed among the different unit processes, these percentages are distributed among the processes in proportion to the consumption of each of the resources. The water elimination stage uses a chiller that also has associated a high energy consumption.

Next, the impact categories were grouped into three areas of protection: human health, ecosystems and resources. Next, the results were normalized. The results obtained are shown in Fig. 5, in which the endpoint results are expressed in terms of milipoints of impact (mPt), which are directly proportional to the environmental impact produced. There is a clear predominance of the impact on human health, mainly caused by the CO_2-removal stage. Based on this, a series of improvements and alternatives are proposed in Section 3.4.2 to prevent the exhaust gas from being emitted into the atmosphere.

3.4. Interpretation

Our results show that the highest environmental impact is generated by the emission of the CO_2 stream and the energy consumption associated mainly with the compression stage. This section compares our results with those obtained by other researchers. Nevertheless, it must be noted that different modelling choices may lead to different results.

Ardolino et al. [29] studied several biogas upgrading systems (membrane separation, water scrubbing, chemical absorption with amine solvent, and pressure swing adsorption), including the use of biomethane as fuel. The study combined environmental and economic study. Results indicated that membrane separation technology shows the best results and Pressure Swing Adsorption (PSA) technology the worst results due to the consumption of activated carbon and zeolites. In any case, the biogas upgrading alternative depends on the specific conditions of each case, including economic aspects and commercial strategies. Other similar study [30] about the environmental and economic impact of PSA technology for biogas upgrading, found that electricity consumption and CO_2 emissions are the main impacts of the process. The authors suggest that the use of green electricity would reduce environmental impacts by up to 70 %. Including the economic impact study in the present analysis might have provided relevant data on the feasibility of the PES upgrading process.

Lorenzi et al. [31] carried out a comparative LCA of two biogas upgrading technologies, a high-pressure water scrubbing plant and high-temperature electrolysis in solid oxide electrolyzer cells, followed by a methanation stage. The authors indicate that in the biogas upgrading process, the separated CO_2 is generally released into the atmosphere, which carries an important part of the negative impact of the process. This impact could be improved if CO_2 is recycled to produce CH_4, which is the case in our study.

Since we also found that the energy consumption of the compression stage and the elimination of CO_2 into the atmosphere are the stages with the highest environmental impact of the process, an alternative scenario for energy consumption and some recommendations for the use of CO_2 are analyzed and described below.

3.4.1. *Comparison with alternative scenario*

This section includes a comparison with a proposed alternative scenario, described next. The stage compression 2 has a high environmental impact in some categories, mainly due to the energy consumption of the high-pressure biogas compressor. The current energy consumption of this equipment in the plant comes from the electricity grid, i.e. it is a resource that uses fossil materials and therefore has a high impact in some categories, as can be seen in Section 3.3. However, this equipment could alternatively operate with the electricity generated in the cogeneration unit installed in the plant itself. Therefore, a 50-kW cogeneration unit fed with the gas stream generated in the nitrogen removal stage of the biogas scrubbing and enrichment process was fed. Hence, instead of consuming electricity from the Spanish energy mix, the gas generated in the biomethane plant would be used.

Fig. 6 compares the impact caused by both alternative compression systems for each impact category. For the global warming categories, the new scenario in which the energy consumed by the compressor comes from the cogeneration has a greater impact than the initial scenario. After analyzing both unit processes in detail, it was found that the air emissions caused by the cogeneration unit itself during operation are higher than the emissions produced by the electricity, considering the system boundaries. However, in the rest of the categories analyzed, the impact is much lower if electricity from cogeneration is used compared to the use of conventional electricity, as expected.

The results were normalized and aggregated into the areas of protection (Fig. 7). Despite the greater impact produced by the cogeneration process in the global warming categories, the impact of this process is lower in the three areas of protection. The single score is considerably lower in the cogeneration scenario (3.34 mPt) than in the original scenario (5.10 mPt). There is a 34.51 % reduction in the overall environmental impact in the scenario using cogeneration to power the plant. This reduction is particularly significant in the 'human health' category, accounting for almost 38 % of reduction.

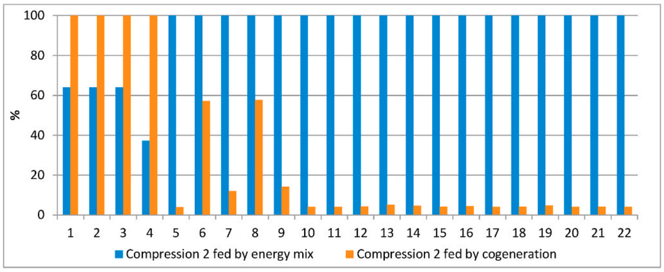

Fig. 6. Comparison of the proportional impact produced by the process Compression 2 fed by energy mix and fed by cogeneration in each impact category. The numbers in X axis represents each of the impact categories defined in Table 5.

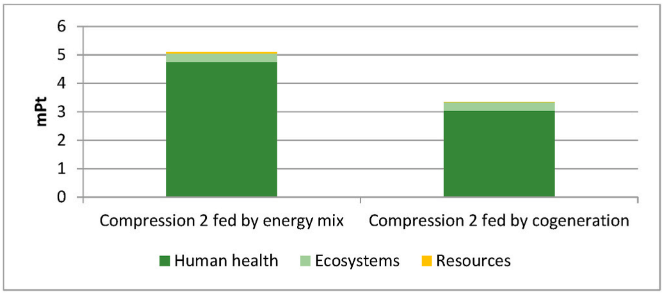

Fig. 7. Comparison of the impact produced by the process compression 2 fed by energy mix and fed by cogeneration in the areas of protection.

3.4.2. *Recommendations*

As presented in the previous section, the stage with the highest overall environmental impact is the CO_2-removal stage, caused mainly by direct emissions into the atmosphere of the same component that is eliminated from the biogas. Therefore, this section provides a recommendation to use this CO_2-rich gas in other applications.

The CO_2-rich gas stream obtained in the biomethane plant has the composition shown in Table 1 (off-gas). Almost 90 % of the gas is CO_2, and the rest is split between CH_4 and N_2 (4.6 % and 4.9 %, respectively) and a small proportion of oxygen (0.8 %).

Carbon capture, utilization, and storage (CCUS) is becoming a very popular decarbonization solution. CO_2 can be captured and stored in underground geological reservoirs with the purpose of reducing the CO_2 concentration in the atmosphere. Alternatively, CO_2 can be an alternative raw material to fossil fuels such as oil, natural gas or coal and therefore be used in a wide range of industrial applications, including the production of valuable chemicals [32]. This has clear environmental benefits, because a gas that would otherwise be emitted into the atmosphere and create an environmental impact is used as raw material. Table S1 briefly describes the two alternatives of storing or using the captured CO_2.

Captured CO_2 can undergo a chemical, biochemical, photochemical, or electrochemical conversion process to manufacture valuable chemical compounds; or it can simply be purified, removing compounds that are not needed or that may be harmful, and used directly in numerous industrial applications. The different processes in which captured and transformed CO_2 can be used are listed in Table S2.

Regarding the CO_2-rich gas purification process, there are several methods. For example, some companies, such as the German company Pentair Haffmanns, have a specific technology for this process. They propose a CO_2 scrubbing plant connected to biomethane plant. The installation includes a CO_2-condensation unit to remove the methane and nitrogen, with a storage tank and a CO_2 evaporator to liquefy it and sell the liquid CO_2 to the consumer.

Once purified, CO_2 can be used in numerous industrial fields. The main potential uses identified in Spain are the following:

1. Carbon fertilization in greenhouses: this increases the concentration of CO_2 inside the greenhouse, thereby increasing the production of certain fruits and vegetables.
2. Wastewater treatment: this allows the alkaline pH of wastewater, especially industrial wastewater, to be reduced to tolerable levels.
3. Food applications in the brewing and carbonated soft drinks industry: CO_2 can be injected in the brewing process of beer and carbonated soft drinks.
4. Food applications for remineralization of drinking water: this application is widely used in desalination plants, with the aim of regulating the hardness of drinking water to avoid corrosion problems in pipes and alterations in water properties.
5. Obtaining dry ice: it can be used in both the food and non-food industry, as it has multiple applications in the chemical and

pharmaceutical industry, food industry, industrial cleaning, etc. It is obtained from the solidification of liquid CO_2, with the help of an ice pelletizer.

It is important to note that in most applications the gas needs to reach a purity of 99.99 % CO_2, which is considered food grade. In other industrial applications, such as wastewater treatment or the production of dry ice for industrial cleaning, a minimum purity of 99.5 % CO_2 is required.

It is additionally advised that a techno-economic analysis of the industrial plant be conducted. While our study provided an estimation of the system's overall environmental impact and identified potential avenues for its reduction, it is also crucial to ascertain the technical and economic viability of these options. The industrial plant under study is already in existence, thereby demonstrating its technical viability. Based on discussions with company personnel, the economic performance of the system is also deemed favorable. The challenge is to incorporate a CCUS solution, as described in this section, into the existing system. CCUS options have been the subject of study for a number of years, and there are numerous instances of successful implementation of such options at an industrial level, which serves to demonstrate their technical viability. However, the economic performance of the industrial plant incorporating a CCUS solution may be compromised in the short term due to the high investment costs. In the long term, such economic performance will largely depend on regulatory aspects. A detailed economic study of such an industrial plant is beyond the scope of this study, but is considered for future work.

4. Comparative environmental impact analysis of the use phase of biomethane as vehicle fuel

This section compares the use of the biomethane generated in the process described in the previous section as a vehicle fuel, with the use of two types of commercial fuel: diesel and petrol. Two vehicles were considered: a 3.5-tonne light-duty vehicle (a panel van) and a 16-tonne heavy-duty vehicle (a lorry intended to collect and transport solid urban waste). Their empty tare weight was considered, along with a yearly travel distance of 20,000 and 75,000 km for the light-duty and heavy-duty vehicle, respectively. Therefore, the functional unit was set as 70,000 and 1,200,000 tkm (tonne-kilometre), respectively.

The system boundaries included the emissions to air associated with the fuel consumption during vehicle driving on the road, i.e., a tank-to-wheel analysis. The following emissions to air were considered: CO, CO_2, NOx, VOC, PM2.5 and SO_2. The environmental impact categories analyzed were global warming, particulate matter, tropospheric ozone formation and terrestrial acidification. The environmental impact associated with the production of the fuels and with the vehicle maintenance was excluded from the study scope. The methods, data sources and software used to calculate the environmental impact were the same as in Section 3.1. This section shows the results obtained by the methodology ReCiPe 2016 endpoint H/A v1.03.

Fuel consumption and distance travelled per year for both vehicles are listed in Table S3. The emission factors considered to calculate the emissions generated for each contaminant and each vehicle are listed in Table S4. The data from Tables S3 and S4 were used to calculate the air emissions for both vehicles, listed in Table 6.

Petrol emits the highest amounts of pollutants for a light-duty vehicle that covers 20,000 km. This is generally due to the higher consumption of petrol compared to diesel for an engine of the same power. Diesel, on the other hand, emits the highest amounts of particulate matter and sulfur dioxide. Diesel is the fuel that emits the highest amounts of pollutants for a heavy-duty vehicle that covers 75,000 km.

The following subsections examine the environmental impact of the light-duty vehicle and of the heavy-duty vehicle, respectively.

4.1. *Light-duty vehicle*

Table 7 shows the absolute environmental impact results for the endpoint indicators of the light-duty vehicle, while Fig. 8A compares the impact to the endpoint indicators produced using the three fuels in the light-duty vehicle. The fuel with the highest environmental impact during its use phase is petrol. It is only surpassed by diesel for fine particulate matter formation and terrestrial acidification due to higher particulate matter and NOx emissions. However, in the categories affecting global warming, although the CO_2 emission factors are the same for diesel and petrol, the average consumption of petrol in a vehicle of this type is higher than that of diesel, hence the emissions are higher and contribute more to the environmental impact in terms of global warming.

Fig. 8B shows the impact to the areas of protection produced using the three fuels in the light-duty vehicle. There is a clear predominance of the impact on human health. The impact of petrol is higher than that of diesel for both human health and ecosystems. The use of biomethane has a much lower impact, particularly on human health. There is no environmental impact to resources because the only impact being considered within the study scope is that of fuel use once it reaches the vehicle's tank, therefore excluding the use of natural resources to produce the fuels. It is obvious however that, if considering such impact, it would be lower for biomethane than for diesel and petrol, since the last two are fossil fuels.

4.2. *Heavy-duty vehicle*

Table 8 shows the absolute environmental impact results for the

Table 7

Characterization results for each impact category considered, compared to those by the use of diesel and biomethane by a light-duty vehicle.

Impact category	Unit	Diesel	Petrol	Biomethane
Global warming, Human health	DALY	4.3338E-08	5.3824E-08	3.7677E-08
Fine particulate matter formation	DALY	1.8900E-08	1.7027E-08	1.6219E-09
Ozone formation, Human health	DALY	2.0392E-10	2.6401E-10	1.9840E-11
Global warming, Terrestrial ecosystems	species.yr	1.3076E-10	1.6240E-10	1.1368E-10
Ozone formation, Terrestrial ecosystems	species.yr	2.9229E-11	4.1204E-11	2.9540E-12
Terrestrial acidification	species.yr	2.1068E-11	1.8791E-11	1.5350E-12
Global warming, Freshwater ecosystems	species.yr	3.5726E-15	4.4370E-15	3.1059E-15

Table 6

Emissions to air from the light and heavy-duty vehicle use, considering travelling distance and different fuels (diesel, petrol and biomethane).

Vehicle	Fuel	CO_2, kg	CO, kg	VOC, kg	NOx, kg	PM, kg	SO_2, kg
Light-duty vehicle covering 20,000 km	Diesel	3266.92	7.63	1.59	15.37	1.13	1.41
	Petrol	4060.76	195.16	18.70	16.94	0.026	0.11
	Biomethane	2841.75	8.00	0.70	1.40	0.026	0.003
Heavy-duty vehicle covering 75,000 km	Diesel	108,451.10	259.41	65.71	1142.00	32.17	57.84
	Biomethane	92,576.25	192.38	8.78	438.75	0.68	0.07

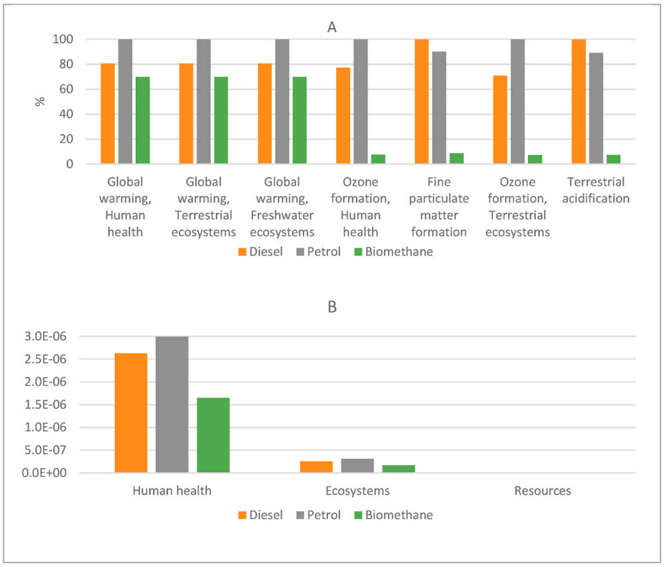

Fig. 8. Environmental impact of the light-duty vehicle with diesel, petrol and biomethane. A) Comparison of the impact with endpoint indicators; B) Comparison of the impact to the areas of protection.

Table 8
Characterization results for each impact category considered, compared to those by the use of diesel and biomethane by a heavy-duty vehicle.

Impact category	Unit	Diesel	Biomethane
Global warming, Human health	DALY	8.3891E-08	7.1549E-08
Global warming, Terrestrial ecosystems	species.yr	2.5312E-10	2.1588E-10
Global warming, Freshwater ecosystems	species.yr	6.9156E-15	5.8982E-15
Ozone formation, Human health	DALY	8.9872E-12	1.1988E-12
Fine particulate matter formation	DALY	2.5630E-08	3.6548E-10
Ozone formation, Terrestrial ecosystems	species.yr	2.0495E-12	2.7339E-13
Terrestrial acidification	species.yr	1.0218E-11	1.3229E-14

endpoint indicators of the heavy -duty vehicle, while Fig. 9A compares the impact to the endpoint indicators produced using the two fuels. The fuel that has the greatest environmental impact is diesel, as expected due to the significant differences in the emission factors, which are generally much lower for biomethane.

Fig. 9B shows the impact to the areas of protection produced using the three fuels in the heavy-duty vehicle. There is a clear predominance of the impact on human health. The use of biomethane has a much lower impact, particularly on human health. As with the light-duty vehicle, there is no environmental impact to resources within the study scope.

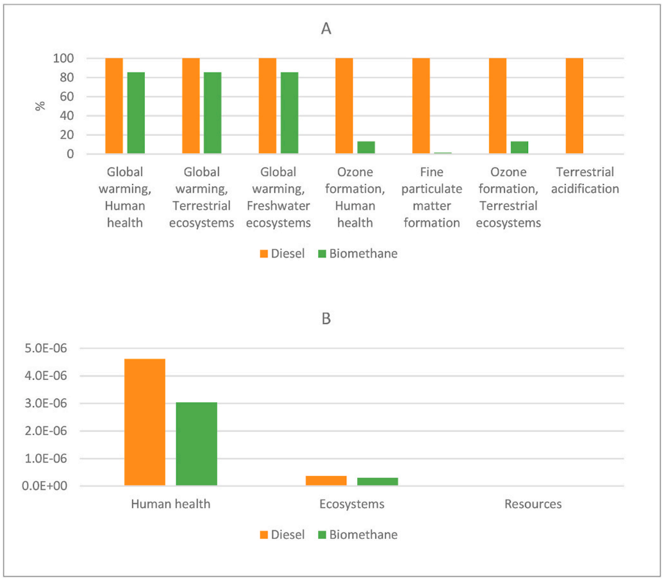

Fig. 9. Environmental impact of the heavy-duty vehicle with diesel and biomethane. A) Comparison of the impact with endpoint indicators; B) Comparison of the impact to the areas of protection.

5. Conclusions

This article analyzes the environmental impact of a biomethane production plant that uses landfill biogas as a feedstock. In Europe, biogas is currently produced primarily through anaerobic fermentation using agricultural residues, manure and energy crops (74 %), and secondly by landfill gas recovery (17 %). The biomethane plant studied permits the utilization of landfill biogas that would otherwise be emitted into the atmosphere, resulting in a significant environmental impact, as well as replaces the use of conventional natural gas, whose production also has a considerable impact on the environment. The aim of this article was to identify the processes within biomethane production that have the highest environmental impact, with a view to further optimizing the overall process. These processes were found to be the CO_2 removal, which contributes 84 % to global warming, and the second stage of biogas compression, which contributes 37 % to fossil resources scarcity.

Given the significant impact of the CO_2 removal stage, recommendations were put forth regarding the potential for capturing and using the CO_2 that is emitted into the atmosphere. This would considerably reduce the impact of the biomethane production plant.

Furthermore, an alternative scenario was proposed to reduce the considerable environmental impact of the second stage of biogas compression, which is mainly due to energy consumption. This scenario consists of supplying this electrical energy by a cogeneration plant installed on the premises of the plant. The results demonstrate a 34.51 % reduction in the overall environmental impact by using cogeneration to power the plant in all categories except for global warming, due to the emissions of the cogeneration plant itself.

The utilization of biomethane in vehicles was also assessed and compared with the use of diesel and petrol. In light-duty vehicles, petrol is the fuel that contributes the most to atmospheric emissions. It is only surpassed by diesel in the categories fine particulate matter formation and terrestrial acidification, due to higher emissions of particulate matter and SO_2. Overall, using biomethane in a light-duty vehicle reduces the environmental impact by 45 % in comparison to the use of petrol, and by 37 % compared to on the use of diesel. In the case of heavy-duty vehicles, diesel has a greater environmental impact than biomethane across all environmental impact categories. Overall, using biomethane in a heavy-duty vehicle reduces the environmental impact by 33 %, compared to that of diesel. This highlights the environmental benefits of using biomethane in vehicles in comparison to the use of conventional fuels.

CRediT authorship contribution statement

Verónica Godoy: Writing – original draft, Software, Investigation, Formal analysis, Data curation. **María Ángeles Martín-Lara:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Guillermo Garcia-Garcia:** Writing – review & editing, Visualization, Validation, Software, Data curation. **Sunil Arjandas:** Project administration, Funding acquisition. **Mónica Calero:** Writing – review & editing, Resources, Project administration, Funding acquisition.

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 ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.121685.

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