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Comparative Life Cycle Assessment and Costing of Biogas Direct Methanation and Water Scrubbing Upgrade

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Biogas CO2 content can be valorized directly through the methanation process without the need for a cleaning step. By integrating biogas production with a methanation system, a net increase in biomethane yield and productivity can be achieved while reducing greenhouse gas emissions. This study aims to compare the environmental and economic performances of a biogas direct methanation system to those of one of the most widely-used conventional methods, namely water scrubbing, by means of Life Cycle Assessment and Life Cycle Costing methodologies, with specific reference to the Campania region context. Two detailed models were developed using Aspen Plus to produce high-purity methane suitable for direct injection into the natural gas grid. From simulations, inventory data of plant operations are collected and used for environmental and economic assessments. While direct methanation presents higher environmental impacts under current energy scenarios, utilizing renewable energy sources can substantially mitigate these impacts. Similarly, direct methanation becomes a cost-effective alternative to water scrubbing if a surplus of wind energy provides hydrogen.

* 1. Introduction

Biogas is a renewable energy source produced by anaerobic digestion of organic matter. It mainly comprises CH4 and CO2; minor impurities such as hydrogen sulfide, ammonia, and siloxanes can be present. Biogas production is becoming increasingly important due to its potential to reduce dependency on fossil fuels and boost decarbonization efforts. After a cleaning phase to remove impurities that could damage downstream equipment, biogas is typically employed in cogeneration systems to generate electricity and heat. In Italy, in 2022, there were more than 2,000 biogas cogeneration (CHP) plants in operation, with a total capacity of 1.46 GW (Noussan et al., 2024). Alternatively, by removing CO2, biogas can be upgraded to biomethane that can be injected into natural gas grids or used for transportation and industrial applications. To further increase the sustainability of biogas plants, the separated CO2 stream can be stored or converted into methane via the Sabatier reaction (Piso et al., 2023). Recently, the direct methanation of biogas, avoiding the separation of CO2, has been investigated in the literature, and different plants have been developed to demonstrate the technical feasibility (Tommasi et al., 2024). However, the carbon dioxide methanation reaction presents some challenges related to heat management of exothermic reaction and conversion efficiency (Bareschino et al., 2020). Zhang et al. (2020) evaluate the life cycle greenhouse gases (GHG) emissions of biomethane production pathways through biogas upgrading or methanation. They conclude that using low-GHG electricity for electrolysis is crucial for achieving lower emissions than fossil alternatives. Minardi et al. (2023) evaluate the techno-economic and environmental feasibility of producing synthetic methane (SNG) in a wastewater treatment plant, highlighting that while SNG is not currently competitive in the gas market, future cost reductions in technology and lower electricity prices could make it viable. This study aims to broaden the knowledge of biogas upgrading technologies' environmental and economic impacts. To achieve this goal, upgrading models were developed and simulated with Aspen Plus; the resulting operational data were subsequently used to conduct a Life cycle assessment (LCA) and Life cycle costing (LCC) analysis within the context of the Campania region.

* 1. Materials and methods

Direct methanation and water scrubbing were modelled considering a plant size capable to produce about 280 Nm3/h of biomethane. The biogas is assumed to be produced from the anaerobic digestion of a mixture of 70 % manure and 30 % biowaste. When the digester is fed with manure, the resulting biogas can exhibit H2S concentrations of up to 4000 ppm (Singhal et al., 2017). Therefore, it was assumed that the biogas undergoes a preliminary desulfurization phase to remove H2S contaminants. As a result, the biogas is assumed to consist of 60 % CH4 and 40 % CO2 by volume and available at a temperature of 35°C and a pressure of 1 bar. Operational parameters were selected to obtain biomethane compliance with Italian regulatory standards for injection into the natural gas grid. Specifically, process constraints were established to achieve a final biomethane composition containing less than 2.5 % CO2 and less than 2 % H2 by volume.

* + 1. Biogas upgrading by direct methanation

The Sabatier reaction involves the conversion of CO2 and H2 into CH4 and H2O, as described by R1.

|  |  |
| --- | --- |
|  | R1 |

Hydrogen is assumed to be supplied by an alkaline electrolyzer (AEL). The modelling of the AEL system was carried out using a simplified approach (Sánchez et al., 2020). Regarding methanation, a significant challenge lies in managing the heat generated by the highly exothermic Sabatier reaction. The heat released during the reaction increases the temperature within the reactors, which reduces the degree of CO2 conversion due to thermodynamic constraints. Therefore, to achieve high-purity methane suitable for direct injection into the natural gas grid and exploit the heat of reaction, the proposed methanation system consists of three fixed bed reactors arranged in series; the first two operate adiabatically while the last one is cooled. The Aspen Plus flowsheet of the complete plant layout is presented in Figure 1.

A screenshot of a video game

Description automatically generated

Figure 1: Aspen Plus flowsheet for biogas upgrading by direct methanation.

In the electrolyzer section in Figure 1, the NRTL property method is adopted to estimate thermodynamic properties. The feed water is pressurized to 9 bar, mixed with water recycled from the separator and then heated to the operating temperature of the electrolysis cell, set at 75°C. The electrolyzer cell is represented as an RSTOIC reactor in which the water-splitting reaction occurs. The reaction conversion degree is defined based on Faraday’s efficiency. The H2 and O2 produced are separated in an ideal separator. Following separation, the hydrogen is pressurized to 18 bar and sent to the methanation section. In the methanation section, the RKSMHV2 property method was adopted. The selected catalyst was a commercial NiAl2O3, while the kinetic model was taken from Xu and Froment (1989). Methanation reactors were simulated using the RPLUG model, accounting for pressure drops through the catalyst bed with the Ergun equation. Biogas is compressed to the operating pressure of reactors mixed with H2 and H2O and heated to inlet temperature before being fed to the first reactor. Water is recycled from the first flash unit, which is already available at high pressure and added to the reactants in order to lower the temperature and prevent carbon formation. The optimal H2O:CO2 ratio was evaluated through chemical equilibrium calculation. At the exit of the first methanator, the product gas undergoes cooling, and the condensed water is separated from the gas stream. The gas stream is subsequently reheated to the inlet temperature of the second reactor. At the exit of the second methanation stage, a similar sequence of cooling, water removal, and gas reheating is carried out. The third reactor is designed as a cooled shell-and-tube configuration, consisting of 20 tubes operating with a constant coolant temperature. Given the strict limit on the residual content of H2 in biomethane, a conversion greater than 98.7 % is required. Therefore, the system was designed to operate with a sub-stoichiometric H2:CO2 ratio of 3.9, as suggested by Jürgensen et al. (2015). The geometrical dimensions of the three reactors, operating parameters and catalyst properties are reported in Table 1.

Table 1: Parameters adopted in the simulation of biogas direct methanation.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Parameter | Value | Parameter | Value | Parameter | Value | Parameter | Value |
| p | 18 bar | Lm1=Lm3 | 4 m | dm3 | 0.2 m | H2:CO2 | 3.9 - |
| Tin,1=Tin,2 | 270 °C | Lm2 | 4.5 m | U | 10 W/(m2·K) | H2O:CO2 | 0.4 - |
| Tin,3=Tc | 300 °C | dm1 | 0.4 m | dp | 3 mm | ρ | 2350 kg/m3 |
| Tc | 300 °C | dm2 | 0.45 m | Nt | 20 - | ɛb | 0.4 - |

* + 1. Biogas upgrading by water scrubbing

The process layout of upgrading via water scrubbing is reported in Figure 2 (Cozma et al., 2014).

A screenshot of a video game

Description automatically generated

Figure 2: Aspen Plus flowsheet for biogas upgrading by water scrubbing.

Biogas is compressed to 10 bar and mixed with a recycled gas stream from the flash unit before entering the absorption column. Simultaneously, water from the regeneration column, supplemented with a make-up water stream, is pressurized to 10 bar and introduced at the top of the absorption column. The water flows counter-currently to the biogas within the column, absorbing CO2. Due to the elevated operating pressure, methane is also partially absorbed; to enhance methane recovery, the intermediate flash unit separates a methane-rich stream, which is then recycled back into the absorber. A countercurrent air flow regenerates the remaining liquid from the flash vessel once it has been depressurized to 1 bar. To prevent the accumulation of air within the system, 1 % of the regenerated water is purged.

* + 1. LCA and LCC assumption

The two biogas upgrading technologies are named the conventional scenario for water scrubbing and the proposed scenario for direct methanation. To align with the objectives of the study, the functional unit selected for both LCA and LCC is 1 Nm3 of outlet biomethane compliant with Italian regulatory standards, while the system boundary was defined as cradle-to-gate. Concerning the LCA, simulations were performed using OpenLCA software. Environmental impacts were evaluated using the ReCiPe Midpoint H method, with background data from the Agribalyse database. The inventory data of both systems are detailed in Figure 3.

The environmental impacts associated with the manufacturing of methanation reactors are mostly due to the catalyst (Bareschino et al., 2024) . Consequently, the LCA focused on plant operations, excluding the environmental impacts of plant manufacturing but the catalyst. Inventory data for the NiAl2O3 catalyst, not detailed in Figure 3 were taken from Sayyah et al. (2023). Upstream impacts of substrates and potential downstream benefits of digestate utilization were excluded. The methanation process was modelled with complete thermal integration; as a result, no external heat input was required, while 90 % of the excess heat generated in the process was treated as a credit. Avoided environmental impacts were calculated by replacing heat produced by burning natural gas. No credit was assigned for the oxygen produced by the electrolyzer, as it is assumed to not be valorized. However, this byproduct could be repurposed for industrial applications such as oxy-combustion, biological treatments or medical uses, potentially generating additional environmental and economic benefits.

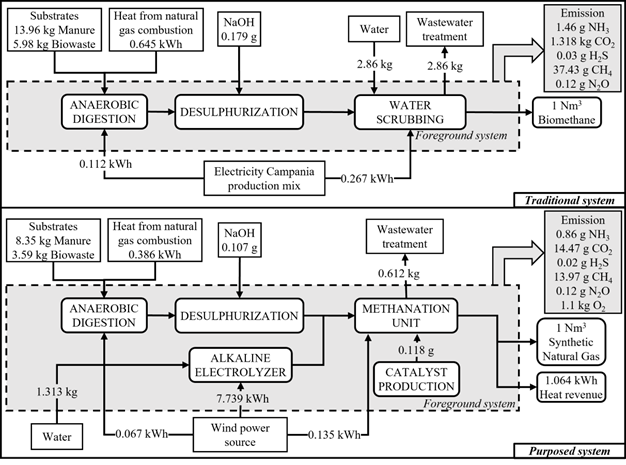


Figure 3: System boundaries and inventory data of conventional and proposed biogas upgrading systems.

The environmental impacts related to transportation were excluded from the analysis. For LCC, the methodology outlined by Turton for estimating bare module costs was applied. All cost data were updated to 2023 using the Chemical Engineering Plant Cost Index and converted to euros. Then, the calculation of capital costs followed the methodology established by the National Energy Technology Laboratory. Specifically, the Total-As-Spent Capital (TASC) includes bare erected costs, engineering, procurement and construction management costs, process contingencies, project contingencies, and additional costs related to startup, financing and other owner’s costs. The TASC was annualized, adopting an interest rate of 5 % across a plant lifetime of 20 years and divided by the annual plant productivity to obtain Capital expenditure in €/Nm3. The operating costs for the systems were calculated on an annual capacity factor of 91.3 %. Labor costs were estimated by multiplying the annual salary of each operator, assumed to be 40 k€, by the number of operators required, one for water scrubbing and two for direct methanation. Maintenance costs were determined to be 3 % of the TASC. The annual cost of raw materials was calculated using unit prices of 0.19 €/kWh for electricity and 0.3 €/m3 for water. Additionally, a carbon tax of 24.6 €/t of CO2 emissions was applied to quantify the environmental cost of CO2 released in the water scrubbing system. The cost of producing biomethane was then calculated by adding operating costs to the capital expenditure. The economic calculations excluded the processes of anaerobic digestion and biogas desulfurization. Instead, a 0.30 €/Nm3 cost was adopted to represent the combined biogas production and desulfurization phases. The environmental impacts and economic performances of the plant operational phase were assessed under two distinct electricity mix scenarios. The conventional system is electrically driven by the current electricity mix in the Campania region, as reported by the Italian Transmission Operator mix comprises 8.5% hydroelectric, 44.3 % natural gas-fueled conventional power plants, 36.9 % wind, and 10.3 % photovoltaic energy (TERNA, 2024). The proposed system is assumed to be electrically driven by excess renewable energy. In particular, the environmental impacts of electricity supply are derived from wind power, while for economic calculation, electricity is produced at zero cost.

* 1. Results

Figure 4 presents the environmental impact assessment results for both the conventional and proposed systems. The conventional system is evaluated under two scenarios: the current energy production scenario and a wind energy production scenario. In this context, shifting to wind-generated electricity notably reduces the impacts on water consumption, mineral resource scarcity, and fossil resource scarcity, with decreases of 21%, 17%, and 13%, respectively. In the proposed scenario, the results indicate that the direct methanation system exhibits lower environmental impacts across all categories. Only water consumption impacts are similar for direct methanation and water scrubbing in the renewable scenario, being both 1.59·10-3 m3/Nm3. The most significant improvement is in fossil resource scarcity, where the proposed scenario reduces the impact by 75 %. Global warming is also significantly reduced in the proposed system, decreasing by 61 %, from 2.43 kgCO2eq/Nm3 for the conventional system in the renewable scenario to 0.94 kgCO2eq/Nm3 for the proposed system. For all other categories, the impact reduction between the conventional system powered by wind energy and the proposed system ranges from 51% in ozone formation, terrestrial ecosystems to 42% in freshwater eutrophication.

A graph of different sizes and colors

Description automatically generated with medium confidence

Figure 4: Environmental impact results for the conventional system under the current electricity mix in the Campania region and conventional and proposed systems under wind-driven electricity production.

Figure 5 presents a comparative LCC analysis of conventional biogas upgrading technology versus direct methanation. The latter has the highest capital expenditure, significantly more expensive than water scrubbing.

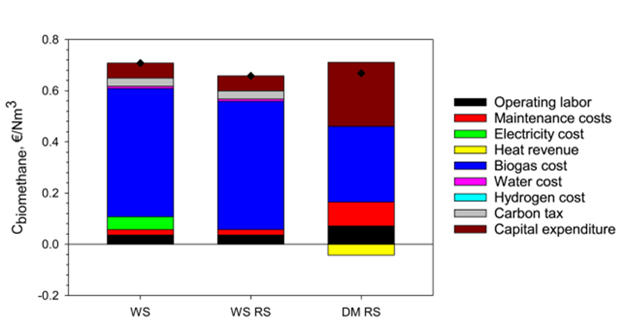


Figure 5: LCC results for the conventional (WS) proposed systems under the current energy mix and for the conventional (WS RS) proposed systems (DM RS) under the renewable energy scenario.

It is approximately 0.06 €/Nm3 for water scrubbing and 0.25 €/Nm3 for direct methanation. Labor and maintenance costs are 0.036 €/Nm3 and 0.022 €/Nm3 for water scrubbing and 0.072 €/Nm3 and 0.093 €/Nm3 for methanation, respectively. The cost of electricity is 0.05 €/Nm3 for water scrubbing in the current energy production while for the renewable scenario under the assumption made is zero. The purchase of biogas represents the largest expense in water scrubbing, accounting for about 0.50 €/Nm3 of biomethane cost, while in the case of methanation, it affects the cost of biomethane by about 0.30 €/Nm3. This difference partially arises from the fact that water scrubbing requires a biogas flow rate 1.66 times higher than that needed for methanation to achieve the same biomethane output. The cost of water is negligible for both systems. The carbon tax contributes 0.032 €/Nm3 for water scrubbing, while heat credits allow a profit of 0.043 €/Nm3 for direct methanation. Overall, the LCC analysis reveals that biomethane produced by water scrubbing costs 0.708 €/Nm3 with the current energy production mix and 0.658 €/Nm3 in the renewable energy scenario; while biomethane produced via biogas direct methanation costs 0.668 €/Nm3. Note that biogas costs significantly influence the final biomethane price, representing approximately 90% of the total cost in the water scrubbing scenario.

* 1. Conclusions

The LCA indicates that direct methanation outperforms water scrubbing in all impact categories, resulting in a reduction of CO2-equivalent emissions by 1.49 kgCO2eq per normal cubic meter of biomethane produced. From an economic perspective, assuming the electricity used is generated from surplus wind energy and available at zero cost, the cost of biomethane production via direct methanation is 0.67 €/Nm3, making it economically competitive with water scrubbing, which costs 0.66 €/Nm3.

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Nomenclature

dm – Diameter of reactors, m

dp – Catalyst diameter, mm

ɛb – Bed void fraction, -

Lm – Length of reactors, m

Nt – Number of tubes in the cooled reactor, -

p – Operating pressure, bar

ρ – Catalyst density, kg/m3

T – Temperature, °C

U – Heat transfer coefficient, W/(m2·K)

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