From Biogas to Propulsion and Power: A Life Cycle Perspective on Fuel Synthesis and CHP Integration

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Abstract Anaerobic digestion of organic waste offers a promising pathway for energy production and sustainable waste management. Within this framework, five pathways for biogas energy utilization were evaluated, and their environmental performance was compared, focusing on marine transportation and combined heat and power (CHP) production. In Scenarios 1 and 2, biogas is upgraded to biomethane, while the captured CO_2 is used to synthesize additional methane (Scenario 1) or methanol (Scenario 2). The upgraded methane is used to produce CHP, while the synthesized fuels are used for marine transportation. In Scenarios 3 and 4, the upgraded methane is liquefied and used in marine transportation. Finally, in Scenario 5, the direct use of biogas for CHP, without further upgrading or fuel synthesis, was evaluated. A Life Cycle Assessment (LCA) was performed using OpenLCA software, Ecoinvent database, and the Environmental Footprint method. Regarding Global Warming Potential, Scenario 1 causes the lowest impact, while Scenario 5 causes the highest. In the scenarios where CO_2 is utilized to produce methanol instead of methane, the impact is higher by 3.3-3.4%. These results suggest that additional criteria, such as fuel handling and life cycle cost, should also be considered in future decision-making.

Keywords: Maritime transportation; Energy transition; Power-to-x; Electrofuel; Greenhouse Gas emissions

1. Introduction

The production of biogas through anaerobic digestion is a promising pathway for both clean energy production and sustainable waste management. Biogas can be either utilized directly to produce CHP or upgraded to biomethane, which can substitute for fossil methane. The CO_2 contained in the biogas can either be released into the atmosphere after upgrading or captured and reacted with H_2 to synthesize methanol or methane, which are considered alternatives for decarbonizing marine transportation (Savva et al., 2025).

In this study, five different biogas energy utilization scenarios are assessed. In all scenarios, the first step involves biogas production and purification. In scenarios 1-4, the upgrade of biogas and H_2 production from electrolysis are also included. In Scenario 1, CO_2 reacts with H_2 to produce methane, which is liquefied and transported to a port for use as marine fuel in dual fuel mode with marine gas oil (MGO). The upgraded biomethane is used to produce CHP. Scenario 2 follows the same process as Scenario 1, but methanol is produced instead of methane. Scenarios 3 and 4 are structurally similar to Scenarios 1 and 2, respectively, with the difference that the upgraded biomethane is liquefied, transported to the port, and used as a marine fuel. In Scenario 5, the biogas is used directly to produce CHP without upgrading or fuel synthesis.

2. Materials and Methods

LCA was conducted according to ISO standards to assess and compare the environmental impacts of the 5 alternative pathways of biogas energy utilization. Since both propulsion energy and electricity from CHP are produced from the scenarios, the System Expansion – Additive method was applied to solve multi-functionality. The functional unit is defined as the "Transportation of 10,000 tons of payload over 1 km with a RoPAX vessel and the production of 2,037.75 MJ of electricity from CHP". In scenarios where bio- or electrofuels do not fully meet the functional unit, the shortfall energy is produced by fossil methane to ensure comparability. System boundaries are set as "Cradle-to-Grave", including biogas production and purification, and, where applicable, biogas upgrade, electrolysis, methane or methanol synthesis, methane liquefaction, fuel transportation, fossil fuels extraction and processing, and finally, fuels utilization.

Life Cycle Inventory was developed based on literature data (Balcombe et al., 2021; Collet et al., 2017; Fedeli et al., 2023; Fridell et al., 2021; Gerloff, 2021; Lombardi and Francini, 2020; Uusitalo et al., 2017). Energy consumption for each vessel was calculated based on the LHV and density of each fuel, considering the lost cargo space due to fuel storage volume. Electricity required for the upstream process of bio- and electrofuels was assumed to be provided by wind turbines (30% efficiency), and lithium-ion batteries, while heat was assumed to be provided by an electric heater with 100% efficiency. OpenLCA software was used to perform the analysis, and the Ecoinvent database was used for background data. Finally, Environmental Footprint v3.1 was selected as the impact assessment method. The impact categories that are included in this study are: Global Warming Potential (GWP), Acidification Potential (AP), and Human Toxicity Carcinogenic Potential (HCTP).

3. Results

In Figure 1, the relative comparison between the different pathways is presented. Regarding GWP, the highest impact is caused in Scenario 5, where biogas is used directly to produce CHP. In contrast, the lowest impact is caused in scenario 1, where CO_2 is captured and utilized to synthesize methane, and the upgraded biomethane is used in CHP. Scenarios that synthesize methane from CO_2 led to a lower impact than the scenarios that synthesize methanol. This is due to a higher final use efficiency of methane, which leads to a lower fossil natural gas demand. However, due to a lower upstream impact in the life cycle of methanol compared to methane, the increase in GWP from scenario 1 to 2 is only 3.4%, while from scenarios 3 to 4 is 3.3%. Moreover, the use of upgraded biomethane to produce CHP rather than as a marine fuel reduces GWP by 3%, due to the lower electricity demand for the liquefaction and transportation to the port.

Regarding AP, scenarios 1 and 3 cause the lowest and nearly identical impact, while scenarios 2 and 4 cause the highest, and identical results between them. The increased impact in the methanol scenarios is due to the higher NO_x emissions that occurred in the methanol final use compared to methane, and due to the increased fossil LNG demand. Similarly, scenario 5 causes a higher impact compared to scenarios 1 and 3, due to increased NO_x emissions from biogas combustion and higher fossil LNG production.

Finally, regarding HCTP, the highest impact is caused in the 5th scenario, due to the highest fossil LNG production. Scenarios 3 and 4, where the upgraded biomethane is used as a marine fuel, outperform scenarios 1 and 2. This is due to the higher impact that is caused by fossil LNG, which is not required, compared to the fossil natural gas provided by pipelines to produce CHP.

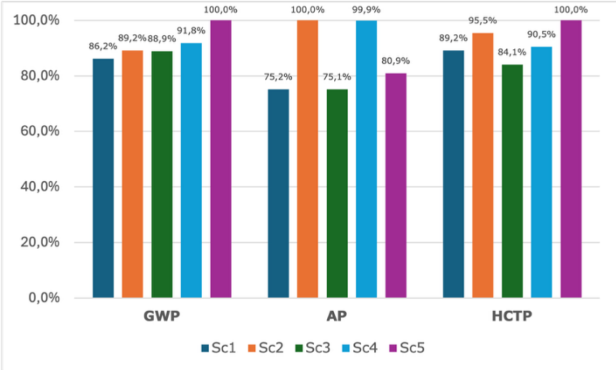

Figure 1. Relative environmental comparison between the Scenarios

4. Conclusions

This study demonstrates that capturing the CO_2 content of biogas and utilizing it to synthesize electrofuels is crucial to achieve further reduction in GWP. In all of the evaluated categories, the lowest environmental impact is caused in the scenarios where methane is produced, instead of methanol. In terms of GWP, it is more beneficial to utilize the upgraded biomethane to produce CHP, as it avoids further liquefaction and transportation. Finally, despite that the CO_2-to-methane scenarios perform better overall, the increase in GWP in the CO_2-to-methanol scenarios is modest (3.3-3.4%). Therefore, additional criteria, such as fuel handling, storage logistics, and life cycle cost, should be considered in future assessments and decision-making.

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