EVALUATING DECARBONIZATION POTENTIAL OF E-METHANOL-TO-GASOLINE FOR ROAD TRANSPORTATION IN SAUDI ARABIA USING LIFE-CYCLE ASSESSMENT

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Overview

Aligned with the global efforts moving towards sustainable energy systems and the need to triple renewables capacity by 2030, the transport sector in Saudi Arabia is set to significantly increase the implementation of clean transportation technologies. The focus will be shifted towards technologies that utilize fuels derived mainly from renewable sources. Electrofuels (e-fuels), which are fuels produced from electrolytic hydrogen, are among the highly prioritized solutions by policymakers to decarbonize the transportation sector and are expected to play a critical role in the country's energy landscape [1]. The burgeoning field of e-fuels, characterized by the conversion of electrical energy into chemical energy, emerges as a strategic approach to managing excess renewable energy. This is particularly pertinent in the scenario of Saudi Arabia, an eminent oil-producing country with abundant renewable energy, currently transitioning towards an energy portfolio that is more diverse and less GHG-intensive, in alignment with the objectives delineated in the Saudi Green Initiative [2]. Today, the country's energy mix is almost entirely reliant on fossil fuels with annual greenhouse gas (GHG) emissions from fuel combustion amounting to 483.6 million tons [3-5]. However, the country's solar and wind capacities are expected to grow and contribute 35% and 15% respectively to the electricity generation by 2030 [6] .

This research studies the environmental impacts of e-fuels within the Saudi Arabian road transportation sector, concentrating on the production of e-gasoline via the methanol-to-gasoline (MTG) synthesis process. The study is innovatively structured to incorporate a well-to-wheel (WtW) life-cycle assessment (LCA), focusing on the integration of renewable hydrogen, sourced from solar or wind energy, through proton exchange membrane (PEM) electrolysis, combined with carbon dioxide sequestration techniques. Given the nation's heavy reliance on fossil fuels and the consequential GHG emissions, with the transport sector being a significant contributor, the study is aligned with the Saudi Green Initiative's targets of energy diversification and GHG emission reduction. The study contemplates various CO_2 source scenarios, encompassing Carbon Capture and Storage (CCS) (specifically at Yanbu and Jubail) and direct air capture (DAC) by both low-temperature (LT) and high-temperature (HT) variants. The objective is to delineate the most efficacious method for e-fuel production in terms of minimizing the carbon footprint of the nation's road transportation sector.

Methods

In this study, sources of carbon dioxide are delineated as stemming from LT DAC and HT DAC powered by renewable electricity, alongside point sources (PS) in Yanbu and Jubail operating on grid-based power, and maritime operations implementing ship-based carbon capture (SBCC) for delivery at Duba port. The CO_2 streams from Yanbu and Jubail encompass ammonia production, petrochemical operations, power and desalination facilities, and refinery activities, with allocations determined using annual emission data. In line with the overall framework, the e-MTG synthesis facility, the DAC unit, and the hydrogen production unit based on PEM electrolysis are all assumed to be located in Neom. Captured CO_2 from PS and SBCC is transported via truck, pipeline, or ship. This analysis examines the WtW GHG emissions of ten e-MTG production scenarios located in Neom, Saudi Arabia, featuring diverse CO_2 origins and transport methods.

The scope of this study spans the entire lifecycle from feedstock acquisition to on-road utilization, including the Scope 3 emissions of power plant, battery storage, and the PEM electrolyser. This encompasses energy demands and emission profiles of mixing wind and photovoltaic (PV) power plants in the process. However, energy consumption and emissions associated with the construction of CCS, DAC, and e-MTG fuel production facilities are excluded. This methodology follows the ISO 14040 and 14044 standards. The functional unit chosen for this study is 1 MJ of e-MTG gasoline. An Aspen Plus model for e-MTG gasoline is developed, building on established literature to integrate the

CO_2-to-methanol and CO_2-to-gasoline pathways [7-9]. This integration enables precise quantification of GHG emissions associated with direct environmental flows.

The LCA analysis uses the GREET 2023 model as the major tool to build the life-cycle inventory using ecoinvent database and the literature. Additional public reports are used as supplements, especially for data specific to the kingdom. The LCA results are compared with those of conventional fuels as well as alternative fuels used in road transportation, aiming to provide a comprehensive assessment of fuel potential for transport decarbonization in Saudi Arabia.

Results

By conducting a life cycle assessment of e-MTG gasoline, the majority of emissions, at approximately 73.2g CO_2eq. per MJ, were primarily linked to the combustion phase, while the production stage contributed emissions ranging between 29.8 and 63.5gCO_2eq. per MJ. However, the results show that the use of different CCS and DAC technologies yielded different GHG emissions due to differences in CO_2 transportation scenarios and energy efficiencies.

In the evaluated scenarios, e-MTG gasoline demonstrates marked GHG emission reductions, ranging from 28.6 to 62.3 gCO_2eq per MJ, compared with 92.1gCO_2eq per MJ for conventional gasoline. Under a 32.1% wind and 67.9% solar energy mix, e-gasoline derived from HT DAC achieves the lowest global warming potential, reducing GHG emissions by 67.7%. E-gasoline obtained via LT DAC follows at 58.6 gCO_2eq per MJ, influenced by the comparatively higher life cycle impacts of the absorbent. In PS and SBCC cases, pipeline-based CO_2 transport consistently emits less than ship and truck transport, with truck systems producing the highest emissions. Pipeline and truck delivery of CO_2 from SBCC each yield 32.7 and 36.6 gCO_2eq per MJ, respectively. Sources from Yanbu and Jubail vary between 51.4 and 63.5gCO_2eq per MJ, with Yanbu-based options exhibiting lower overall emissions.

Conclusions

In ten e-MTG gasoline production scenarios within Saudi Arabia's evolving energy landscape, a well-to-wheel life-cycle assessment indicates substantial greenhouse gas emission reductions compared with conventional gasoline. The most favorable outcomes arise from sourcing CO_2 via HT and LT DAC, both yielding notable decreases in global warming potential. Variations observed among pipeline, ship, and truck transport highlight the significance of CO2 transport distance and energy efficiency, with pipeline scenarios generally recording the lowest GHG emissions, while truck scenarios incur the highest. These findings align with Saudi Arabia's Green Initiative, demonstrating e-fuels as a pivotal step toward a broader, lower-carbon energy mix and emphasizing the importance of renewable energy and advanced carbon capture technologies in mitigating transportation-sector emissions. Future evaluations may encompass alternative green hydrogen production technologies, including PEM, solid oxide electrolyzer cell, and Alkaline electrolyzers.

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