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Fueling a green future: unlocking the environmental potential of CO_2-derived power-to-X liquid fuels *via* life cycle assessment

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Decarbonizing the transport sector requires integrating renewable energy with carbon capture technologies to produce sustainable fuels. This study evaluates four wind-powered Power-to-X (P2X) fuel systems, each using a different CO_2 source: biogas, cement production, direct air capture (DAC), and steel manufacturing. Life cycle assessment (LCA) across seven environmental impact categories shows that all P2X pathways result in substantially lower environmental impacts compared to conventional fossil- and biomass-based fuels, with global warming potentials of 2480 and 1710 kg CO_2 eq. per t_{fuel}, respectively. The P2X systems achieved a global warming potential (GWP) of 81.3–97.9 kg CO_2 eq. per t_{fuel}, corresponding to 98% greenhouse gas savings relative to the RED III fossil fuel benchmark. The cement-derived CO_2 scenario offers the lowest impacts due to reduced energy and material demands in CO_2 capture, while DAC incurred the highest burdens due to elevated energy and material requirements. Under Finnish conditions, utilization of excess heat from the P2X processes could supply 555–595 households, displacing 1191.6–2456.4 t CO_2 per year from light fuel oil and 1709.9–1832.8 t CO_2 per year from natural gas, while generating €827k–886k in annual revenue. These findings highlight the potential of strategically sourced CO_2 and renewable energy integration to deliver low-carbon fuels with significant environmental and socio-economic co-benefits in regions with comparable renewable and district heating infrastructures.

Sustainability spotlight

The global transport sector is a major contributor to greenhouse gas emissions, and decarbonizing it is critical for meeting climate targets and limiting global warming. Current liquid fuels rely heavily on fossil resources, which are unsustainable and contribute to air pollution and climate change. This study addresses the urgent need to produce low-carbon, renewable alternatives by evaluating wind-powered CO_2-derived Power-to-X (P2X) liquid fuels, considering different CO_2 sources. The sustainable advancement of this work lies in demonstrating that strategic selection of CO_2 sources, coupled with renewable energy integration, can achieve up to 98% greenhouse gas savings relative to the RED III fossil fuel comparator, while also providing additional benefits such as district heating and economic value creation. By highlighting the environmental and societal co-benefits of P2X systems, this work contributes to the transition toward sustainable energy systems. It aligns with the following UN Sustainable Development Goals: affordable and clean energy (SDG 7), industry, innovation, and infrastructure (SDG 9), responsible consumption and production (SDG 12), and climate action (SDG 13).

1. Introduction

The urgent global imperative to mitigate climate change demands a rapid transition from fossil-based energy systems to sustainable alternatives that drastically reduce greenhouse gas (GHG) emissions. Among these alternatives, green methanol has emerged as a promising candidate due to its versatility, renewable origin, and compatibility with existing industrial processes. Green methanol, produced from renewable feedstocks such as captured carbon dioxide and green hydrogen, serves as a promising fuel and chemical precursor.[1,2] Its compatibility with existing infrastructure facilitates integration across various energy systems.[3]

The production of green methanol from captured carbon dioxide exemplifies a carbon capture and utilization (CCU) technology that contributes to global efforts to reduce GHG emissions.[4,5] CCU involves capturing CO_2 from industrial sources or directly from the atmosphere and converting it into value-added products such as fuels and chemicals. Understanding the environmental impacts of CCU pathways, particularly the utilization of CO_2 in fuels like green methanol is essential for evaluating their potential in supporting a sustainable, low-carbon energy future.[6]

The transport sector remains the major contributor to GHG emissions in Europe, accounting for nearly 26% of total, with road transport responsible for 43.9%.[7] Decarbonizing this

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sector is central to the European Green Deal's ambition of achieving net-zero emissions by 2050.[8,9] However, to realize these targets, significant investments are needed, particularly in alternative technologies.[10]

Power-to-X (P2X) for methanol synthesis has gained significant attention over the years due to its potential for decarbonizing the transport and chemical industries. Several studies have reviewed the technology, highlighting advancements in P2X systems for methanol production.[3,11–13] Techno-economic analyses have also been conducted, assessing the economic feasibility of green methanol production from renewable electricity.[14,15] Furthermore, the conversion of green methanol to valuable products such as formaldehyde,[16] acetic acid,[17] and dimethyl ether (DME)[18,19] has been explored, emphasizing the versatility of green methanol in the chemical industry. Life cycle assessment (LCA) studies have investigated the environmental implications of methanol synthesis[5,20] and downstream conversions, highlighting their potential to reduce greenhouse gas emissions compared to fossil-based fuels.[21,22] In addition, integrated techno-economic analysis and LCA of green methanol have been conducted,[23,24] providing a holistic understanding of their environmental and economic trade-offs.

Among the various downstream applications of green methanol, olefin oligomerization represents a key pathway for converting methanol-derived olefins into hydrocarbons suitable as drop-in transportation fuels, such as diesel and jet fuels.[25,26] In our previous work, we evaluated the techno-economic feasibility of converting green methanol into liquid transport fuels *via* methanol-to-olefins (MTO) and Mobil Olefins to Gasoline and Distillate (MOGD) syntheses within the P2X framework.[18] However, our earlier study did not include a comprehensive environmental assessment, particularly an LCA, leaving the environmental impacts of the pathway largely unexplored.

Currently, an increasing number of LCA studies have investigated green methanol synthesized *via* P2X pathways. However, only a limited number of these studies focus on downstream products derived from green methanol. For instance, Thonemann and Pizzol[27] conducted a consequential LCA of CCU into methanol and kerosene, evaluating both near- and long-term scenarios. Their results indicate that kerosene produced *via* synthetic fuel pathways result in a higher GWP compared to conventional kerosene. Matzen and Demirel[28] conducted a cradle-to-grave LCA of green methanol and DME. The fuels were produced *via* wind-powered electrolysis for H_2 and CO_2 captured from ethanol fermentation, resulting in over 80% reductions in GHG emissions and fossil depletion. Similarly, Zhaurova *et al.*[29] assessed the environmental impact of a power-to-gasoline plant in Finland, using CO_2 from cement production as the carbon source. The study focused primarily on GHG emissions, providing a climate-centric evaluation of the process. While these studies assess downstream products synthesized from green methanol within the P2X framework for sustainable fuel production, comprehensive environmental assessments integrating multiple impact categories remain scarce, particularly for MTO–MOGD pathways. Specifically, comparative evaluations of CO_2 feedstocks such as industrial point sources *versus* direct air capture (DAC) are lacking. DAC technologies have shown promise for achieving negative emissions but entail distinct energy and material requirements that must be carefully evaluated. This highlights a critical gap in understanding the full environmental implications of using methanol in synthetic fuel and chemical production.

Building on our previous work,[18] this study addresses existing knowledge gaps by conducting a comprehensive LCA of the MTO–MOGD processes within the P2X context. To provide a holistic perspective on sustainability and scalability, several impact categories were evaluated to characterize the performance of the integrated systems. By comparing different CO_2 capture sources and examining trade-offs related to carbon capture and circularity, this study bridges techno-economic modeling with environmental sustainability metrics. The results of an LCA can be influenced by modeling assumptions and decisions, particularly those concerning system boundaries and input parameters, which are often subject to uncertainty. Therefore, a sensitivity analysis was also conducted to assess the robustness of the outcomes and their responsiveness to variations in key variables. The findings are expected to make a significant contribution to the ongoing discourse on sustainable fuel production by filling important knowledge gaps in the LCA of P2X technologies. Although the LCA was conducted within the Finnish context, the methodology and findings are applicable to other regions with similar energy infrastructures and industrial sectors. To the best of the author's knowledge, this study represents one of the first comparative LCAs of CO_2-derived fuels within the P2X MTO–MOGD framework.

2. Materials and methods

2.1. Goal and scope

The goal of this study is to assess the environmental performance of producing transport fuels *via* oligomerization, employing green methanol as a renewable carbon feedstock. The scope of the LCA follows a cradle-to-gate system boundary, consisting of all processes from raw material acquisition to the production of liquid transport fuels (Fig. 1). This includes CO_2 capture, hydrogen production through water electrolysis, methanol synthesis, and the subsequent conversion of methanol into fuels. The use and end-of-life phases are excluded due to the scope and the identical downstream MTO–MOGD processes in all scenarios. Their exclusion is further supported by limited data availability, given the emerging status of P2X technologies. Four scenarios are evaluated, each differing in the source of CO_2 used for methanol synthesis. Different CO_2 capture sources are compared to assess their impact on the system's overall environmental performance. The LCA is conducted in accordance with the ISO 14040/44 guidelines.[30,31] The functional unit of this study is defined as 1 ton of liquid fuel produced *via* the MTO–MOGD pathway. Since no integrated conventional MTO–MOGD fuel production dataset exists in common LCA databases, the reference cases were constructed using relevant ecoinvent processes for fossil- and biomass-based methanol production. All systems were modeled using a functional unit of 1 ton, corresponding to the total liquid fuel output of the P2X systems, ensuring a functionally equivalent comparison.

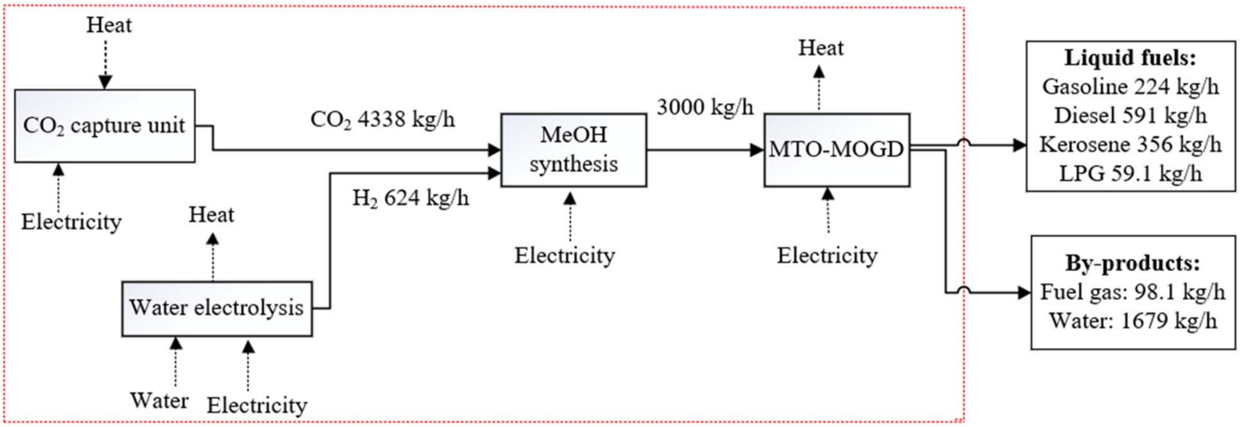

Fig. 1 Schematic of the integrated renewable fuel production system with mass and energy flows; the dashed line indicates the system boundary.

2.2. Life cycle inventory

The life cycle inventory (LCI) used in this study consist of both background and foreground data. Background data related to the production of chemicals and energy were sourced from the ecoinvent database (v3.10). The foreground data of the MTO–MOGD process were obtained from our previously developed model in Aspen Plus.[18] For the upstream stages, CO$_2$ capture, hydrogen production, and methanol synthesis, LCI data were obtained from peer-reviewed literature. The data were adjusted to represent a pilot-scale methanol production capacity of 3000 kg h^{-1}, corresponding to the input demand of the downstream conversion process.

2.2.1. CO$_2$ capture. CO$_2$ capture is a critical enabling step in green methanol production, as it provides the essential carbon feedstock needed for methanol synthesis. This study considers four representative CO$_2$ sources: biogas upgrading, direct air capture (DAC), cement production, and steel manufacturing. In biogas upgrading, CO$_2$ is separated from methane *via* chemical scrubbing using alkanolamines, such as monoethanolamine (MEA), enabling the recovery of biogenic CO$_2$.[32] Cement production, a major fossil-based point source of CO$_2$, emits CO$_2$ primarily through the calcination of limestone. Post-combustion capture using amine-based systems is a viable mitigation strategy and allows recovery of concentrated CO$_2$ for fuel synthesis.[29] DAC offers a decentralized, climate-independent source of CO$_2$ by chemically binding atmospheric CO$_2$ using solid or liquid sorbents. However, it has high energy requirements for sorbent regeneration, typically met with low-grade heat.[33] Similarly, steel production, particularly from blast furnace operations, generates CO$_2$-rich off-gases that can be treated by chemical absorption to capture CO$_2$, and waste heat from steel plants can support regeneration steps.[34] Integration of these CO$_2$ capture processes with the overall system, utilizing excess heat from water electrolysis or fuel synthesis for solvent regeneration enhances energy efficiency and promotes circularity by closing energy loops.

2.2.2. H$_2$ production. Water electrolysis is a key method for producing green hydrogen. It involves the decomposition of water in an electrolyzer into hydrogen and oxygen using electrical energy. The primary types of electrolyzers include alkaline electrolyzers (AELs), polymer electrolyte membrane (PEM) electrolyzers, and solid oxide electrolyzer cells (SOECs). AEL

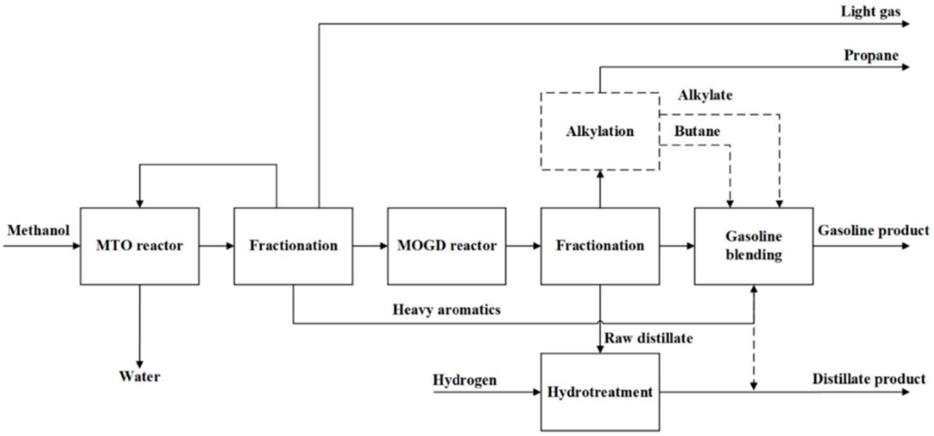

Fig. 2 Block diagram of the methanol-to-olefins (MTO) and Mobil olefins to gasoline and distillate (MOGD) processes.[18]

technology is cost-effective and technologically mature but has slower dynamic responses and operate at lower current densities.[35,36] PEM technology offers a compact design, higher hydrogen purity, faster response times, and better adaptability to intermittent renewable energy sources.[36,37] Additionally, PEM electrolyzers operate at higher current densities and pressures.[38] These characteristics make them particularly suitable for integration with modern energy systems and hydrogen storage infrastructure, where efficiency and operational flexibility are critical. Furthermore, excess heat is generated by PEM electrolyzers.[39] This heat can be effectively utilized in the integrated MTO–MOGD system, especially for CO_2 capture processes that require thermal energy. However, PEM electrolyzers suffer from low durability of electrodes and electrolytes, as well as the high cost of raw materials.[36] The SOEC on the other hand offers high efficiency but requires elevated temperatures,[40] which limits its applicability under standard conditions. In this study, PEM technology was selected due to its higher efficiency and adaptability to fluctuating renewable energy sources. The associated LCI data were obtained from the literature (Table 2).[41]

2.2.3. Methanol synthesis. The production of green methanol involves the catalytic synthesis of methanol from renewable feedstocks, primarily hydrogen produced *via* water electrolysis powered by renewable electricity, and carbon dioxide captured from biogenic sources, industrial point sources, or directly from the atmosphere. This route offers a promising alternative to conventional fossil-based methanol synthesis, contributing to significant reductions in GHG emissions and supporting circular carbon economy objectives.[3,42] The methanol synthesis process is commonly performed over a $Cu/ZnO/Al_2O_3$ catalyst under high pressure (50–100 bar) and at moderate temperatures (200–300 °C).[43,44] The reaction follows the overall stoichiometry (eqn (1)):

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{1}$$

In this study, the LCI data for green methanol synthesis including energy consumption, material flows, and emissions (Table 3) were obtained from ref. 45.

2.2.4. Methanol to MTO–MOGD. The MTO–MOGD data presented in this study were modeled using Aspen Plus simulation in our previous publication. The block diagram of the model is shown in Fig. 1, with a detailed description available in ref. 18. Briefly, methanol enters under atmospheric conditions, is pumped and heated to 2 bar and 450 °C, and converted in the MTO reactor to dimethyl ether (DME), water, light olefins, and additional water. The reactor operates isothermally with high-pressure (HP) steam generation. Effluent cooling separates water, hydrocarbons, and non-condensable gases, which are utilized for high-temperature heat generation. Durene is removed from olefins *via* distillation and sent for heavy gasoline treatment. Light olefins are oligomerized in the MOGD reactor at 40 bar and 200 °C, producing liquefied petroleum gas (LPG), gasoline, and distillates through two-step distillation. Distillates are hydrotreated at 40 bar and 300 °C to saturate double bonds, yielding paraffinic kerosene and diesel fractions. Hydrogen is recovered at 99.6% purity and recycled. Aromatic gasoline undergoes hydroisomerization to reduce durene content by 57% in an isothermal reactor at 16 bar and 345 °C, with hydrogen recovery of 99.7%. Heat integration includes HP steam from light gas combustion and furnace cooling, recovering 1.1 MW of heat above 500 °C and an additional 0.1 MW *via* a flue gas boiler. The LCI for downstream fuel production is provided in Table 4.

2.3. Scenario study

This study evaluates four scenarios within a LCA framework, representing integrated fuel production systems encompassing CO_2 capture, hydrogen production *via* water electrolysis, methanol synthesis, and methanol-to-fuel conversion. All process configurations and operational parameters are held constant across scenarios, with the only variation being the CO_2 source and capture technology for methanol synthesis. The selected CO_2 sources represent a spectrum of near- and long-term opportunities in Finland's energy and industrial landscape. They represent both point-source integration with existing industrial emitters and future-proof options such as DAC, all of which are relevant under Finland's commitment to climate neutrality and renewable energy deployment.[4]

- Scenario S1: CO_2 is sourced from biogas upgrading, with capture using MEA. Hydrogen is produced *via* renewable-powered water electrolysis. The captured CO_2 and H_2 are converted to methanol, which is subsequently upgraded to synthetic fuels.
- Scenario S2: CO_2 is captured from cement plant flue gas using MEA-based chemical absorption. Hydrogen is generated *via* water electrolysis. The CO_2 and H_2 feed the methanol synthesis process, followed by conversion into liquid fuels.
- Scenario S3: CO_2 is captured directly from ambient air using a zeolite-based solid sorbent DAC system. Hydrogen is produced *via* electrolysis. The captured atmospheric CO_2 is synthesized into methanol, which is then converted into liquid fuels.
- Scenario S4: CO_2 is captured from steel production flue gas using post-combustion capture with MEA and activated carbon. Electrolytic hydrogen reacts with the CO_2 to produce methanol, which is further processed into synthetic fuels.

In each system, excess heat is generated during water electrolysis and MTO–MOGD processes. The thermal energy demands for CO_2 capture in all scenarios can be fully met by this excess heat. Therefore, heat flows and recovery were not explicitly modeled, as available thermal energy exceeds process requirements. This assumption supports the study's focus on comparing environmental impacts related to primary energy and material inputs, ensuring a clear and consistent assessment of system performance.

In addition to the four integrated P2X process scenarios, two reference MTO–MOGD pathways are modeled using ecoinvent datasets.[46] These reference cases differ in their methanol feedstock and the electricity source used in MTO–MOGD production: one uses biomass gasification derived methanol with process energy assumed to be entirely with renewable wind electricity (S5), aligning with Finland's National Energy and Climate targets;[4] the other uses fossil-based methanol imported into Finland with grid electricity as process energy (S6). The latter is consistent with current import practices of methanol to meet demand in Finland.[47]

2.4. Life cycle impact assessment

To evaluate the environmental impacts, the life cycle impact assessment (LCIA) was conducted using SimaPro 9.6.0.1, with the ecoinvent 3.10 database as the background database.[48] The analysis employed the ReCiPe 2016 midpoint method, focusing on seven impact categories: global warming potential (GWP), ozone formation, human health (OFH), freshwater eutrophication (FE), marine eutrophication (ME), land use (LU), fossil resource scarcity (FRS), and water consumption (WC). These categories were selected based on the primary environmental assessment criteria mandated by Finnish regulatory authorities for evaluating new industrial facilities.[49]

2.5. Sensitivity analysis

The robustness of the model and the influence of key assumptions were assessed through sensitivity analysis. Perturbation analysis was utilized to evaluate the extent to which variations in individual input parameters impact the overall model outcomes. This approach involves calculating the sensitivity ratio (SR), as defined in eqn (2),[50] to quantify the relative importance of each parameter. Parameters with SR values greater than 0.8 are considered to have a significant effect on the LCA results, with SR values exceeding 1.0 indicating critical influence, while those below 0.2 suggest minimal impact.[51]

$$\mathrm{SR} = \frac{\dfrac{\Delta\mathrm{result}}{\mathrm{initial\ result}}}{\dfrac{\Delta\mathrm{parameter}}{\mathrm{initial\ parameter}}} \tag{2}$$

3. Results and discussion

The environmental impacts of the four P2X scenarios are evaluated across seven midpoint impact categories. Detailed process-level contributions for each category are provided in Table SII of the SI.

In contrast to our previous work,[18] which focused on process design and chemical fundamentals, the present study emphasizes system-level environmental and sustainability performance, leveraging insights from prior chemical process modelling.

Global warming potential (GWP) is the most prioritized indicator in LCA studies. As shown in Fig. 3(a), all scenarios achieve substantial reductions compared to the reference fossil case of 2480 kg CO_2 eq. per t_{fuel}. Scenario S2, using CO_2 from cement, achieves the lowest GWP (81.3 kg CO_2 eq. per t_{fuel}), representing a 96.7% reduction due to low energy and material demands of cement-based CO_2 capture. This is closely followed by S1 with a GWP impact of 81.3 kg CO_2 eq. per t_{fuel}. Scenarios S3 and S4, based on DAC and steel production CO_2, yield slightly higher GWPs of 97.9 and 96.6 kg CO_2 eq. per t_{fuel},

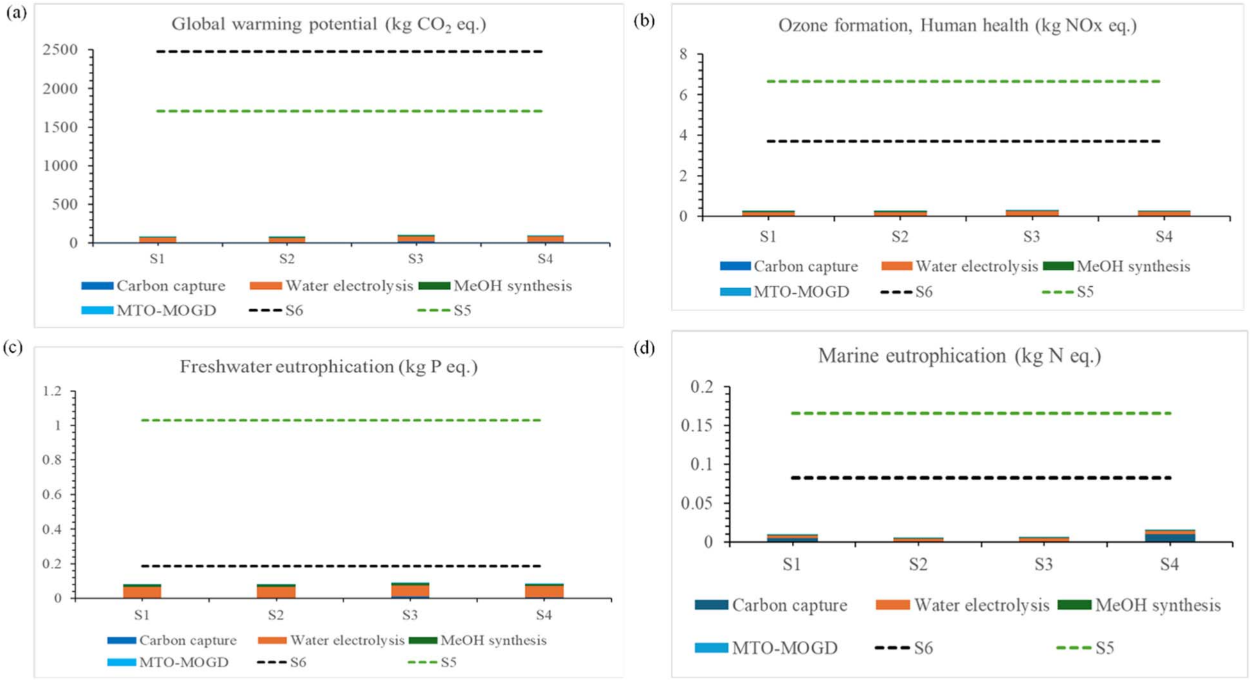

Fig. 3 Life cycle impact assessment results for (a) global warming potential, (b) ozone formation, human health, (c) freshwater eutrophication, and (d) marine eutrophication. Results are shown for the integrated MTO–MOGD process, compared with the reference biomass-based MTO–MOGD (green dashed line) and fossil-based MTO–MOGD (black dashed line).

respectively, mainly driven by material-related impacts: zeolite contributes 86.9% of capture emissions in S3, and MEA accounts for 93.4% in S4. Water electrolysis remains the dominant GWP contributor (67–80%) due to its high electricity demand for hydrogen production. However, compared to biomass-based MTO–MOGD (S5), the P2X scenarios have GWPs that are about 17 to 21 times lower than S5, depending on the CO_2 source (Fig. 3(a)). This difference is primarily attributed to upstream emissions related to biomass harvesting, transportation, and the gasification process inherent to the biomass pathway. Nevertheless, when benchmarked against the fossil-based MTO–MOGD reference (S6), scenario S5 demonstrates a substantial GHG reduction, achieving a GWP that is 31% lower than S6.

Ozone formation-related human health impacts (OFH), expressed as kg NO_x eq. per t of liquid fuel, are substantially reduced across all P2X scenarios relative to the reference case (2.4 kg NO_x eq. per t_{fuel}) (Fig. 3(b)). Water electrolysis contributes 67–79.7% of total impacts. In CO_2 capture, wind electricity dominates in scenarios S1 (90.6%) and S2 (97%), while zeolite and MEA dominate capture emissions in S3 (84%) and S4 (90.7%), respectively. Overall, the P2X scenarios realize 91.8–93% reductions compared to the fossil-based reference. In contrast, S5 is about 80% greater than S6.

Freshwater eutrophication (FE) decreases by 52–57.1% across scenarios compared to the S6 case, driven mainly by water electrolysis (72–80% of total impact). Also in this impact category, the capture stage impacts vary by scenario, with wind electricity dominating in S1 (93.4%) and S2 (97.8%), and material impacts significant in S3 (zeolite 76.7%) and S4 (MEA 86%). Scenarios S1 and S2 exhibit the lowest FE impact at 0.08 kg P eq. per t_{fuel} due to efficient CO_2 capture (Fig. 3(c)). Additionally, the FE impact of P2X scenarios is between 11.5 and 12.8 times smaller than S5. However, the biomass-based scenario (S5) has an FE impact that is 5.6 times greater than S6. This disparity stems primarily from the substantial freshwater demand associated with biomass cultivation, processing, and gasification as characterized in the ecoinvent database.

Regarding the marine eutrophication (ME) impact category, all the P2X scenarios show notable reductions compared to the fossil fuel reference (0.034 kg N eq. per t_{fuel}) (Fig. 3(d)). Scenario S2 achieves the lowest impact at 0.005 kg N eq. per t_{fuel}, with emissions largely dominated by water electrolysis (81%). The ME impact is followed by S3, which exhibits a slightly higher impact than S2 at 0.006 kg N eq. per t_{fuel}, 69% of which is attributed to water electrolysis. For S1, the impact contributions are nearly split between CO_2 capture (43%) and water electrolysis (47%). Scenario S4 shows the highest impact, with CO_2 capture responsible for 67%, mostly from MEA (99.5%), and water electrolysis contributing 27%. Methanol synthesis and MTO–MOGD stages contribute 5–13% and 1–3%, respectively, across all P2X scenarios. Furthermore, the P2X scenarios reduce the ME impact by 88–93.8% compared to S6 and are 17.1–32.2 times smaller than S5, depending on the CO_2 source.

Land use impacts show substantial differences across pathways. The biomass-based MTO–MOGD pathway exhibits the highest land use at 5860 m^2a crop per t_{fuel}, reflecting the extensive land occupation required for biomass cultivation. The

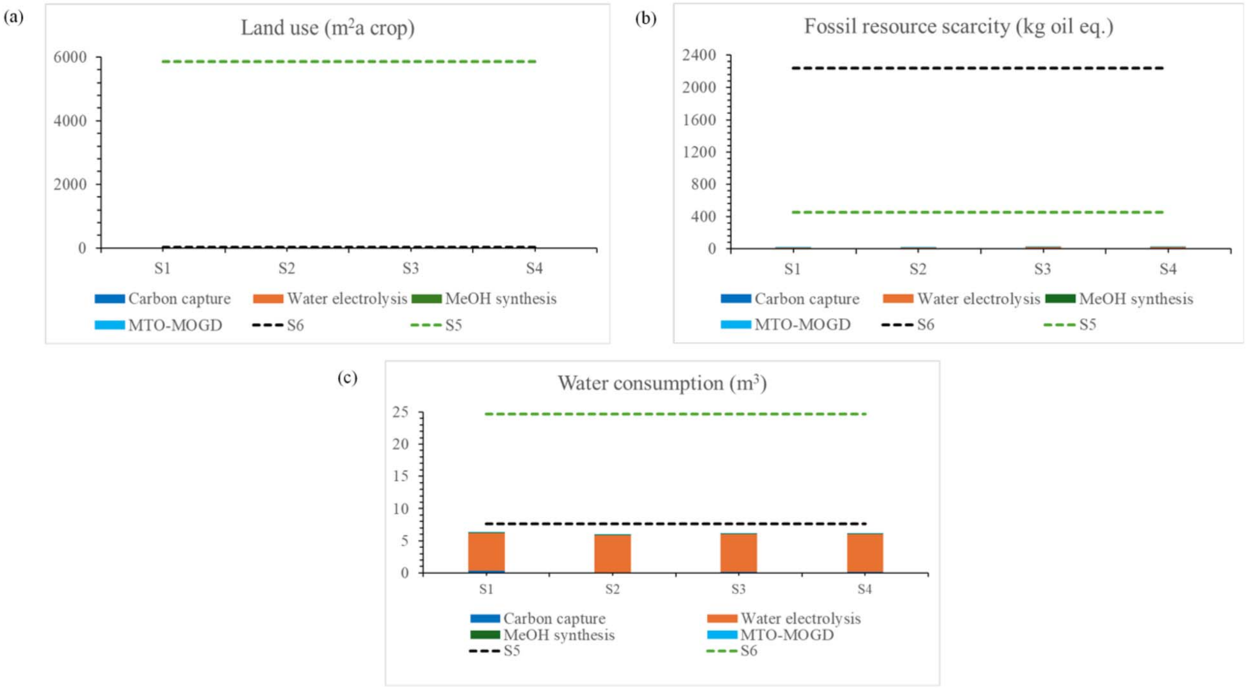

Fig. 4 Life cycle impact assessment results for (a) land use, (b) fossil resource scarcity, and (c) water consumption. Results are shown for the integrated MTO–MOGD process, compared with the reference biomass-based MTO–MOGD (green dashed line) and fossil-based MTO–MOGD (black dashed line).

fossil-based reference shows 29.8 m^2a crop per t_{fuel}, primarily associated with land occupation for oil extraction infrastructure, processing facilities, and related industrial activities. In contrast, the P2X scenarios demonstrate the lowest land use, ranging from 4.96 to 5.50 m^2a crop per t_{fuel}, driven mainly by material requirements for renewable energy and process infrastructure rather than feedstock production. However, with regard to process contributions across P2X scenarios, about 73–80% are attributed to water electrolysis, largely from wind electricity (98.5%) (Fig. 4(a)). CO_2 capture impacts are dominated by wind electricity in S1 (93%) and S2 (98.8%), reflecting energy demands in these process stages. In scenarios S3 and S4, zeolite (76%) and MEA (89.3%) dominate capture-stage land use impacts, respectively, due to the upstream environmental burdens associated with their production.

Fossil resource scarcity (FRS) impacts are mainly driven by water electrolysis (62.2–79.8%) owing to its renewable electricity consumption. Similar to LU, the contributions of the carbon capture stage vary across scenarios. In S1 and S2, the impacts are dominated by wind electricity (80.5% and 95%, respectively). On the other hand, zeolite consumption (80.5%) is the main driver in S3, and in S4, MEA consumption accounted for 89.3% of the total CO_2 capture impact. Methanol synthesis contributes 12–15.5%, and MTO–MOGD contributes minimally (2–2.9%). However, the FRC impacts are more than 97% lower than the reference case at 1254.03 kg oil eq. per t of fuel produced (Fig. 4(b)). In comparison to S5, the P2X scenarios are approximately 18 to 23 times smaller. However, the FRS impact of S5 is reduced by 79.6% compared to the reference fossil case, S6.

Water consumption (WC) decreases by 17.1% to 21.6% across all P2X scenarios compared to S6, with the water-intensive electrolysis stage contributing 87.6% of total WC impact. This highlights the critical role of electrolysis in the overall water footprint of P2X synthetic fuel systems. In the carbon capture stages, water use for CO_2 recovery from biogas in S1 accounts for 95.3% of capture-related WC. In contrast, electricity use dominates WC in S2 (96.3%), while zeolite sorbent consumption drives S3 (86.6%), and MEA chemical demands contribute to S4 at 5.7 m^3 per t_{fuel}. Methanol synthesis (2.2%) and MTO–MOGD (0.4%) impacts remain minimal due to efficient wind electricity use and heat integration. Similar to FE and ME, the WC impact of S5 is approximately 3 times greater than S6. This is attributed to extensive water use in biomass cultivation, processing, and gasification, as modeled in ecoinvent.

In general, the evaluation of four distinct scenarios (S1–S4) reveals substantial GHG mitigation potential, with emission intensities ranging from 81.3 to 97.9 kg CO_2 per t of fuel produced. When expressed in the EU-relevant metric of g CO_2-eq. per MJ, the emissions fall between 1.9 and 2.3 g CO_2-eq. per MJ. These results correspond to 97.6–98.0% reduction in GHG emissions compared to the established fossil fuel comparator of 94 g CO_2-eq. per MJ defined under the Renewable Energy Directive for renewable fuels of non-biological origin (RFNBOs).[52] Thus, all scenarios exceed the 70% emission reduction threshold for RFNBO certification, underscoring the climate mitigation potential of the CO_2-derived fuel systems.

The results indicate that while the biomass-based MTO–MOGD pathway achieves 31.1% GHG reductions relative to the fossil-based reference, it remains substantially more carbon-intensive than the P2X pathways by a factor of 17.5 to 21, depending on the CO_2 source. This outcome indicates the critical influence of feedstock-related emissions in biomass-based pathways, particularly those associated with biomass harvesting, transportation, and gasification processes. In contrast, the P2X scenarios benefit from fully renewable wind electricity and efficient heat integration, which effectively eliminate most process-related emissions. However, it is important to emphasize that these results represent an idealized best case for P2X, which is highly dependent on the availability of low-carbon electricity and CO_2. If the P2X system rely on grid electricity, its GWP would increase substantially, reducing the performance gap relative to biomass-based pathways. Consequently, while biomass-based MTO–MOGD does not achieve the same climate performance as the modeled P2X scenarios, it still represents a meaningful decarbonization route compared to fossil-based systems, particularly in regions where renewable electricity or DAC technologies are constrained.

Nevertheless, the biomass-based reference achieves clear reductions in GWP and FRS compared to the fossil-based reference, mainly due to renewable carbon and wind-powered fuel conversion. However, it exhibits higher impacts in other categories such as land use and water consumption, reflecting known biofuel trade-offs.[53,54] This underscores the importance of assessing multiple environmental indicators beyond GHG emissions. It is noteworthy that the ecoinvent dataset, while practical, may not fully represent Finland-specific biomass types or conversion technologies, which could affect the accuracy of environmental impact estimates. Furthermore, applying wind electricity only to the downstream MTO–MOGD step, while upstream methanol production retains default energy inputs, represents a conservative assumption about renewable energy penetration. A truly decarbonized pathway would require renewable energy integration across both methanol production and fuel conversion stages.

While LCA studies specifically focused on the MTO–MOGD process in the context of P2X systems are limited, our results are comparable with similar pathways reported in the literature. For instance, Zhaurova *et al.*[29] found that a power to gasoline plant powered by renewable electricity achieved a 53% reduction in GHG emissions, while scenarios relying on grid electricity with fossil energy shares resulted in higher emissions than the reference case. In comparison to the present study, scenario S2 utilizing CO_2 captured from cement production, achieved a 90.8% reduction in GWP relative to the reference case. Similarly, scenario S3 using DAC yields an 88.9% reduction, which is consistent with the findings of Micheli *et al.*,[55] who reported an equivalent reduction in GWP for P2L kerosene produced with wind electricity and DAC. These outcomes highlight the importance of using renewable electricity, especially wind power in minimizing environmental impacts in P2X fuel production. Furthermore, Fernández-Torres *et al.*[56]

demonstrated that P2X gasoline can contribute to carbon emission reductions and enhance circular resource use. These findings align with the present study, in which system-level heat integration and internal energy production significantly reduced environmental impacts and promoted circular resource use. In scenarios S3 and S4 of this study, the environmental burden from zeolite and MEA used in CO_2 capture is primarily attributed to their production, as modeled in ecoinvent.[46] While Meunier *et al.*[21] identified heat demand for MEA regeneration as the dominant contributor, both findings underscore the significance of MEA in carbon capture-related impacts.

Furthermore, the cement capture-based scenario (S2) consistently exhibits the lowest environmental impact among the studied options. This outcome is primarily due to lower electricity consumption and substantially reduced chemical input requirements for CO_2 capture from cement compared to the other processes. Biogas capture demonstrated higher electricity use, greater solvent (MEA) consumption, and the formation of additional byproducts such as ammonia and acetaldehyde, which contribute to its slightly higher environmental burden than S2 (see Table 1). DAC and steel-off gas capture processes exhibited higher overall environmental impacts, primarily due to energy intensity and material requirements intrinsic to these technologies. These results underscore that, while cement capture currently offers the most favorable environmental profile based on the system boundaries and assumptions applied in this study, improving energy efficiency and byproduct management in alternative capture technologies is essential for their long-term sustainability.

Table 1 LCI of CO_2 capture processes[29,32–34]

Parameter/flow	Biogas	Cement	DAC	Steel
Inputs				
CO_2 (kg)	—	4820	4554.90	4815.18
Biogas (m^3)	712.12	—	—	—
Water (kg)	390.12	—	—	0.73
Electricity (kWh)	51.62	22.70	84.46	9.18
Heat (MJ)	829.42	551.20	730.49	578.31
MEA (g)	35.61	4.68	—	4424.76
NaOH (g)	—	—	—	347.04
Activated carbon (g)	—	—	—	195.21
Zeolite sorbent (kg)	—	—	3.42	—
Outputs				
CO_2 (kg)	4338	4338	—	4338
Ammonia (g)	49.54	—	—	—
Acetaldehyde (g)	1309.68	—	—	—
CO_2 emission (kg)	—	482	—	477.18
Wastewater (kg)	—	2125.62	—	724.45
Waste (kg)	—	7.01	—	21.23

Table 2 LCI inputs and outputs associated with production of hydrogen by means of P2X[41]

Input		Output	
Water (kg)	6034.08	H_2 (kg)	624
Electricity (kWh)	2384.08	Heat (MJ)	1369.31
		Oxygen (kg)	4992

Table 3 LCI for methanol synthesis[45]

Input		Output	
H_2 (kg)	624	Methanol (kg)	3000
CO_2 (kg)	4338	Water (kg)	1710
Electricity (kWh)	428.33	CO_2 emissions (kg)	150

Table 4 LCI for MTO–MOGD

Input		Output	
Methanol (kg)	3000	Gasoline (kg)	224
Electricity (kWh)	114	Diesel (kg)	591
Heat (MJ)	2480.4	Kerosene (kg)	356
Cooling (MJ)	2372.4	LPG (kg)	59.1
		Fuel gas (kg)	98.1
		Heat (MJ)	7966.8
		Water (kg)	1679

In terms of water use in the integrated systems, the primary water demand arises from hydrogen production *via* electrolysis, while water is also generated as a by-product during methanol synthesis and downstream methanol-to-fuel conversion (see Fig. 2). Henriksen *et al.*[57] highlighted that the environmental impact of electrolysis is strongly influenced by upstream electricity generation, with electricity driving both GWP and water consumption, making the process highly sensitive to the electricity grid mix. This is further supported by findings, which demonstrate that FE impacts are considerably higher under a fossil-based electricity supply but substantially reduced when renewable sources such as wind are used in liquid fuel production.[58] In addition, Shi *et al.*[59] emphasized the need for accurate assessment of water use in hydrogen electrolysis, highlighting that reported water scarcity footprints are often overestimated and highly dependent on the geographic and technological context. However, the study by Meunier *et al.*[21] demonstrated that recycling process water can further improve environmental performance. Although water recycling was not considered in this study, it represents a promising avenue for future optimization to reduce water consumption and enhance the sustainability of P2X fuel production.

Beyond the quantified scenario results, the performance of CO_2 capture sorbents and methanol synthesis catalysts directly influences the energy requirements and environmental impacts of P2X systems. Improvements such as lower sorbent regeneration energy, enhanced stability, extended lifetimes, and higher catalyst conversion efficiency can reduce electricity demand and material use. Continued innovation in these chemical components is therefore expected to further strengthen the sustainability and GHG mitigation potential of CO_2-derived fuels, complementing the system-level findings reported in this study.

Building on these insights regarding chemical component performance, overall, this study demonstrates that the strategic utilization of CO_2 streams from industrial sources such as biogas, cement, and steel can further mitigate environmental impacts and advance circular economy objectives supported by EU policies.[60] Such integration not only reduces reliance on fossil carbon sources but also strengthens supply chain resilience. However, future optimization of P2X pathways requires enhanced integration of variable renewable electricity to reduce upstream emissions, alongside advances in CO_2 capture efficiency to lower overall carbon intensity.[3,61] Advancements in catalyst development and reactor design can improve reaction efficiency, increase selectivity, and enable process intensification in hydrogen production and methanol synthesis.[62] A holistic assessment integrating environmental impacts, techno-economic feasibility, and regulatory frameworks is essential to accurately evaluate the scalability and sustainability of P2X fuels. Furthermore, their deployment will depend on compliance with evolving regulations, such as RED III, which establish sustainability criteria and carbon intensity thresholds that define market eligibility within the EU.

3.1. Utilization of excess heat

To contextualize the potential of excess heat, the CO_2 emission displacement potential was first quantified for the four P2X scenarios (S1–S4), using emission factors of 266.7 kg CO_2 per MWh for light fuel oil and 199 kg CO_2 per GJ for natural gas.[63] As illustrated in Fig. 5, scenario S1 enables displacement of approximately 2292 t CO_2 per year from light fuel oil and 1709 t CO_2 per year from natural gas, representing the lowest displacement among the four scenarios. Scenario S2 yields the highest displacement with 2456 t CO_2 per year and 1832 t CO_2 per year for light fuel oil and natural gas, respectively. While modest relative to national emissions, these values are significant within the context of the pilot-scale study.

Additionally, the theoretical revenue from the sale of excess heat for residential heating supply was calculated. The annual revenue from the sale of excess heat is calculated using eqn (3). Continuous operation at 7884 h per year corresponding to a capacity factor of 0.9 was assumed based on typical plant operational data.[45] The usable heat efficiency estimation accounts for heat losses from recovery[64] and distribution.[65] The number of household that could be supplied was estimated using an average annual household heating demand of 15471 kWh per year in Finland in 2023.[66]

$$R = \frac{P \times H \times E \times n_{\mathrm{use}}}{C_1 \times C_2} \times S, \qquad (3)$$

where $P =$ production rate (t per h), $H =$ annual operating hours (h per year), $E =$ excess heat (MJ per t), $n_{\mathrm{use}} =$ usable heat efficiency, $C_1 =$ conversion factor (MJ to kWh), $C_2 =$ conversion factor (kWh to MWh), and $S =$ average selling price (€ per MWh).

Under these assumptions, the recoverable excess heat from the system ranges from 8.59 to 9.21 GWh per year across four scenarios, which could meet the heating needs of approximately 555 to 595 detached or semi-detached houses in Finland (Fig. 6). If sold at an average market price of €96.26 per MWh,[67] the excess heat could provide a supplementary revenue stream of approximately €827k to €886k per year for the integrated MTO–MOGD plant. This additional thermal energy represents a meaningful opportunity to offset fossil-based heating, complementing the environmental benefits quantified in the LCA. Further details on the calculation methodology and assumptions are provided in Tables SIII and SIV of the SI. Therefore, integrating this heat recovery with local district heating systems supports sector coupling and circular economy principles. Such integration enhances the overall sustainability of P2X systems, particularly in cold climates where heating demand is significant, and may improve both environmental and economic outcomes, facilitating broader adoption.

3.2. Sensitivity analysis

Table 5 presents the SR values for the climate change impact category across all scenarios. Detailed sensitivity results for all seven impact categories are available in Tables SV–SXI of the SI.

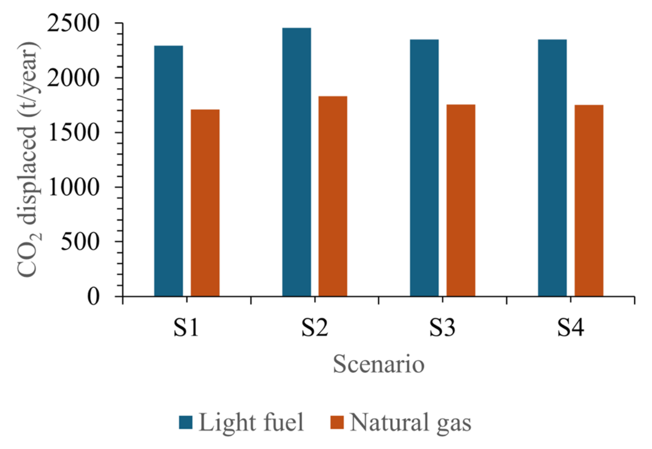

Fig. 5 Annual CO_2 displacement from light fuel oil and natural gas across four scenarios.

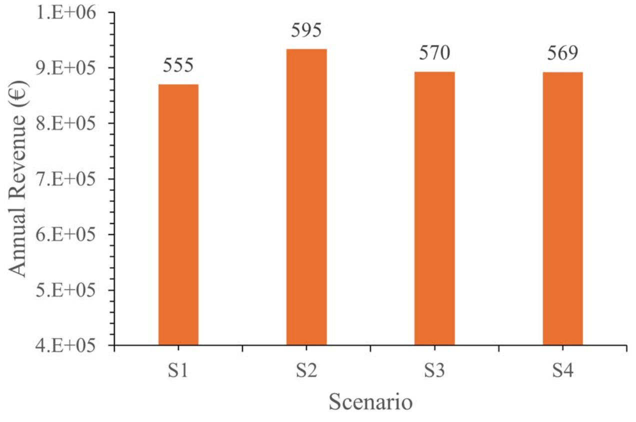

Fig. 6 Estimated annual revenue from excess heat in four P2X scenarios (S1–S4). The number of Finnish detached or semi-detached households that could be supplied with this excess heat is indicated on top of each bar. Household heating demand is based on an average of 15 471 kWh per year.

Table 5 Sensitivity ratios for the global warming potential impact category of the analyzed scenarios

	S1	S2	S3	S4
CO_2capture				
Biogas	0.0	—	—	—
CO_2	—	0.0	0.0	0.0
Electricity	0.8	1.0	0.1	0.0
H_2O	0.1	—	—	0.0
MEA	0.1	0.0	—	0.9
NaOH	—	0.0	—	0.0
Zeolite	—	—	0.8	—
Activated carbon	—	—	—	0.0
Water electrolysis				
Water	0.03	0.03	0.03	0.03
Electricity	0.97	0.97	0.97	0.97
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO–MOGD				
Electricity	1.0	1.0	1.0	1.0

In water electrolysis, methanol synthesis, and synthetic fuel production stages, electricity consumption was the most influential parameter across all process stages, reflecting the key role of wind-based energy inputs. For six of the seven impact categories, electricity used in electrolysis exhibited SR values greater than 0.8 in every scenario. In the WC impact category, the water input to electrolysis was the most sensitive parameter, with an SR of 0.88 across all scenarios.

Sensitivity in the CO_2 capture stage varied depending on the CO_2 source. In scenarios S1 and S2, electricity consumption was the dominant parameter across all categories. In S2, SR values were slightly below 0.8 for ME (0.77) and FRS (0.75). In scenario S3, zeolite was the sensitive parameter, with SR values above 0.8 in all categories except FE with an SR value of 0.74. In scenario S4, MEA production and regeneration consistently showed the highest sensitivity, with SR values exceeding 0.8 for all impact categories.

These findings are consistent with the LCIA results and demonstrate that electricity consumption and material inputs related to CO_2 capture are the main factors influencing environmental impacts in the power-to-X fuel systems analyzed in this study. This consistency between sensitivity analysis and LCIA enhances the robustness of the results.

4. Conclusions

This study presents a comparative cradle-to-gate LCA of four CO_2 sources for liquid fuel production *via* P2X MTO–MOGD, all powered by a consistent wind-based electricity supply. The GWP values ranged from 81.3 to 97.9 kg CO_2 eq. per t of liquid fuel, indicating substantial reductions compared to fossil- and biomass-based reference values of 2480 and 1710 kg CO_2 eq. per t_{fuel}, respectively. All seven evaluated environmental impact categories demonstrated improved performance relative to the reference cases. Among the P2X scenarios, the cement-derived CO_2 scenario exhibited the lowest overall environmental impacts, while biogas, DAC, and steel-derived CO_2 scenarios showed slightly higher but still significant environmental benefits. Utilizing excess heat from the P2X process could displace 1191.6–2456.4 t CO_2 per year from light fuel oil and 1709.9–1832.8 t CO_2 per year from natural gas, while generating €827k–886k in annual revenue. Sensitivity analyses highlight that minimizing electricity consumption and optimizing CO_2 capture materials are critical factors for further reducing the environmental impacts of CO_2-derived synthetic fuels. These results demonstrate that the strategic integration of renewable electricity with carbon capture technologies can significantly advance green chemical manufacturing and support broader goals of industrial decarbonization and the circular economy transition. The findings provide valuable guidance for future research and policy aimed at sustainable, low-carbon fuel production pathways.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5su00824g.

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