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Evaluating the potential of e-fuels for decarbonizing European truck transport: A techno-economic and life cycle approach

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ABSTRACT

Heavy-duty road transport remains a challenging sector to decarbonize, as full electrification of long-distance trucking is currently constrained by limitations in energy density and charging infrastructure. Alternative fuels such as hydrogen, biodiesel, and e-fuels are thus gaining increasing attention. In parallel, the cement industry is a major source of unavoidable, process-related CO_2 emissions, offering an opportunity to use captured industrial CO_2 as a feedstock for e-fuel production. This study evaluates the production of e-methanol and Fischer-Tropsch (FT) diesel from captured CO_2 at an Austrian cement plant as a base case. Several system configurations are analyzed, including different electricity supply options across Europe and the use of biogenic versus fossil CO_2. An integrated framework combining process simulation, techno-economic analysis, and life-cycle assessment is applied to compare both fuel pathways. Results show that the climate impact of e-fuels is highly dependent on the electricity mix. When non-renewable electricity is used, climate impacts are 100-440% higher than those of fossil diesel. In contrast, a wind-based Austrian scenario achieves the lowest impact, corresponding to a 44-50% reduction compared to fossil diesel. Overall, cement-plant-based power-to-liquid concepts offer limited near- to mid-term mitigation potential under current European energy conditions and deliver climate benefits primarily when based on biogenic CO_2, high process efficiencies, and low-carbon electricity. The study further highlights key differences between the fuels, with FT-diesel being a certified drop-in fuel, while e-methanol still requires technical and regulatory validation, underscoring the need for technology-specific and system-level assessments.

Keywords: Technoeconomic Analysis, Life Cycle Analysis, Process Design, Aspen Plus, Synthetic Fuels, Methanol, Fischer-Tropsch Synthesis, Power-to-Liquid

INTRODUCTION

The transport sector contributes approximately 30% to the EU's CO_2 emissions, with 72% attributable to road transport [1, 2]. While the decarbonization of domestic transport is progressing with an increasing deployment of electric vehicles, the electrification of long-distance freight transport poses several challenges due to limitations in energy density, vehicle payload, and charging times [3]. Therefore, alternative low-carbon fuels such as hydrogen (H_2), biodiesel, and alcohols are increasingly discussed as complementary solutions for heavy-duty transport applications [4, 5]. Among these options, e-fuels (also known as synthetic fuels produced from captured carbon dioxide (CO_2) and renewable H_2) are widely discussed as promising alternatives to fossil fuels. In this context, Fischer-Tropsch (FT) diesel represents a well-established e-fuel pathway, producing paraffinic diesel-range fuel that is fully compatible with existing engines and infrastructure. In contrast, alcohol-based e-fuels, particularly e-methanol, offer an alternative pathway characterized by comparatively simpler process steps and high system flexibility, as methanol is a well-established platform chemical that can be used both as an energy carrier and as a versatile chemical feedstock. While FT-diesel is functionally seen as a drop-in fuel for heavy-

duty diesel engines and is certified under EN 15940 [6], the large-scale deployment of e-methanol in road transport requires adapted engine concepts and further regulatory validation [7, 8].

Despite their potential, e-fuel production is highly energy-intensive, mainly attributable to the substantial H_2 demand [9]. As H_2 production via electrolysis dominates the energy consumption of the Power-to-Liquid (PtL) pathways, the environmental performance of e-fuels is strongly dependent on the carbon intensity of the electricity supply [10]. In addition to H_2 as key reactant, large quantities of CO_2 are required as a carbon source, shifting attention toward industrial point sources. In this context, the cement industry represents one of the largest sources of unavoidable, process-related CO_2 emissions, accounting for almost 4% of the European CO_2 emissions in 2022 [11]. These emissions originate mainly from the energy intensive calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$). Captured CO_2 from cement plants can theoretically serve as a potential carbon feedstock for e-fuel production, conceptually linking the decarbonization of both industry and transport sectors.

However, the utilization of fossil-derived industrial CO_2 for e-fuel production is subject to regulatory restrictions. Under the Renewable Energy Directive (RED) restrict, the eligibility of such pathways for renewable fuels of non-biological origin (RFNBOs) is limited to the period up to 2040, after which permanent CO_2 storage through carbon capture and storage (CCS) is required [12]. These regulatory conditions add a system-level constraint that must be considered when assessing cement-based power-to-liquid concepts. Thus, e-fuels represent a promising pathway for the decarbonization of heavy-duty road transport and cement industry, but imply distinct economic and ecological trade-offs, making a comparative assessment essential.

Against this background, the present study investigates whether e-methanol and FT-diesel produced from captured CO_2 at a cement plant can deliver economic and environmental benefits compared to fossil diesel. The assessment is conducted under realistic European electricity supply scenarios and the prevailing regulatory framework, enabling a comparative evaluation of both e-fuel pathways with respect to their potential role in a future low-carbon transport system.

METHODS

System scope and reference case

This study investigates industrial-scale power-to-liquid fuel production integrated into a cement plant. All assessments are based on a hypothetical, steady-state plant configuration representing a commercial-scale installation. The reference system is anchored to a cement plant located in Austria with annual CO_2 emissions of 750 $ktCO_2$/year [13]. Unless stated otherwise, plant scale, capture technology, electrolysis concept, and process design assumptions are kept constant across all cases to enable a consistent comparison.

Process routes considered

The investigated system includes CO_2 capture from cement plant flue gas using a monoethanolamine (MEA)-based solvent scrubbing unit and H_2 production via alkaline electrolysis (AEL), which are applied uniformly across all cases. MEA-based CO_2 capture is used as the reference technology. Alternative capture concepts may affect absolute results but are not expected to alter the relative comparison between the assessed fuel pathways.

Downstream of CO_2 capture and H_2 production, two alternative CO_2 conversion routes are examined: (i) direct hydrogenation of CO_2 to methanol, and (ii) conversion of CO_2 via the reverse water-gas shift reaction followed by FT-synthesis to diesel-range hydrocarbons. These two routes define the technological scope of the study and are assessed across all scenarios. Detailed process descriptions are provided in the following section.

Methodological approach

The methodological framework employed for the assessment of the economic and environmental performance of the evaluated fuel pathways is presented in the *Supplementary Material* (Figure S1), whereas the scope of the study is depicted in **Figure 1.** The integrated approach comprises three principal stages: (1) process design and simulation, (2) subsequent economic process evaluation within a techno-economic assessment (TEA), and (3) life cycle assessment (LCA). According to this framework, the investigated process routes are modelled in Aspen Plus® (V14) to generate mass and energy balances, which serve as the basis for plant design, equipment sizing, and the identification of potential energy savings through heat integration by applying a thorough pinch analysis. Equipment costs were estimated using the Aspen Process Economic Analyzer® (APEA). The resulting simulation data are subsequently used as input for the TEA, in which the process is evaluated based on the efficiency, stream data and economic indicators, while a custom-built Excel-based TEA tool integrates unit cost data with mass and energy balances to calculate capital (CAPEX), operating expenditures (OPEX), and net production costs (NPC). In parallel, the same data are transferred to the LCA to quantify environmental impacts (focusing on climate change) using the SimaPro software and ecoinvent database. This integrated approach is applied to both e-methanol (i) and FT-diesel (ii) pathways, enabling a transparent comparison with conventional diesel under identical system boundaries.

Scenario definition

Scenarios are defined as variations of external

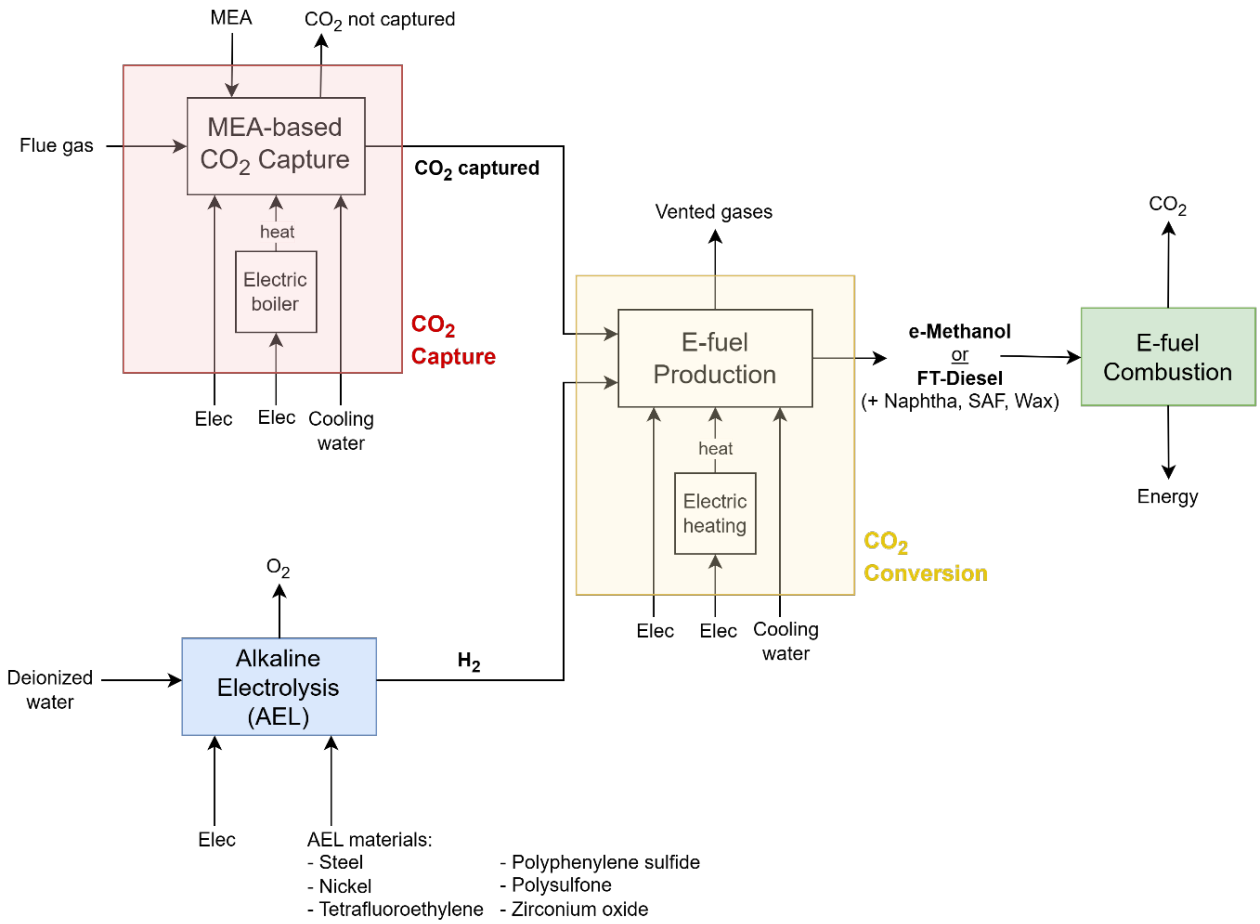

Figure 1. Scope of the study, consisting of four main blocks: (1) CO_2 capture from a cement plant; (2) H_2 production with alkaline electrolysis; (3) e-fuel production from CO_2 and H_2; and (4) e-fuel combustion.

boundary conditions applied to the reference system, while the plant configuration and process design remain unchanged. The comparison is carried out for Austria (base case) and other European countries, listed in the *Digital Supplementary Material* section S3, to assess the influence of the electricity grid mix on the climate change (CC) damage category (computed according to the GWP100 of the IPCC AR6 method). Grid-based electricity scenarios are evaluated to reflect current system conditions and constraints, rather than to imply compliance with additionality requirements under RFNBO regulation.

The scenarios differ with respect to (i) the carbon origin (fossil vs. biogenic CO_2) and (ii) the electricity supply for electrolysis and auxiliary processes. Hence, the following scenarios to mitigate CC of e-fuels in Austria are explored: (1) AT, fossil CO_2 from the cement plant is combined with H_2 produced using the electricity grid; (2) AT_BIO, biogenic CO_2 is combined with H_2 produced using the electricity grid; (3) AT_PV, fossil CO_2 is used as feedstock while the entire process (electrolysis, CO_2 capture, and CO_2 conversion) is powered by electricity from solar panels (PV); (4) AT_PV+BIO, biogenic CO_2 is used as feedstock for a process entirely powered by electricity from PVs; (5) AT_BIO+RENH2, biogenic CO_2 is used as feedstock and PV panels are powering the electrolyzer only, while remaining electricity demand is supplied by the grid; (6) AT_WIND, fossil CO_2 is used as feedstock while the entire process is powered by electricity from wind turbines.

Process simulation

The simulations are performed as steady-state flowsheet models, covering the whole process starting from CO_2 and H_2 to the final products. The methanol route was modeled as a three-stage fixed-bed reactor system with direct CO_2-to-methanol conversion (ratio of CO_2:H_2=1:3.08), following the configuration and operating conditions developed by [11] and [12]. Reaction kinetics for CO_2 hydrogenation were described using a Langmuir-Hinshelwood-Hougen-Watson (LHHW) model taken from [13]. Intermediate condensation between reactor stages was implemented to deduct H_2O and methanol, which enhances overall CO_2 conversion. Downstream of

the synthesis step, the water-methanol mixture is upgraded via a two-stage distillation, including one high- and one low-pressure distillation column.

The FT-diesel route consists of a high-temperature rWGS reactor operating at T = 950 °C and p = 11 bar(g) followed by low-temperature FT synthesis, adopting the process concept and product distribution models by [14]. Catalyst specific data for the rWGS reaction were derived from [15]. An elevated system pressure in the rWGS step was selected to avoid intermediate recompression prior to FTS. The FT reactor itself operates at a CO:H_2 ratio of 1:2.08, which is maintained by adjusting the H_2 feed. Unreacted gaseous components (CO_2, CO, H_2, CH_4, and light hydrocarbons) are recycled to the rWGS inlet, increasing carbon efficiency. Downstream of the FT reactor, a separation unit based on three distillation columns was implemented to obtain naphtha, kerosene, diesel, and wax fractions. Most of the wax is recycled in a hydrocracking unit to increase the diesel yield, while 10 wt% is withdrawn and sold as a by-product.

Techno-economic assessment

The techno-economic evaluation was based on the calculation of the NPC, expressed on both an energy (NPC_e in EUR/MWh) and mass basis (NPC_m in EUR/kg), which represents the product price required to achieve the economic break-even point. This approach is widely applied in the assessment of Power-to-X and CO_2 conversion processes and enables a consistent comparison of alternative process routes and plant configurations [14, 16]. Additionally, different energy pricing scenarios were considered to reflect different energy markets and price variability across Europe, which can be found in the Digital S*upplementary Material* (Table S1).

The NPC were determined by dividing the plant's total annualized cost by its annual product output. CAPEX values were derived from the major equipment costs obtained from process simulations, including reactors, heat exchangers, compressors, separation units, and utilities. These basic equipment costs were converted into total installed costs using standard installation and indirect cost factors according to the methodology originally proposed by Peters M. et al. [16].

Life cycle assessment

The impact assessment of e-methanol (i) and FT-diesel (ii) compared to fossil diesel is carried out according to a cradle-to-wheel approach using the Environmental Footprint (EF) 3.1 method [17] and the Ecoinvent 3.11 cut-off database [18] in Simapro v10.3. The combustion of 1 MJ of fuel, including emissions, is chosen as the functional unit (FU). The modeled production processes consist of four main blocks depicted in **Figure 1**. While the environmental impact assessment of H_2 production considers both energy consumption for operation and materials required for the electrolyzer, construction stages (i.e., facility and machinery) for MEA-based capture and e-fuel production units are excluded from the scope of the analysis due to lack of reliable data. Moreover, allocation methods are applied where co-products are produced: economic allocation for electrolysis (H_2/O_2) and energy-based allocation for the FTS to distribute the impact between FT-diesel and co-products (naphtha, kerosene, and wax). The modeling details can be found in the *Supplementary Materials* section S4.

Environmental impacts are evaluated using the climate change category (CC, kg CO_2-eq/FU), expressed relative to fossil diesel (=100%), and a single-score indicator (µPt/FU), representing the weighted aggregation of all impact categories (e.g., acidification, eutrophication, ecotoxicity, or water use).

RESULTS

The results of the process simulation, TEA, and LCA for the investigated e-methanol and FT-diesel pathways are presented in the following sections. Detailed results of the mass and energy balances, the calculation of the CAPEX and NPC, as well as the calculation of the climate change damage category from the LCA are provided in the *Supplementary Materials*.

Economic study

The following section summarizes the TEA results for the two investigated scenarios: e-methanol (i) and FT-diesel (ii). **Table 1** presents a breakdown of the main cost structure split into CAPEX and OPEX, and the resulting total and relative NPC values. Further details are available in the *supplementary material* (section S4).

From a techno-economic perspective, results indicate a clear differentiation between the two pathways. The FT-diesel route is characterized by substantially higher capital requirements. Total equipment costs amount to 1, 154 MEUR, compared to 343 MEUR for the e-methanol route. This reflects the additional synthesis, upgrading and separation units required along the FT pathway (pre-rWGS, hydrocracker, distillation). Investment in electrolysis is likewise higher for the FT route (717 MEUR vs. 631 MEUR), driven by increased demand for hydrogen. Although both pathways are based on an overall stoichiometric requirement of approximately 3 moles of H_2 per mole of CO_2, the FT diesel route exhibits electrolysis costs that are around 13% higher compared to scenario (i). This is mainly due to light hydrocarbons that are formed in the FT reactor and are recycled back to the rWGS unit, where they are partially converted into CO. This additional loop requires the addition of hydrogen for maintaining the targeted CO/H_2 ratio upstream of the FT reactor. This is further amplified by H_2 consumption in the downstream hydrocracker and slight losses in

the FT recycle loop. Consequently, the annualized capital cost (ACC) is almost twice as high for FT-diesel as for e-methanol (142 MEUR/a vs. 74 MEUR/a).

OPEX in both pathways are dominated by electrolysis-related costs. The annual replacement costs (ARC) of the electrolysis stack are 29 MEUR/a for the e-methanol route and 33 MEUR/a for the FT-diesel route, accounting for around 6.4% and 9.8% of total operating expenses (OPEX), respectively. Despite having a higher hydrogen demand and a higher share of electrolysis-related OPEX, the total OPEX of the FT-diesel route are lower than that of the e-methanol route (338 MEUR/a vs. 453 MEUR/a). This is primarily due to revenues from FT co-products (e.g. gasoline, naphtha, kerosene, wax and light gases), which are credited as sales and reduce the net OPEX of the FT pathway by around 7.7% compared to the single-product e-methanol route.

The interaction between higher CAPEX and lower OPEX results in slightly lower annual total net production costs (NPC_t) for the FT-diesel route than for e-methanol (513 vs. 556 MEUR/a). However, this apparent advantage is reversed when costs are normalized to the main product output. The NPC_m for FT-diesel is 7.16 EUR/kg, compared to 1.40 EUR/kg for e-methanol. The energy-specific NPC is 590 EUR/MWh for FT-diesel and 250 EUR/MWh for e-methanol.

Table 1: CAPEX and OPEX for e-methanol (i) and FT-diesel (ii) based on boundary conditions of the cement plant in Austria.

	Units	Process Route (i)	(ii)
CAPEX			
Total electrolysis costs	MEUR	631	717
Total equipment costs	MEUR	343	1, 154
Annualized capital cost [ACC]	MEUR/a	74	142
OPEX			
Annual replacement costs of electrolysis stack [ARC]	MEUR/a	29	33
Total OPEX	MEUR/a	453	338
NPC			
Total net-production costs [NPC_{total}]	MEUR/a	556	513
Mass specific [NPC_m]	EUR/kg	1.40	7.16
Energy specific [NPC_e]	EUR/MWh	250	590

To account for regional differences within Europe, country-specific electricity prices for 2025 were used to calculate the NPC_e, while all other techno-economic parameters and the process configuration remained constant. The resulting NPC spans a range of approximately 300-700 €/MWh for the e-methanol route and 700-1, 000 €/MWh for the FT-diesel route (**Figure 2** and **Figure 3**). Lower energy-specific production costs were observed in the Nordic countries (SE, FI, DK, EE, LV) as well as in south-western Europe (PT, ES).

Environmental study

The impacts in the CC damage category (kg CO_2 eq/FU), relative to fossil diesel (=100%), of e-fuels produced using electricity from different grid mixes (residual mixes with 2023 as reference year, except for Austria, market mix (2021) since residual mix is not available for this country) is depicted in **Figure 4**. Moreover, the overall environmental impact of e-fuels represented by the single score (µPt/FU), is depicted in **Figure 5**.

As expected, using non-renewable-sourced electricity to produce e-fuels results in a CC impact which is higher than the one of fossil diesel for the same energetic work. While CC of e-fuels are usually 100-300% higher than the fossil option, carbon-intensive mixes lead to even higher CC increases as can be observed for Germany (DE), Greece (GR), and Poland (PL). Indeed, the medium voltage electricity grid mix in Germany and Poland is dominated by hard coal (55% and 73%, respectively), while Greek electricity mix relies heavily on natural gas (52%). On the other hand, the lowest CC is achieved in France (FR) and Sweden (SE), respectively +34% and +35% compared to fossil diesel, attributable to two low-carbon grid mix profiles: Swedish electricity is heavily decarbonized through renewables (hydropower, wind turbines, and bioenergy, representing >50%) and nuclear energy (42%), whereas electricity is almost entirely produced from nuclear energy (88%) in France.

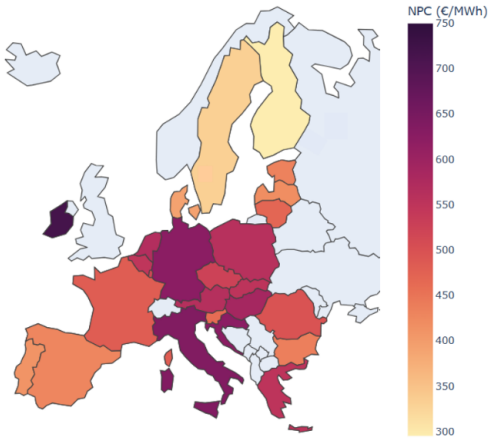

Figure 2. Influence on the NPC_e (€/MWh) for the e-methanol route (i) of regional electricity prices. The reference year for the economic assessment is 2025.

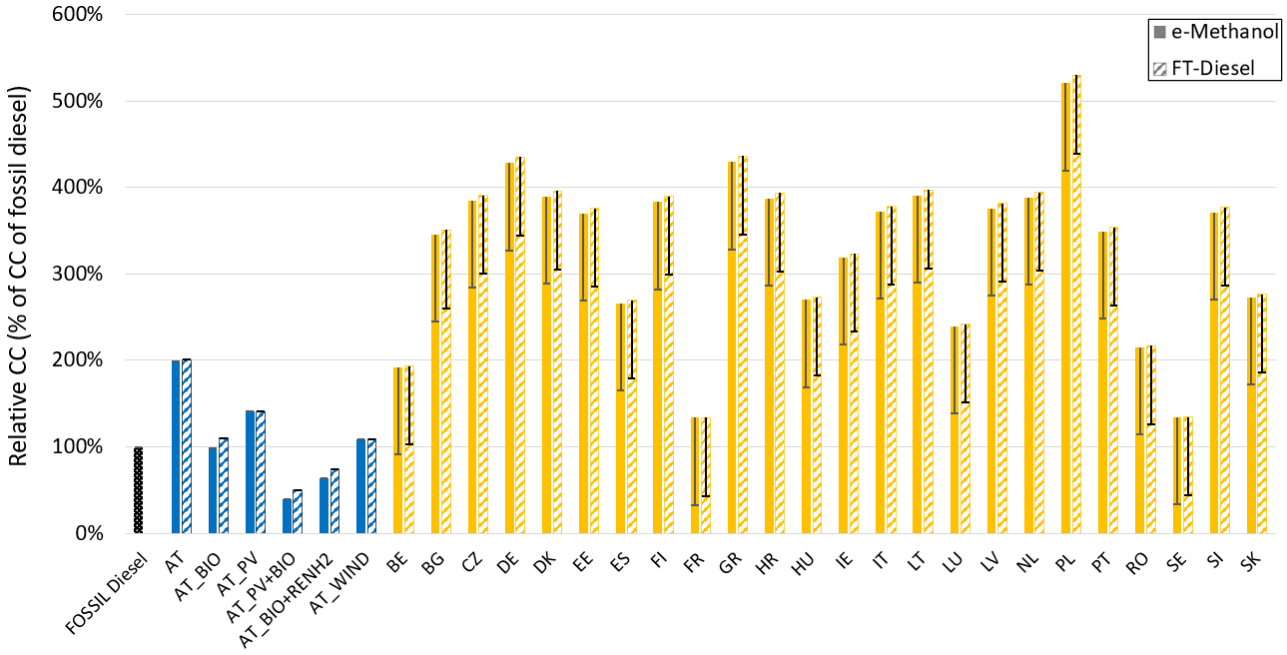

Figure 4. Damage assessment of CC for e-methanol (solid bars) and synthetic diesel (hatched bars) across Europe (fossil diesel = 100%), assessed using Environmental Footprint 3.1 method (v1.04).

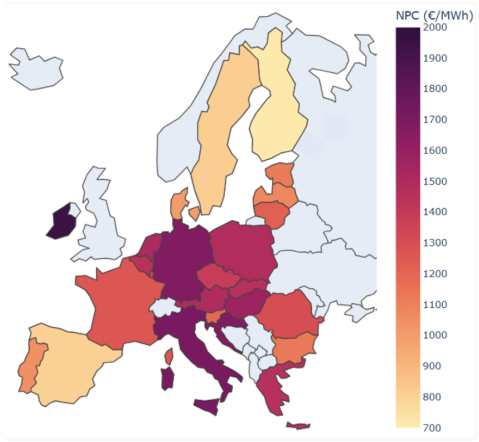

Figure 3. Influence on the NPC_e (€/MWh) for the FTS-diesel route (ii) of regional electricity prices. The reference year for the economic assessment is 2025.

When using the Austrian electricity grid mix, e-methanol combustion is associated with a CC of 0.178 kg CO_2 eq/FU, i.e., almost twice the one of fossil diesel. Nearly 40% of the CC is attributable to the combustion of the e-methanol, as CO_2 captured from the cement plant and used as feedstock is considered fossil (Figure S4).

If biogenic CO_2 is used instead, e.g., from a biogas production plant, the emissions during e-fuel combustion would not contribute to CC anymore since the characterization factor for biogenic carbon in EF 3.1. method is 0. Moreover, approximately 30% of the CC is linked to the AEL while electricity demand for CO_2 capture and e-methanol production further contribute 20%. These contributions could be reduced by using low-carbon electricity, e.g., PVs or wind turbines.

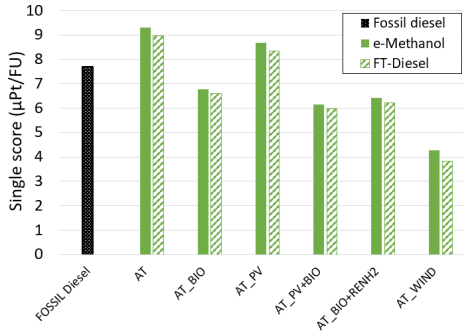

Figure 5. Single score of e-methanol (solid bars) and FT-diesel (hatched bars) for different Austrian scenarios, assessed using EF 3.1 method (v1.04).

The benefit of using biogenic CO_2 can be observed in **Figure 4**, represented by error bars for different European countries, excluding Austria where the AT_BIO scenario is used instead. Despite reducing the CC by 19-75% and 17-68% for, respectively, e-methanol and FT-diesel compared to initial estimations, switching towards biogenic carbon-rich feedstock alone is not sufficient in most cases to achieve a lower CC than fossil diesel. Only the French and Swedish electricity mixes enable net reductions of the CC for both e-fuels (56-67%) compared to the fossil alternative.

Utilizing PV-based electricity (AT_PV) decreases CC

by 29-30% compared to AT, but remains 41% more impacting than fossil diesel combustion. Moreover, as can be seen on **Figure 5**, AT and AT_PV scenarios are also associated with the highest single scores, indicating the worst environmental impact among all Austrian options. On the contrary, combining biogenic CO_2 and solar energy reduces CC by 25-36% when solar energy powers H_2 production only (AT_BIO+RENH2) and by 50-60%, compared to fossil diesel, when PVs cover process electricity demand entirely (AT_PV+BIO). Despite clear reduction in the CC damage category, the overall environmental burden mitigation compared to the fossil alternative is limited (17-23% lower single score) due to materials requirements for PVs.

Finally, the CC of e-fuels in AT_WIND scenario is only 9% higher than the one of fossil diesel. Such a small gap could be reduced by improving the energy efficiency of electrolysis or CO_2 capture and conversion processes, reducing the flow rate of vented flue gas, or increasing the capture efficiency to above 90%. However, AT_WIND scenario presents the lowest environmental impact (44-50% reduction compared to fossil diesel), suggesting this is the most sustainable Austrian configuration.

CONCLUSIONS

The limited electrification potential of long-distance heavy-duty transport underlines the need for low-carbon fuels with high energy density. While the utilization of captured CO_2 from cement plants is often discussed as a promising mitigation pathway, this study demonstrates that cement-based PtL concepts are fundamentally constrained by high energy demand, limited renewable electricity availability, large electrolyzer scale requirements, and regulatory uncertainty, particularly under RFNBO requirements restricting fossil CO_2 utilization beyond 2040. While both e-fuel pathways are technically feasible at process level, their system-level feasibility is constrained by low-carbon electricity availability, grid integration, and electrolyzer scale requirements, reaching hundreds of megawatts in the investigated configurations. Such capacities exceed current installation levels and raise practical challenges related to grid integration, investment risk, and operational flexibility [7, 12].

The techno-economic assessment of e-methanol and FT-diesel production from captured CO_2 at an Austrian cement plant highlights a clear differentiation between the two e-fuels, while both remain significantly more expensive than their fossil counterparts. For the Austrian base case, the NPC_e (dominated by electrolysis-related operating costs) amount to 565€/MWh for e-methanol and 1, 498€/MWh for FT-diesel, compared to approximately 81€/MWh for fossil methanol [19] and 155€/MWh for fossil diesel [20], with similar cost relationships observed across other European countries. Under current European market conditions, the production of e-fuels remains economically uncompetitive, even before considering additional limitations such as renewable electricity availability and infrastructure requirements, highlighting the continued need for funding mechanisms and process improvements to close the cost gap.[19, 20]

From an environmental perspective, the LCA highlights the dominant influence of the electricity supply on environmental impacts. When e-fuels are produced using residual or market-based grid electricity mixes, the CC impacts exceed that of fossil diesel in most investigated regions, with CC values 100% to more than 400% higher than fossil diesel for carbon-intensive grid mixes, consistent with previous findings on electricity mix sensitivity in PtL pathways [8, 21, 22]. Substitution from fossil to biogenic CO_2 feedstock alone is insufficient to achieve lower CC than fossil diesel in most cases. This is reflected in Austrian scenarios where using biogenic CO_2 with grid electricity improves environmental outcomes but remains above fossil diesel. However, the lower energy penalty associated with CO_2 capture from biogas streams, due to higher CO_2 concentration than in cement flue gases, suggests overestimated CC impacts of biogenic-CO_2-based e-fuels when uniform capture assumptions are applied [23]. Meaningful greenhouse gas emission reductions are achievable only when biogenic CO_2 is coupled with low-carbon electricity systems (e.g., AT_PV+BIO reducing CC impacts by 60% and 50% for e-methanol and FT-diesel, respectively, compared to fossil diesel). Consequently, the environmental viability of these process routes is strongly dependent on the availability and large-scale deployment of renewable electricity. However, other environmental impact categories should be considered to avoid burden displacement and make a sound decision about renewables deployment. Moreover, the present assessment evaluates absolute environmental impacts relative to fossil diesel and does not explicitly account for substitution effects. Although e-fuels are intended to replace fossil fuels and enable a secondary use of industrial CO_2, such system-level effects are not fully reflected in the current LCA. Thus, a comprehensive evaluation of substitution effects and their implications for fossil fuel replacement is therefore identified as an important subject for future studies.

Overall, the findings highlight that PtL assessments are highly sensitive to boundary-condition assumptions. Optimistic conclusions regarding climate benefits of e-fuels often rely on implicit assumptions of abundant low-cost, low-carbon electricity and large-scale electrolysis deployment, which are not yet realized within the European energy system. Consequently, meaningful evaluation of industrial CO_2-based e-fuel pathways requires realistic, system-consistent boundary conditions to ensure robust and policy-relevant conclusions [23, 24]. Results indicate that cement-plant-based PtL concepts offer

limited near- to mid-term mitigation potential under current European energy system conditions. Future PtL concepts should therefore prioritize biogenic CO_2 sources, efficiency improvements, and access to additional low-carbon electricity, while ensuring that synthetic fuels are deployed where they complement direct electrification and deliver the highest climate benefit. The fundamentally different characteristics of FT-diesel, a certified drop-in fuel for existing engines and infrastructure, and e-methanol, which is still undergoing technical and regulatory validation, highlight the necessity of technology-specific and system-level evaluation when defining their roles in a future low-carbon transport system. In this context, the study emphasizes that e-fuel pathways based on industrial CO_2 utilization can only be meaningfully assessed when grounded in realistic assumptions regarding renewable electricity availability and electrolyzer scale-up.

DIGITAL SUPPLEMENTARY MATERIAL

Abbreviations and modeling details can be accessed here: LAPSE:2026.0026

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