Development of e-kerosene from the hydrogenation of CO_2 with renewable hydrogen

Summary

The transition of the energy and transport sectors toward climate neutrality requires the rapid deployment of low-carbon fuels capable of replacing fossil-derived products in hard-to-abate applications. Among these, sustainable aviation fuel (SAF) represents a critical challenge due to the stringent energy density, safety, and certification requirements of the aviation sector. In this context, Power-to-Liquid (PtL) routes based on renewable hydrogen and captured CO_2 are increasingly recognized as a necessary complement to bio-based alternatives.

This work investigated the CO_2-Modified Fischer-Tropsch (MFT) synthesis as a potential pathway for e-fuels production, combining catalyst development, kinetic modeling, process simulation, and techno-economic analysis within a coherent framework. Particular attention was devoted to iron-based catalysts, which are attractive due to their lower cost, intrinsic water-gas shift activity, and suitability for CO_2-rich feeds which allow direct CO_2 conversion with significant energy savings with respect to traditional Fischer-Tropsch configurations.

From an experimental perspective, the influence of catalyst pre-treatment conditions on the structural evolution and catalytic behavior of a Na-promoted Fe_3O_4 catalyst was systematically studied with the objective of maximizing kerosene production. By combining Mössbauer spectroscopy with detailed hydrocarbon analysis (DHA), the work demonstrated a strong correlation between iron carbide phase composition and liquid hydrocarbon selectivity. These results highlighted the central role of catalyst activation and carburization control in shaping product distributions toward fuel-relevant fractions with physical properties closer to regulations' requirements. The role of zeolite in the upgrading of FT-derived hydrocarbons has been investigated with an experimental campaign focused on the optimization of e-gasoline production. The research highlighted how Fe-based and zeolite synergy can lead to synthetic gasoline with physical properties much closer to commercial requirements significantly increase both the selectivity of product distribution to a gasoline range oil and Research Octane Number (RON) of the liquid products.

Building on experimental insights, two industrially plausible MFT process configurations were developed and simulated. The first scenario favored higher CO concentrations at the reactor inlet to maximize kerosene selectivity, at the expense of increased reforming and recirculation duties. The second scenario reduced reforming intensity and significantly improved energy efficiency, but shifted the product slate toward lighter hydrocarbons, increasing naphtha production and reducing kerosene yield.

Finally,a comprehensive techno-economic analysis revealed that, alongside with very high carbon efficiencies (≈99.5%) and competitive energy efficiencies (up to 56.5%), iron-based MFT routes revealed competitive compared to more consolidated e-kerosene pathways such as conventional Fischer-Tropsch (FT) and Alcohol-to-Jet (AtJ). Break-even e-fuel prices for MFT were found to lie between 4000 and 5000 €/t, in the same cost range of FT and AtJ. The selling prices of

e-fuels were derived using a composition-based methodology rather than assumed market values. In the absence of established and stable markets for power-based fuels, product values were constructed by linking fossil fuel reference prices with regulatory incentives. These include avoided CO_2 emissions monetized through the EU Emissions Trading System (ETS) and renewable fuel multipliers defined under RED III and ReFuelEU Aviation regulations.

Sensitivity analyses and Monte Carlo simulations identified electricity price, electrolyzer CAPEX, and carbon capture costs as the dominant economic drivers. The strong dependence of e-kerosene cost on electricity price and availability was explored through geographically resolved scenarios across EU member states. The results clearly showed that regional energy mixes and access to low-cost, high-availability electricity sources play a decisive role in determining the economic feasibility of PtL fuels, reinforcing the need for coordinated industrial and policy strategies. The analysis of cost redistribution mechanisms showed that mandate-driven approaches can decouple retail prices from production costs, allowing renewable fuels to enter the market with limited impact on end users. Applied to e-SAF, these mechanisms can significantly lower the effective selling price for airlines and mitigate increases in jet fuel prices and airfares.