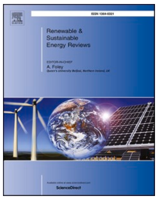
Renewable and Sustainable Energy Reviews 216 (2025) 115648

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Economic feasibility of low-carbon ethylene, propylene and jet fuel production

S. Kim [a,*], P.E. Dodds [a,b], I. Butnar [a]

[a] Institute for Sustainable Resources, University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK
[b] Energy Institute, University College London, Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK

ARTICLE INFO

Keywords:
Techno-economic analysis
Synthetic fuels
Green ethylene
Fischer-tropsch
Methanol synthesis
Energy systems

ABSTRACT

Jet fuel and key chemical building blocks (e.g. ethylene) cannot easily be substituted with zero-carbon alternatives and remain interconnected in a low-carbon future. Fischer-Tropsch and methanol synthesis offer pathways toward large-scale production of low-carbon synthetic hydrocarbons. This paper estimates the future costs of low-carbon ethylene, propylene, and jet fuel via those routes with feedstocks of either biomass or electricity with captured CO_2. It finds while biobased hydrocarbons could fall below 1.1 USD/kg, electricity-based hydrocarbons using atmospheric CO_2, even with the optimistic views, result in 4 USD/kg for ethylene, 2.3 USD/kg for propylene and 2.9 USD/kg for jet fuel. Using industry-captured CO_2 as the carbon source could cut production costs by 28 %, but its future availability is likely to be limited. Offsetting existing hydrocarbon industries through direct air carbon capture and storage is projected to be more economical compared to electricity-based hydrocarbons. This research highlights the necessity for transitioning to a net zero power system to reduce electricity prices. As these technologies each produce multiple products and their business cases depend on sales of all products, a coherent cross-sectoral strategy to incentivise low-carbon fuels and chemicals would be valuable to ensure that the overall production reflects demand throughout a low-carbon transition.

1. Introduction

Large-scale synthetic hydrocarbon production could be important in mitigation pathways, particularly to supply low-carbon jet fuel for aircrafts and building-block chemicals (i.e., ethylene and propylene) that are used by the chemicals industry to produce most plastics. Through the conversion of low-carbon feedstocks such as biomass, waste or hydrogen with captured CO_2 into synthetic gas (CO, hydrogen and CO_2) coupled with a mature synthesis technology, such hydrocarbons could be produced at very large-scales in the near term. A number of process schemes exist that can conduct such conversions that is separated by two main synthesis steps: Fischer-Tropsch (FT) and methanol synthesis.

Economic evaluations which estimate the future cost of low-carbon synthetic hydrocarbon plants for jet fuel production from FT are available [1], owing to the considerable interest in sustainable aviation fuels (SAF) across academia [2], industry [3] and government [4]. SAF can also be produced via the methanol-to-jet fuel pathway, though most studies have focused on methanol-to-gasoline [5,6]. While methanol-based jet fuel has been demonstrated [7], it lacks ASTM test certification for current flights [8]. There is industry interest in this pathway with proprietary methanol-to-jet technology in development [9]. Cost evaluation studies comparing FT and methanol synthesis pathways to produce jet fuel are available, with Gonzalez-Garay et al. [10] exploring the production cost of power-to-liquid jet fuel from FT and methanol-to-jet pathways using propylene as the intermediate olefin using a spatially explicit model. Schmidt et al. [8] reviews power-to-liquid options for aviation via both FT and methanol synthesis by comparing across cost data supplied by fuel manufacturers.

No such cross-pathway comparisons exist for large-scale, low-carbon ethylene and propylene production, and their costs have remained relatively unexplored until recently, despite 25 % of global methanol demand dedicated to their production from fossil fuels [11]. Li et al. [12] examines bio-ethylene costs from methanol, and Nyhus et al. [13] explores methanol-mediated ethylene production costs using UK offshore wind and atmospheric CO_2, projected up to 2035. FT processes can also produce building block chemicals by replacing fossil-derived naphtha with low-carbon FT-naphtha in steam crackers [14]. However, most efforts have focused on optimising middle-distillate fuels (C_{12}–C_{20}) such as diesel and jet fuel [1]. There is limited consensus on the potential to maximise FT-naphtha yields (C_6–C_{12}) or whether this could enable viable business cases. Consequently, the cost-competitiveness of

---

* Corresponding author.
E-mail address: seokyoung.kim.14@ucl.ac.uk (S. Kim).

https://doi.org/10.1016/j.rser.2025.115648
Received 23 October 2023; Received in revised form 20 March 2025; Accepted 20 March 2025

Abbreviations

BECCS	Bioenergy with carbon capture and storage
BTX	Benzene, toluene and mixed xylenes
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
FT	Fischer-Tropsch
H_2	Hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
L-DAC	Liquid hydroxide sorbent direct air capture
MTO	Methanol-to-olefins
MTP	Methanol-to-propylene
PSC	Point-source carbon dioxide
S-DAC	Solid adsorbent direct air capture

producing ethylene and propylene from FT-naphtha remain uncertain.

1.1. *The value of a systems approach for costing synthetic hydrocarbon production*

Formulating a fair comparison of production costs from individual process simulations is inherently challenging due to differing approaches to economic evaluation, regional influences on feedstock prices, and variability in the assumed techno-economic data for technology supply chains [1]. Furthermore, hydrocarbon plants inherently involve co-production, yielding a range of outputs with limited flexibility to adjust their proportions, making business cases dependent on overall plant output and the value of each product. However, there are no standard guidelines for calculating individual product costs in multi-outputs hydrocarbon facilities. Techno-economic studies often group synthetic liquids (e.g., “FT liquids” or “products”), rather than presenting levelised costs for each commodity, while studies that focus on a single product often offset costs with fixed co-product revenues [12], which may fluctuate with future demand in decarbonised energy systems.

Replacing fossil fuels from aviation and chemical feedstocks are often treated as separate challenges [15,16]. Yet both sectors share low-carbon resources (e.g., renewable electricity, electrolytic hydrogen, biomass, atmospheric or point-source CO_2) and technologies (FT and methanol synthesis), while producing co-products that address cross-sectoral demands. Understanding the cost-competitiveness and co-production implications of these technologies from a systems perspective is crucial to identify the most appropriate low-carbon production systems of the future. A single coherent framework for assessing production costs from all these technologies, using consistent assumptions, is needed. This paper proposes a framework for harmonised production cost calculations and applies it to synthetic hydrocarbons for the first time.

1.2. *Contribution and structure of this paper*

This paper estimates current and future production costs of low-carbon ethylene, propylene and jet fuel using FT and methanol synthesis technologies with low-carbon feedstock, i.e. biomass, grid electricity, point source or atmospheric CO_2. It evaluates competitive routes for each product, identifies key cost components, and conducts sensitivity analysis on influential parameters on the overall costs. Uncertainty in feedstock prices over time and the resulting carbon prices required to match with fossil counterparts are determined. By employing a consistent and balanced methodology, it provides a platform for a fair comparison between two principal synthesis technologies, assessing their potential to de-fossilising each sector while identifying synergistic benefits or competitive challenges.

The paper is structured as follows. Section 2 outlines the technological supply chains, ranges in their costs and feedstock prices, and the framework for harmonised production cost calculations. Section 3 presents the results, including competitive pathways for each product, followed by a sensitivity analysis and a comparison with a low-carbon counterfactual. Section 4 discusses challenges and opportunities of synthetic hydrocarbons, and Section 5 concludes.

2. Methods

Most of the technologies discussed in this work are not available at commercial scale as an integrated plant, so there are substantial uncertainties in the cost and performance data. Three scenarios (optimistic, central, and pessimistic) are proposed to understand the impact of these uncertainties. The optimistic scenario projects the lowest levelised cost of production of commodities by assuming the lowest technology cost, highest plant performance and the lowest feedstock price considered plausible in a given year. The pessimistic scenario takes the opposite approach to project the highest plausible levelised cost of production. For a few technologies, the feedstocks required are interconnected. For example, e-fuel pathways that consume CO_2 from DAC would require electricity to supply both primary feedstocks. In such cases, the same commodity price is used for all feedstocks.

2.1. *Technologies*

Fig. 1 show the full supply chains considered for the levelised production cost calculations for synthetic methanol, naphtha, ethylene, propylene, and jet fuel.

2.1.1. *Electrolysis*

Three dominant types of electrolysers are considered for the production of hydrogen in this analysis: alkaline, proton-exchange membrane (PEM), and solid oxide electrolyser cells (SOEC). Alkaline electrolyser and PEM operate under low-temperature (80–120 °C) whereas SOEC utilises high-temperatures (500–900 °C) and uses heat as a reaction input to reduce the electricity input per unit output and hence has a higher electrical efficiency. Co-electrolysis (i.e. direct conversion of water and CO_2 to produce hydrogen and CO) is possible via SOEC, rendering the reverse water gas shift reaction redundant in preparation for FT and methanol reactors that utilise CO as the main feed.

$$2H_2O \rightarrow 2H_2 + O_2$$

2.1.2. *Direct air capture*

Two direct air capture (DAC) technologies are considered in this study to provide CO2 for synthetic hydrocarbons. The first is high-temperature (800 °C) DAC with a liquid hydroxide sorbent (hereafter referred as L-DAC). The second (S-DAC) is low-temperature (85–120 °C) DAC using an amine material bonded to a porous solid support. Investment and operating cost and the feedstock requirements per a unit of CO_2 captured in the future is highly contested in the literature. Here, the current cost of DAC is reflected, then a 6 % cost reduction rate until the projected floor (i.e., lowest possible) investment and operating costs and electricity and heat requirements are reached. The assumed costs are listed in the Supplementary material. Other types of DAC systems are at a very early stage of development, with very uncertain costs, so were not considered in this study.

2.1.3. *Biomass gasification*

Lignocellulosic biomass undergoes partial oxidation that results in a combination of CO, hydrogen and a small amount of CO_2. Impurities such as particulates, tars and hydrogen sulphide are unavoidable when

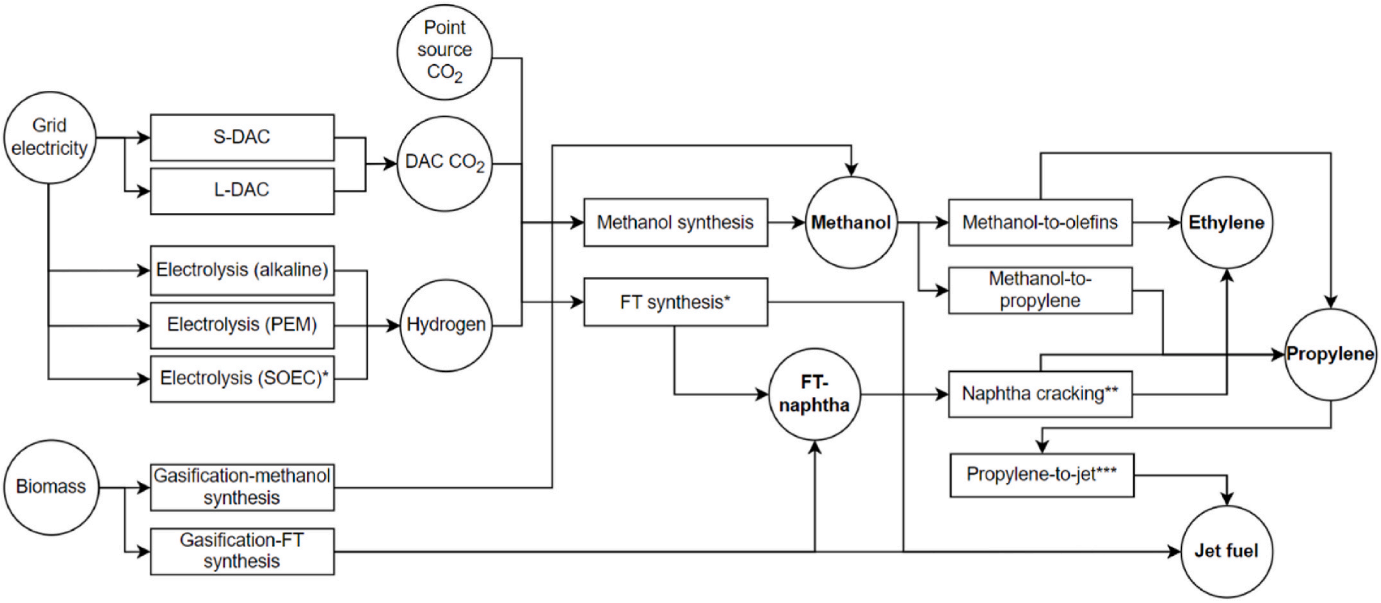


Fig. 1. Resources, technologies and synthetic hydrocarbons from Fischer-Tropsch and methanol synthesis. *FT does not require reverse water-gas-shift reactor in case SOEC are selected. **Steam cracking of naphtha results in ethylene, propylene, BTX aromatics and other fuel products. The latter two are not displayed but considered in the calculations in the work. ***Propylene-to-jet technology co-produce gasoline (referred also as petrol), that is not illustrated in the figure but considered in the calculation. Minimal quantities of light gases resulting from FT and methanol synthesis are presumed to either supply essential process heat or be eliminated as components of flue gases for the purposes of this analysis.

burning biomass, incurring additional clean up equipment and cost [17]. The gas stream also requires conditioning via the water-gas-shift reaction to achieve an appropriate H_2:CO ratio for subsequent synthesis steps (i.e. FT or methanol synthesis). This analysis does not include carbon capture and storage operations, which would marginally impact the investment costs by around 2 % [18].

2.1.4. *Methanol synthesis*

Methanol can be synthesised in a single step from CO and hydrogen or by direct hydrogenation of CO_2. A third approach is a two-step process of steam electrolysis and reverse water gas shift reaction to produce syngas followed by methanol synthesis [19]. Commercial methanol synthesis processes are designed with adjoining process loops spanning multiple synthesis reactors to exhaust the carbon content of the feed, leading to a very high conversion rate [20].

$$CO + 2H_2 \rightleftharpoons CH_3OH$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

2.1.5. *Fischer-Tropsch synthesis*

FT synthesis converts a mixture of CO and hydrogen into a pool of prominently paraffinic hydrocarbons (i.e. C_nH_{2n+2}). Reaction temperature and the catalyst type determine the carbon number distribution and thus the dominant fuel type [21]. High-temperature FT with a cobalt catalyst could maximises jet fuel production with the remainder comprised with naphtha-grade compounds [22]. If point-source CO_2 is the carbon source, the H_2:CO ratio is adjusted appropriately via a reverse water gas shift reactor. This analysis considers 70 % jet fuel (i.e. the reported maximum slate for jet) [3] and the remainder as naphtha co-product as fixed outputs from refining FT liquids.

$$nCO_2 + (3n+1)H_2 \longrightarrow C_nH_{2n+2} + 2nH_2O$$

$$nCO + (2n+1)H_2 \longrightarrow C_nH_{n+2} + nH_2O$$

2.1.6. *Methanol-to-olefins*

Light olefins are produced from methanol via two main reaction steps. Methanol is first dehydrated to dimethyl ether (DMO). Next, the equilibrium mixture of methanol, DMO and water is reacted under the presence of either ZSM-5 or SAPO-34 catalyst to form C_2–C_5 olefins [23]. The C_4+ hydrocarbons (i.e. butane and pentane derivatives) are generally recycled as additional ethylene and propylene sources. This process is well developed and a quarter of methanol in the world is used to produce olefins through methanol-to-olefins (MTO) [11]. A third-generation technology, that is licensed to build five commercial methanol-to-olefins units, reportedly produces 0.33 t ethylene and 0.31 t propylene per t methanol [24].

2.1.7. *Methanol-to-propylene*

The reaction mechanism for methanol-to-propylene (MTP) is the same as MTO but with propylene as the predominant hydrocarbon product, with the commercial process by Lurgi [25] producing 0.9 Mt of propylene annually [26]. While the MTP process generates minor quantities of organic liquid by-products suitable for gasoline and fuel gas refinement, it is possible to significantly reduce this stream and achieve nearly complete conversion into propylene through cracking [27]. This analysis assumes 0.43 t propylene per t methanol, in line with Gonzalez-Garay et al. [10].

2.1.8. *Propylene-to-jet*

C_2–C_4 olefins can produce predominantly paraffinic hydrocarbon fuels via oligomerisation to higher olefins followed by hydrogenation to hydrocarbons in the range of gasoline and jet fuel [28]. This analysis chooses propylene as the feed for such a process and assumes it produces fixed outputs of 50 %wt gasoline and 50 %wt jet fuel [10].

2.1.9. *Naphtha steam cracking*

FT-naphtha grade products are cracked into high-value chemicals via conventional naphtha steam cracking. Naphtha steam cracking delivers a balance portfolio of ethylene, propylene BTX aromatics (a combination of benzene, toluene and mixed xylenes) and butadiene. Following the analysis by the IEA [29], this work assumes 32 %wt, 17 %wt, 10 %wt and 5 %wt, respectively. The remaining stream of fuel products are burned, and the heat is used to satisfy the high heat demand required for the process [30].

2.1.10. Output variability in hydrocarbons and chemicals production

This analysis incorporates the limitations of synthetic hydrocarbon plants in optimising for a single product. Such limitations vary across FT and methanol synthesis technologies. Fig. 2 depicts the fixed hydrocarbon product range considered in this analysis, which aims to optimise jet fuel and ethylene slates as the two main products of interest, taking the highest reported values for these slate for the respective technologies. The methanol-to-propylene technology is able to optimise fully toward propylene [10] and thus excluded in this discussion.

2.1.11. Techno-economics for technologies

The assumed cost and performance characteristics of each technology, including learning rates are documented in the Supplementary material and build on a systematic review in Kim et al. [1] that used a rigorous methodology to review and characterise techno-economic data. It considered only original studies covering full plant supply chains, particularly for hydrocarbon production. In the absence of real-world data for these plants operating at scale, cost and performance estimates for individual plants typically rely on process simulations, which involve significant uncertainty due to variability in process characteristics and economic assumptions, making it challenging to validate the quality of such data for extended assessments [31]. Data extraction in Ref. [1] followed standardised definitions of capital costs and energy efficiencies, with normalisation to a consistent plant scale to eliminate variations from economies of scale. The analysis established useable interquartile ranges for FT and methanol synthesis technologies based on literature spanning 2009 to 2023, identifying and contextualising outliers. The techno-economics of mature downstream processes not covered in Ref. [1], including naphtha cracking, MTO, MTP and PTJ, were validated using the same principles. The relevant data sources are provided in Supplementary material.

Reference plant capacity of 400 MW is selected for all pathways, as the techno-economic data is normalised for a fair comparison assuming commercial scale. Learning rates are applied for bio-based systems (4 % until 2030 and 1 % until 2040) and FT systems (1 % until 2030) to account for improvements in biomass gasifiers and FT catalyst and reactors. For electricity consuming technologies, learning rates are applied to electrolysis and DAC. A plant wide scale factor of 0.67 is used to calculate the benefits of economies of scale where applicable (i.e. industrial processes for FT and methanol synthesis).

2.2. Harmonised production cost calculations

In this study, the levelised cost of producing ethylene, propylene and jet fuel is investigated for FT and methanol synthesis technology pathways. Levelised cost calculations enable simple ranking of different technology alternatives, and this analysis aims to understand the extent of the impact of co-products in the economic evaluation.

2.2.1. Levelised cost of production

The levelised cost calculations are underpinned by Equation (1). The capital recovery factor (CRF) is based on a technology specific 10 % discount rate and the respective lifetime of different technologies that are typically 20–30 years.

$$\mathit{Levelised\ Cost} = \frac{\mathit{CRF}^{*}\mathit{TCI} + \mathit{Fixed\ OPEX} + \mathit{Feedstock\ prices} - [\mathit{Market\ price\ of\ coproducts}]}{\mathit{Target\ product\ produced}} \tag{1}$$

2.2.2. Carbon price to match with fossil counterparts

The carbon price (or the price of carbon avoided) to breakeven with the fossil counterpart are additionally determined built on from the levelised cost which is of current interest [4]. The price support required would simply be the difference between the market price of the fossil counterpart. The carbon price required for breakeven is the cost of avoided emissions that would otherwise be released into the atmosphere after combustion and is shown in Equation (2). The combustion factors, heating values and the fossil fuels prices assumed in this study is listed in the Supplementary material.

$$\mathit{Carbon\ price\ for\ breakeven} = \frac{\mathit{Levelised\ cost} - \mathit{Production\ cost\ of\ fossil\ counterpart}(s)}{\mathit{Commodity\ combustion\ factor}} \tag{2}$$

2.3. Feedstock prices

Table 1 lists the prices taken for the feedstocks considered in this work which include biomass, electricity and point source or DAC CO_2. In anticipating long-term prices for such feedstocks there exist considerable uncertainties, stemming from potential developments in supply-side technologies to produce electricity and CO_2, as well as fluctuations in the international market trade of biomass and possibly electricity. Consequently, a scenario-based approach is adopted to account for the potential ranges of feedstock prices.

Available data on current and projected electricity prices are used for the pessimistic scenario, while the central and optimistic scenarios use estimated values for this analysis. The range assumed in the pessimistic scenario is the projected industrial retail electricity prices published by the UK government [32], broadly assuming no price reduction in the future, consistent with the current conditions [33]. Such prices are an adequate portrayal of the global average before the Russian invasion of Ukraine [34]. The central ranges assume a 75 % transition to renewables in the electricity sector by 2050, with the rest supplied by existing gas-fired power stations, given the intermittent nature of renewables and the challenge of decommissioning existing high-carbon power stations. Optimistic range grid prices are reflective of a fully decarbonised electricity system by 2050, with up to 95 % variable renewable energy, and dispatchable low-carbon generators for the remainder [35]. The industrial retail electricity prices of the modelled electricity systems are drawn via applying an index of 1.49 (the current difference between the strike price and the levelised cost of electricity) to the levelised costs of electricity generation [36] to consider revenue for generators and operational expenditures incurred during route to market.

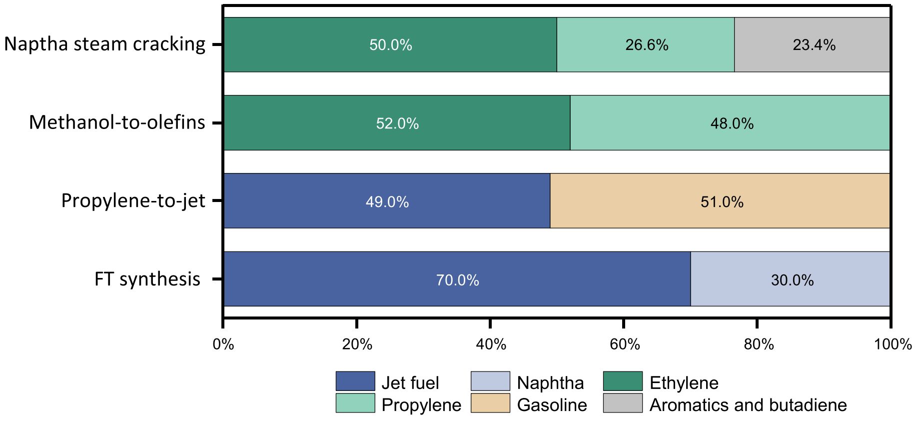


Fig. 2. Fixed hydrocarbon product range (in energy terms) assumed in this work for technologies with unavoidable co-production. Gasoline (from propylene-to-jet) and light-naphtha (from FT) are the same grade fuels and could be interchangeable.

Table 1
Summary of assumed feedstock prices. Biomass, electricity and point source CO_2 sources are referenced in text. The method in calculating DAC CO_2 is included in the Supplementary material, that is influenced by the assumed electricity prices in this study.

Year	Biomass (USD/GJ)			Grid electricity (USD/GJ)			Point source CO_2 (USD/t)			DAC CO_2 (USD/t)		
	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
2020	6.9	10	17	43	43	43	25	30	35	520	536	990
2030	6.9	10	17	43	42	48	25	30	35	400	404	810
2040	6.9	10	17	30	33	52	25	30	35	250	277	730
2050	6.9	10	17	17	22	52	25	30	35	170	214	680

Point source CO_2 is available as a low-carbon feedstock as a by-product from bioethanol plants, and already underpin domestic CO_2 supply chains [37]. Bioethanol plant CO_2 price ranges are taken from the IEA [38]. Although supply and demand impacts on CO_2 prices from these plants are not factored in, potential limitations in their future availability due to industrial decarbonisation efforts are acknowledged. DAC CO_2 prices are interconnected with the grid electricity prices assumed in this study. The heat requirements for solid and liquid sorbent systems are assumed met by using electrolytic hydrogen. Capital and operating expenditure, and energy efficiency of DAC systems take learning, until floor values are reached. The upper cost range of DAC CO_2 (current prices) corresponds to a similar order of magnitude as proposed in a recent economic analysis [39] of 750 USD/t CO_2, while the lower end aligns with the DAC price range established in Marinič and Likozar [40] of 200–400 USD/t CO_2.

The biomass feedstock price ranges are based on typical costs observed in a country that has prior experience in utilising biomass as an energy commodity, primarily for electricity generation [41]. This analysis assumes robust sustainability criteria for biobased hydrocarbons and considers the assumed price range of biomass from forest resource supply chains [42], which do not compete with food or feed. The consensus on the cost per unit of biomass in the current market is reasonably consistent across the literature, with costs mostly below 15 USD/GJ. The global price of biomass could increase substantially as economies strive to meet climate targets, resulting in higher competition and price.

3. Economic feasibility of synthetic hydrocarbons

Table 2 shows the ranges in the levelised costs across the methanol synthesis and FT pathways to produce ethylene, propylene and jet fuel currently and in 2050, and against the current prices of the fossil counterparts.

Fig. 3 presents the levelised costs across the modelled timeframe, enabling a comparison with low-carbon pathways for each hydrocarbon product, using an upper value of 20 USD/kg to eliminate any unreasonably high values that would clearly be uncompetitive.

It is substantially more economical to produce ethylene and propylene through the methanol synthesis pathway across all feedstocks and scenarios. As illustrated in Fig. 3, the only notable proximity to the production cost of methanol-derived ethylene and propylene from the FT pathway is observed in the optimistic scenario for ethylene. However, even in this case, a significant disparity remains when compared to their biomass-derived counterparts from the methanol pathway. This is predominantly due to the low selectivity towards ethylene and propylene throughout the supply chain for the FT route, the total levelised cost

Table 2
Comparison of the minimum and maximum production costs (USD/kg) of ethylene, propylene, and jet fuel across technologies in 2020 and 2050, contrasted with the current prices of the high carbon counterfactuals. MS is methanol synthesis, DAC is direct air capture, and PSC is point source CO_2.

	Ethylene		Propylene		Jet fuel	
	2020	2050	2020	2050	2020	2050
MS-PSC	8.1–10	2.9–11	4.2–5.3	1.8–5.4	8.0–10.9	3.1–11
MS-DAC	12–17	4.0–15	5.9–8.5	2.3–7.6	11–17	4.1–14.9
MS-Biomass	1.3–4.2	1.1–3.9	1.1–2.4	1.0–2.3	1.6–4.3	1.4–4.1
FT-PSC	65–93	24–96	120–180	45–180	5.9–8.4	2.3–8.6
FT-DAC	89–140	31–130	170–270	59–250	8.0–13	2.9–11
FT-Biomass	13–38	10–34	23–71	18–65	1.3–3.5	1.1–3.2
High carbon counterfactual	1.1–1.4	1.1–1.4	0.81–1.3	0.81–1.3	0.59–0.90	0.59–0.90

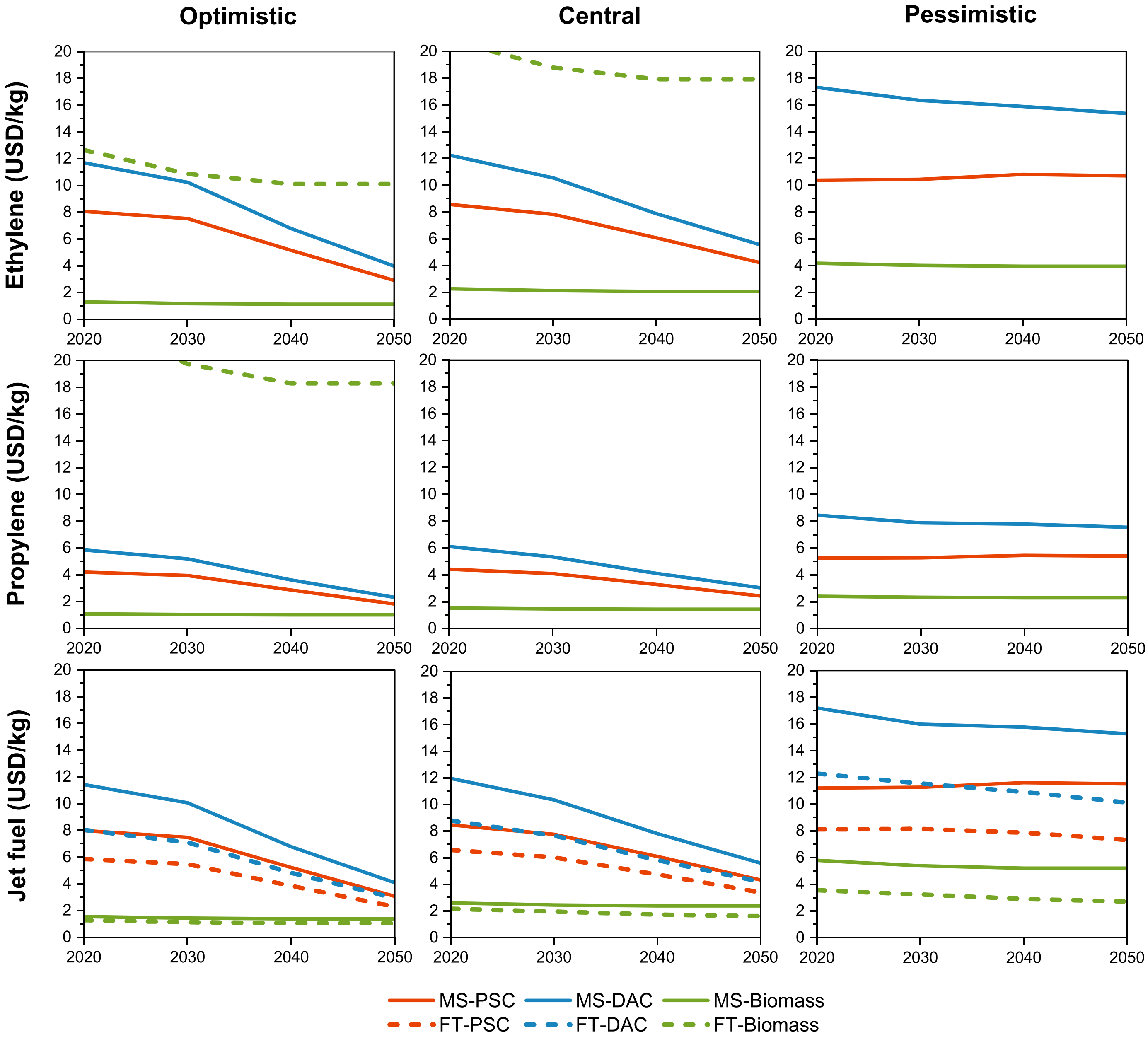


Fig. 3. Production cost of ethylene, propylene and jet fuel from methanol synthesis and FT supply chains in the optimistic, central and pessimistic scenarios that are under 20 USD/kg.

per unit of constructing a single unit of ethylene or propylene as the target product would require substantial amount of low-carbon feedstocks. For example, to produce a tonne of ethylene via the FT route, along the supply chain, 7.3, 0.52 and 0.48 tonnes of jet fuel, propylene, and BTX aromatics (and butadiene) are co-produced, respectively. The revenue from a balanced portfolio of low-carbon co-products along the supply chain are heavily outweighed by the expenses accrued from the electricity price to produce the desired unit of ethylene.

The product yield for propylene is even lower in the FT route, as the naphtha steam cracking yield towards propylene is only 27 %. The potential cost reduction by assuming FT-naphtha will be processed in existing steam crackers in the UK is marginal. This suggest FT is convincingly selective toward middle distillate fuels and FT-naphtha should be considered a premium secondary product in business cases. For FT chemicals to be sold in the future, their product suite of middle distillate fuels must advance first in the market.

On the other hand, producing low-carbon jet fuel is the most economical through FT. The methanol synthesis pathways pose 33 %–56 % and 20 %–48 % higher production cost per tonne of jet fuel from electricity and biomass, respectively, with these differences increasing with time. Cost reduction is primarily driven in the FT synthesis step with improvements in catalysts and reactor technologies [43]. Product yield towards jet fuel is a major feature in the economics of the methanol-to-jet fuel pathway, with the propylene-to-jet technology producing 1.1 tonnes of gasoline for 1 tonne of jet fuel. This observation is confirmed by Gonzalez-Garay et al. [10] whereby the annual investment and electricity requirements are higher for the methanol route compared to FT due to the presence of the relatively large gasoline yield. This study assumes multiple steps to the production of longer chain hydrocarbons from methanol; however, novel proprietary methanol-to-jet technologies are under development that would raise their cost-competitiveness [9].

Ethylene, propylene and jet fuel from biomass are cheaper than plants using grid electricity, particularly in the near term, due to the relatively high assumed cost of electricity compared to biomass. Among the commodities examined in this study, propylene derived from biomass through the methanol synthesis route emerges as the most economically competitive, closely followed by ethylene from the same synthesis pathway compared to the fossil counterparts. The high-value chemicals from biomass are cost-competitive with the production cost of their respective fossil counterparts in the optimistic case. The carbon price required to breakeven in the central scenario for propylene fall under the average carbon price in Europe and in the UK in 2022. The anticipated production cost of ethylene exceeded that of propylene due to the slightly lower investment cost and higher energy efficiency associated with methanol-to-propylene in contrast to methanol-to-olefins, and more importantly, the former does not result in co-production. Jet fuel from biomass (FT) appear also economically viable under the current carbon price in European regions in the optimistic scenario assuming that the current carbon price does not fall in the future. In the pessimistic scenario, carbon prices of 750, 340 and 860 USD/t CO_2 avoided are required for biomass-derived ethylene, propylene and jet fuel to reach cost parity, respectively.

Industrially captured point source carbon is assumed cheaper than securing carbon from DAC across all years by 7- to 20-fold (lower end with floor electricity prices and DAC equipment costs), without the influence of supply and demand considerations in the future. DAC CO_2 production cost could be decreased further by 14 %–18 % if assuming the heat requirements are met exclusively with electricity. Thereby reducing the total levelised cost of ethylene and jet fuel by 5 %–7 % and 4 %–5 %, respectively.

3.1. Cost-competitive technology pathways

Electricity-based hydrocarbons appear far removed to compete in the pessimistic scenario that assume the current electricity prices does not fall in the future, requiring carbon prices of 2400–3700 USD/t CO_2 to breakeven. Under the partially decarbonised central scenario with 75 % renewables in 2050, these hydrocarbons also exhibit high production costs. To achieve breakeven such hydrocarbons would necessitate carbon prices ranging from 760 to 1100 USD/t CO_2 for ethylene, 630–790 USD/t CO_2 for propylene, and 820–1100 USD/t CO_2 for jet fuel. The lower range represents hydrocarbons sourced from point-source CO_2, while the higher range corresponds to DAC CO_2. The figures from the central scenario highlight substantially higher costs compared to the optimistic scenario, which assumes a fully decarbonised power system, with the differences projected to be 1.8, 3.3, and 1.7 times less in 2050 for ethylene, propylene, and jet fuel, respectively. This emphasises the importance of shifting towards a net-zero power system, particularly for energy systems reliant on a constant grid supply to produce low-carbon fuels and chemicals in the future.

Low-carbon methanol and naphtha are intermediaries to ethylene,

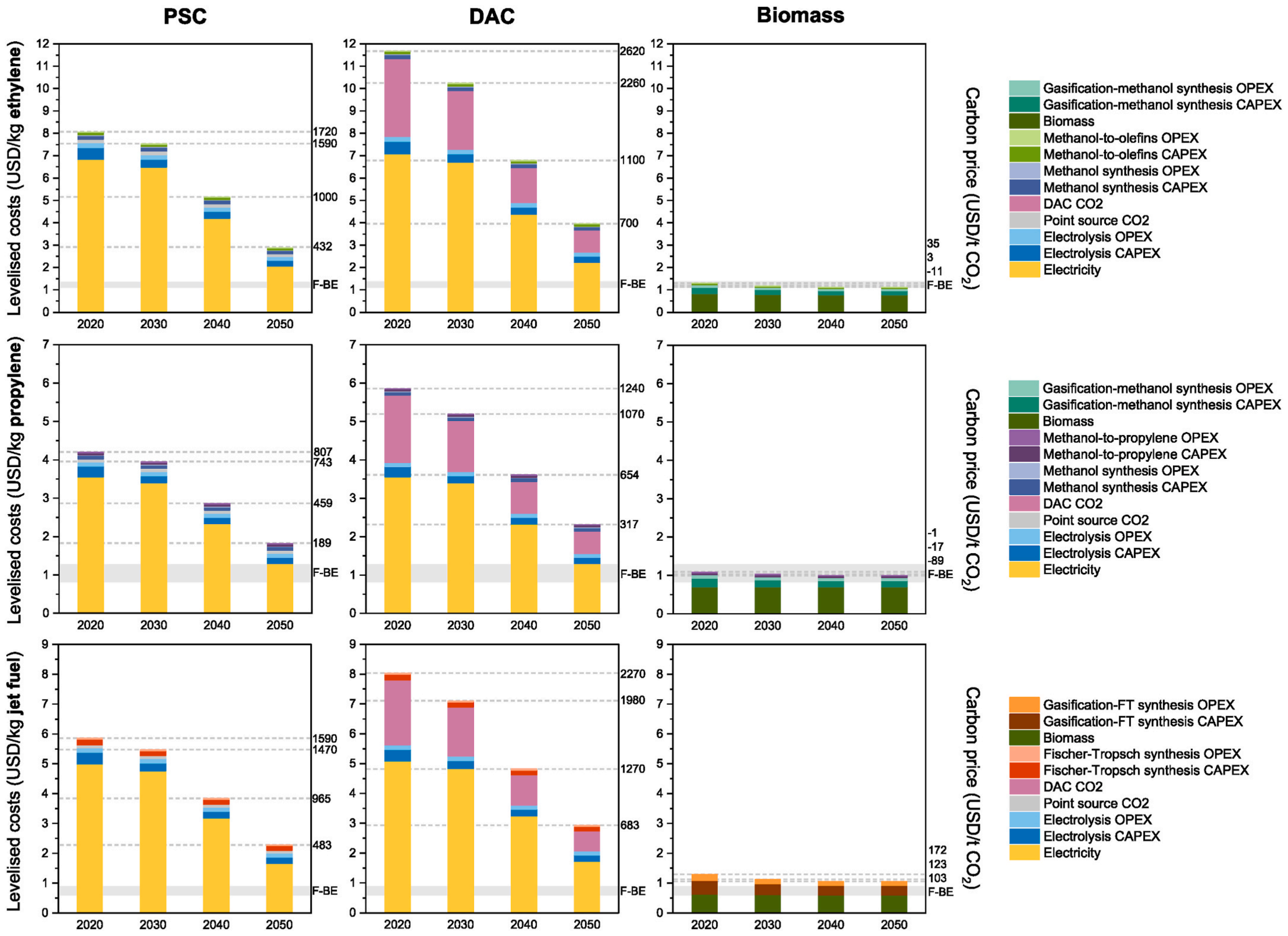


Fig. 4. Cost breakdown of dollars required to produce a kilogram of ethylene (methanol synthesis), propylene (methanol synthesis) and jet fuel (FT) in the optimistic case. Each column reflects discrete carbon sources, PSC (point source CO_2), DAC CO_2 and biomass, respectively. Right axis show the necessary carbon price (USD/t CO_2 avoided) for synthetic ethylene, propylene and jet fuel to break-even with their fossil counterparts. F-BE refers to the break-even point with the price range of the fossil counterparts.

propylene and jet fuel, and those production costs are documented in the Supplementary material (Tables 9–10). Recent estimates are available for the production cost of low-carbon methanol from electricity [44,45] that align with costs presented in this work.

This section focuses on the methanol synthesis pathway to produce ethylene and propylene, and FT pathway to produce jet fuel under the optimistic scenario, as these pathways appears most likely to become competitive in the future. Fig. 4 displays the cost breakdown of those pathways, and the carbon price required to break-even fossil counterparts across the modelled timeframe.

Grid prices dominate the cost of electricity-based hydrocarbons. In terms of the share of the levelised costs, electricity prices are 71 %–85 % for point source CO_2-based and 74 %–77 % for DAC CO_2-based hydrocarbons. Even as significant reductions in grid prices are assumed, these values collectively make up 67 %–70 % of the total levelised costs in 2050. A fully decarbonised grid that is predominantly underpinned by inexpensive renewables coupled with floor technology investment and operating costs is not economically competitive with historical routes using crude oil without carbon pricing. Direct price support or mandatory carbon pricing in relevant sectors would be required to achieve cost parity with the with values listed in Fig. 4. It is important to note that relatively conservative views are taken in this analysis on the transition to a net zero electricity system but depending on government ambition, the cost reductions assumed for electricity-systems in 2050 could be achieved 10–15 years earlier [46].

Another key aspect that drives the economic viability of electricity-based hydrocarbons is the energy and carbon efficiency across technologies. A key trend is identified in this work in that among electrolysis and DAC technology options considered, the technologies that are the most economical under the influence of high feedstock prices are options that are not the cheapest in terms of investment and operating costs, but the most energy efficient (i.e., alkaline electrolysis and S-DAC) under consistently maximum load. The synthesis step to produce ethylene through the methanol pathway is more efficient (~82 %) than FT systems (~66 %–77 %) due to the presence of multiple long-chain hydrocarbons in the resulting FT synthetic-crude. This contributes toward the higher production cost for jet fuel as opposed to producing ethylene via the methanol pathway. These findings highlight the value of innovation

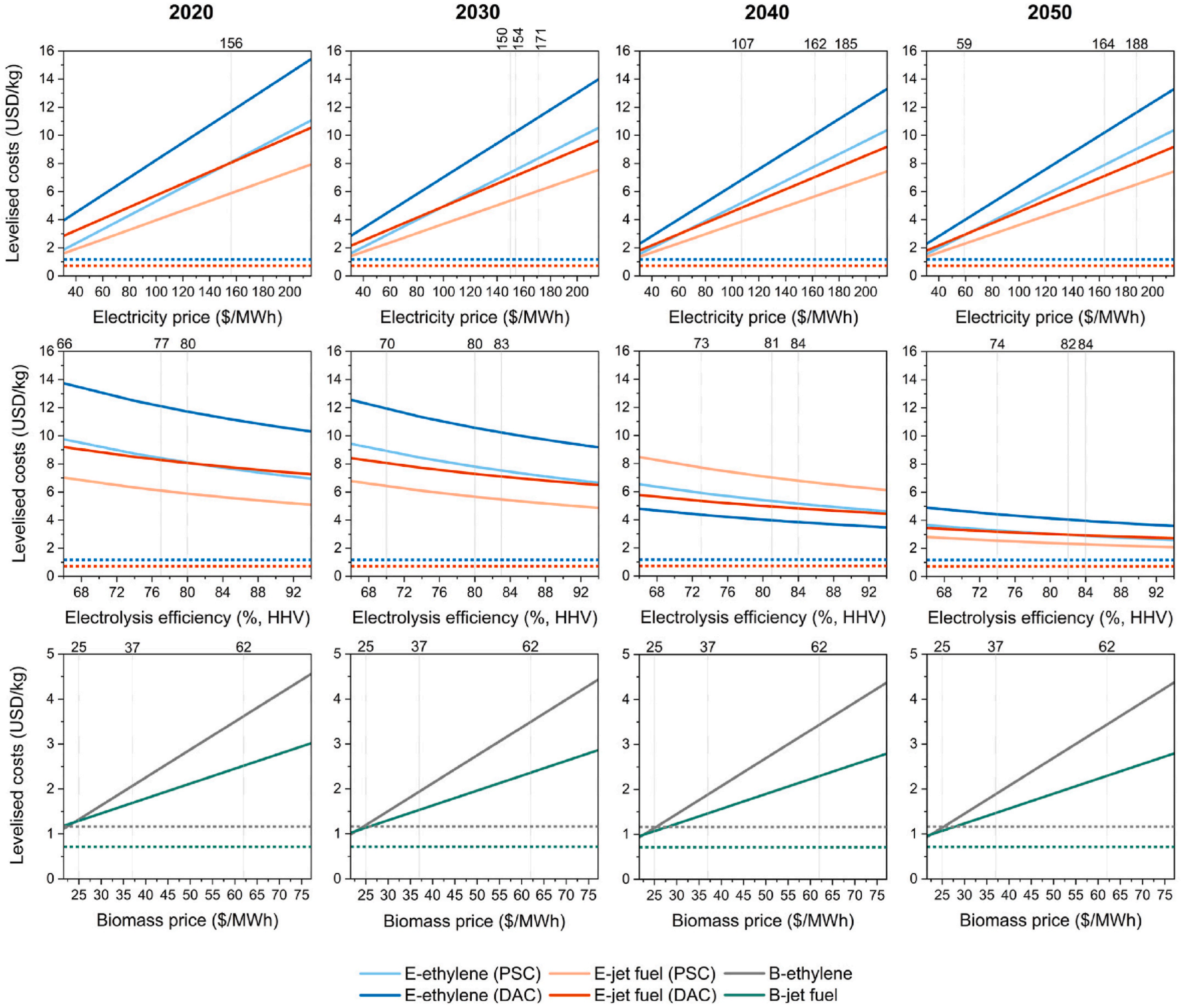


Fig. 5. Ethylene, propylene, and jet fuel production costs at different grid electricity and biomass prices, and alkaline electrolyser efficiency. Horizontal dotted lines reflect prices to break even with fossil counterparts (the differences in the ethylene and propylene central market price are negligible on the figure). Vertical grey lines are optimistic, central, and pessimistic values assumed for the three scenarios previously discussed.

in highly energy and carbon efficient systems. The additional cost of losing less energy and carbon via attaining better system performance outweigh the additional investment needs if the low-carbon feedstock prices are significant enough.

Investment costs of FT and methanol synthesis technologies are only a small part of the overall production cost for electricity-based systems. Conversion from the point of hydrogen and CO_2 to liquid fuels and chemicals does not require investment-heavy equipment units, and the cost ranges reported are relatively narrow. On the other hand, manufacturing syngas from biomass is associated with intensive capital investment. Gasification, and the associated preparation and cleaning units, would typically constitute around 50 %–60 % of the total capital cost of FT biomass-to-liquid facilities. The share of the technology cost (i.e. investment cost and fixed operating costs) in biomass pathways consist of 30 %–35 % and 43 %–51 % of the total levelised cost for ethylene/propylene and jet fuel, respectively. The investment cost ranges of gasification systems in the literature are vast, with upper end reportedly up to 260 USD/GJ for FT and 130 USD/GJ product for methanol synthesis, for plant scales above 150 MW. Using these figures, the resulting prices of jet fuel and ethylene in 2050 are 3.3 USD/kg and 1.5 USD/kg, respectively. This creates a significant uncertainty in assessing the overall cost of ethylene, propylene and jet fuel from biomass.

Regarding technology costs within the breakdown of levelised cost of electricity systems, electrolysis stands out as the largest contributing factor. The proportion of the total capital and fixed operation costs allocated to electrolysis is 61 %–69 % for ethylene and 64 %–71 % for jet fuel, with the lower ranges in 2050 due to technology learning. These shares would likely decrease if the assumed system were smaller in scale, as methanol/FT synthesis and the respective refining steps benefit more from economies of scale (scale factor 0.6–0.7), compared to electrolysis, which typically has a scale factor of 1.

3.2. Sensitivity analysis

Future low-carbon feedstock prices and the majority of the technology parameters (i.e. the investment and operating costs and technology performance) reported in the literature are contentious and pose uncertainties in the results. The central and pessimistic scenarios indicate that low-carbon jet fuel, ethylene, and propylene, especially when derived from electricity, are still far from competitive with fossil fuel alternatives. Achieving competitiveness would require substantial reductions in techno-economic inputs and feedstock prices, even beyond those assumed in the optimistic case. To assess the impact of key variables, a sensitivity analysis was conducted, highlighting how reductions in three of the most influential parameters affect overall production costs.

Fig. 5 show the impact of grid electricity prices, hydrogen production efficiency and biomass prices on the overall production cost. The upper-end and the lower-end values reflect what is theoretically possible, albeit feedstock prices could exceed the upper-end values considered here in the event of a geopolitical conflict. Feedstock prices will vary based on regional characteristics, but the sensitivity ranges used in Fig. 5 should be broadly applicable worldwide. While possible cost variations linked to building and operating such facilities in different regions are acknowledged, these conversions lack definitive guidance and could introduce added uncertainties into the calculations. The plant investment and operating costs estimated in this analysis is largely based on constructing and operating synthetic hydrocarbon facilities in the western European regions and the U.S. While this omission could impact biobased hydrocarbons, for electricity-based hydrocarbons, these variations minimally affect process economics, as the levelised cost of production is primarily driven by feedstock prices.

Electricity prices are by far the most influential parameter for electricity-based hydrocarbons, primarily as a feedstock for electrolysis but also to supply DAC CO_2. The lowest price considered (31 USD/MWh) in Fig. 5 represent the projected levelised cost of electricity from dedicated renewables in Western Europe in 2050, that bypass the revenues for generators and grid fees [36]. In this case, investment and operating cost of dedicated wind or solar farms would be part of the business case of synthetic hydrocarbon plants, with sufficient energy storage or operating with lower capacity factor. DAC CO_2 price could reach 130 USD/t in 2050 under such conditions. As previously mentioned, despite considering the minimum cost of electricity achievable in European regions with substantial potential for offshore wind expansion, it is probable that electricity-based ethylene and jet fuel will necessitate support to achieve cost competitiveness with fossil alternatives. The levelised cost of ethylene, propylene and jet fuel with the grid electricity price assumed in the optimistic scenario (59 USD/MWh in 2050), is 1.8–1.95x, 1.55–1.56x and 1.68–1.75x the cost of a plant with dedicated renewables, respectively, albeit capital and operating costs for energy storage and operating with lower capacity factors should be factored into this calculation which is significant [10].

The energy efficiency of electrolysers plays a crucial role in the cost competitiveness of electricity-based hydrocarbons. The range of efficiencies depicted in Fig. 5 is for alkaline electrolysis, with the lowest performing value of 66 % [47] and the highest projected performance of 94 % [48]. Among technology performances of the modelled system displayed in Fig. 1, the projected energy efficiency of electrolysers has the highest range in the literature. This uncertainty influences the resulting levelised costs of ethylene and jet fuel as feedstock prices are high. By increasing the electrolysis efficiency from the assumed value in the optimistic scenario across years to the theoretical maximum, the resulting ethylene, propylene and jet fuel decrease in the production cost by 12 %–14 %, 10 %–11 % and 11 %–13 %, respectively. Conversely, if the improvements in electrolyser efficiency are not realised and remain at the current value (∼74 %) the expenses would increase by 9 %–11 %, 6 %–7 % and 7 %–11 % for ethylene, propylene and jet fuel, respectively, compared to the reported values in the optimistic scenario.

Biomass price is set to be influential in the business cases of bio-based hydrocarbon plants. As mentioned before, there are uncertainties in the evolution of the market for using biomass for energy purposes. As shown in Fig. 5, an increase in the biomass price from 25 to 62 USD/MWh (i.e. the lowest to the highest reported prices) would increase the production cost of jet fuel and ethylene by 2.5 and 3.4-fold, respectively. If the biomass feedstock price exceeds the prices assumed in this study in the future, the levelised cost of bio-based hydrocarbons could approach the cost of electricity-derived hydrocarbons; for example, for ethylene, the cost could reach 4 USD/kg. Ethylene from the methanol synthesis route is more sensitive to the biomass price than jet fuel from the FT route because the energy efficiency and the product selectivity of the FT route is higher, albeit the entire chain of the methanol synthesis route is modelled cheaper. This explains the cost per tonne ethylene overlapping jet fuel when the feedstock prices are insignificant (i.e. <25 USD/MWh). This makes using municipal solid waste as the primary feedstock attractive potentially resulting in negative feedstock price due to gate fees. Albeit the sorting and preparation of the feedstock before the gasification step is expected to be significantly more expensive, roughly estimated to account for as much as 15 % of the entire gasification-FT plant costs [49]. Additionally, depending on legislation regarding unabated biomass, incorporating carbon capture and storage operations into bio-based systems could result in an overall cost increase of up to 7 % [3].

The degree of co-production strongly influences the levelised cost. In the future, it is possible that some economies may apply the carbon price for specific high-emitting sectors in which case the revenues from co-products could be valued to a greater extent. While this section focuses on jet fuel production from FT, the methanol synthesis pathway to jet fuel is also reasonably competitive but is hindered by the large amounts of gasoline-grade hydrocarbons that are co-produced. The energy efficiency of the methanol synthesis supply chain is 3 % higher than the equivalent FT pathway from a total product-basis. Under scenarios

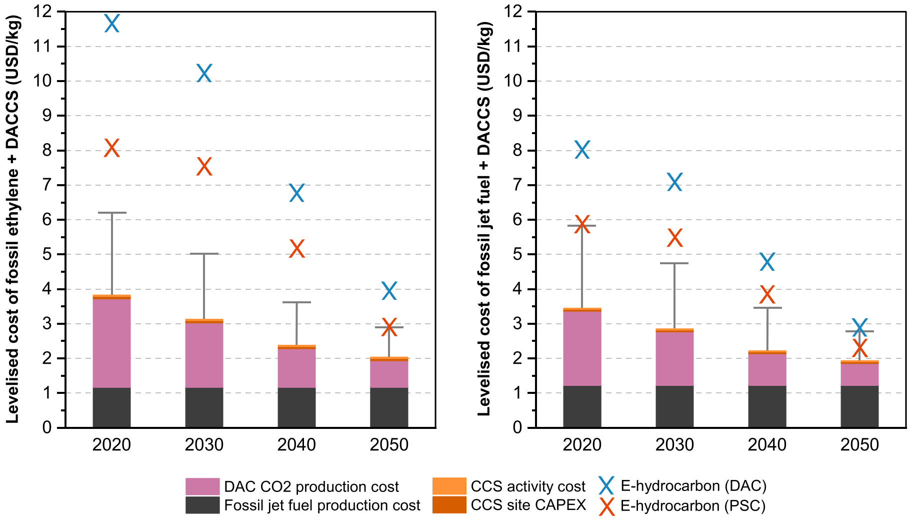


Fig. 6. Levelised cost of fossil counterparts combined with DACCS offsets. CCS activity cost and CCS site CAPEX sourced from the UK TIMES energy system model. Upstream emissions associated with fossil fuel production, transportation and processing calculated using the refinery efficiency of 91 % [51] and sourced from the International Energy Agency [52] which assume the global average reduces to 51 % by 2030. Error bars represent the levelised cost of ethylene or jet fuel + DACCS using fossil fuels from extraction sites with the highest reported upstream emissions from the OCI [53].

where the carbon price for gasoline and naphtha exceeds 300 USD/t of CO_2 released, jet fuel from methanol synthesis becomes marginally cheaper than jet fuel from FT. Technologies with balanced portfolios of low-carbon products could compete with more product-selective technologies under the assumption that the relevant co-products would be servicing sectors that are covered by the carbon price.

3.3. Comparison with a low-carbon counterfactual

In energy system pathways compatible with the Paris Agreement, the mitigation of challenging emissions sources—such as international aviation, shipping, and petrochemical sectors—requires either a move to low-carbon fuels and chemicals or offsetting high-carbon emissions in these sectors using negative emissions. A number of negative emission options exist including nature-based solutions, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS). Lowering the cost of DACCS presents a challenge [50], yet it is not restricted by scale or concerns related to sustainability and land competition, unlike nature-based solutions and bioenergy, so is most suitable for this analysis. The counterfactual system compared in this section is the continued use of fossil jet fuel and ethylene with emissions fully offset by a DACCS supply chain. This is compared with the levelised production cost of electricity-based synthetic hydrocarbons, as the sustainability issue similarly applies to biomass used to produce synthetic fuels and chemicals.

Fig. 6 compares the levelised costs of the two approaches using the electricity prices assumptions of the optimistic scenario. The DACCS supply chain is projected to be more cost-effective than investing in electricity and DAC CO_2-based hydrocarbons throughout all years. The cost gap narrows in the future as a result of reduced electricity prices. DAC-derived ethylene and jet fuel achieve factors of 2 and 1.5, respectively, towards reaching cost parity compared to offsetting the same amount of emissions avoided through DACCS. Point source CO_2-derived electricity hydrocarbons are close to cost-competitiveness and are projected to become nearly cost-competitive by 2050 with the low-carbon counterfactual. However, CO_2 is anticipated to predominantly originate from DAC in future low-carbon economies.

These results are sensitive to several factors. First, oil and gas cost volatility would only affect the production costs of fossil ethylene and jet fuel if electricity prices were decoupled from gas prices as a result of deploying renewables in the future. Second, the emissions intensities of upstream fossil fuels operations, encompassing extraction, transportation, processing and refining, exhibit significant variability between sites (ranging from 120 to 640 kg CO_2 equivalent per barrel of oil) [52–54]. Reliance on fossil fuels from regions with high supply-chain emissions could result in offsetting costs comparable to investing in DAC-based jet fuel in 2050, as depicted in Fig. 6. Third, offsetting emissions using DACCS would require substantially larger underground CO_2 sequestration, requiring faster construction of storage sites and depleting total storage more rapidly. Finally, the aromatics in jet fuel are an indirect greenhouse gas when released at high altitude [55]. FT fuels are predominately comprised with paraffinic compounds with few aromatics, so using the same quantity of FT fuels would lead to lower global warming [56]. This additional global warming caused by fossil-based jet fuel is not normally considered in techno-economic appraisals and is excluded from this study. Accounting for it would increase the counterfactual cost above the levels shown in Fig. 6.

3.4. Comparison of findings with the literature

The optimistic scenario values are largely consistent with the wider literature. For example, the production costs for FT pathways in jet fuel closely correspond to Gonzalez-Garay et al. [10], who report 5.3–6.6 USD/kg for point-source CO_2 and 9.1–10.8 USD/kg for DAC CO_2. The 2050 cost estimates in this work align with ranges from Schmidt et al. [8], indicating 1.1–2.0 USD/kg for point-source CO_2 and 1.5–2.7 USD/kg for DAC CO_2 electricity-based jet fuel in 2050. The bio-ethylene production costs via methanol synthesis are in line with the 1.1 USD/kg reported in Li et al. [12] that assume a lower biomass feedstock price via utilising regional straw availability but a higher technology cost. The central and pessimistic scenarios considered in this analysis offer insight into the economic risks associated with low-carbon fuels and chemicals in the absence of substantial efforts towards transitioning to a low-carbon energy system, an aspect that is frequently overlooked in the literature.

3.5. Limitations and future research

While this analysis provides an in-depth estimation of plausible ranges for the levelised cost of synthetic hydrocarbons, several limitations exist that could be addressed in future research.

- It explicitly assumes synthetic hydrocarbons will be deployed in future energy systems, with levelised costs benefiting from technology learning, eventually reaching nth-of-a-kind costs. Yet if these technologies are not deployed at scale in a timely manner, the technology costs presented for future years could be higher.
- Competition for low-carbon feedstocks (renewable electricity, electrolytic hydrogen, lignocellulosic biomass, DAC CO_2 and point-source CO_2) are not considered in this work. In a highly decarbonised economy, these resources will be in high demand across various sectors, potentially impacting their price and availability. Given the relative low energy efficiencies of synthetic hydrocarbon technologies to the low-carbon counterfactual (as discussed in Section 3.3), governments could steer towards offsetting emissions to optimise limited resources.
- While renewable electricity-based hydrocarbons are generally considered carbon neutral regardless of the CO_2 source, it is crucial to assess detailed supply chain emissions of biobased systems, which are not examined in this work. Future research in this area would benefit from advanced sustainability tools as discussed further in Section 4.1.
- This analysis assumes an uninterrupted supply of grid electricity for electricity-based hydrocarbons, thereby taking advantage of full load factors. However, future work could explore partial load operation to leverage periods of low electricity prices when supply exceeds demand, as electricity prices are the most influential parameter in the economic viability of electricity-based hydrocarbons production.
- For future research, a Monte Carlo simulation could provide valuable insights if process simulation models synthesised previous studies for each plant type and identified uncertainties in each metric, building on prior work [1]. Alternatively, once real plants were built, uncertainty in each metric could be sampled to identify probability distributions. However, in the absence of such studies, plausible distributions are uncharacterisable at present [57], as variations in cost estimations arise from differing assumptions or the level of analysis comprehensiveness, rather than random factors. With appropriate distributions, future research could also examine relationships between plant techno-economic parameters, such as the trade-off between higher capital costs and increased energy efficiency in advanced plant designs. However, without reliable distributions, Monte Carlo analysis could yield misleading results. To mitigate this, a sensitivity analysis was used in this work instead.

4. Challenges for deploying synthetic hydrocarbons

4.1. The availability and sustainability of low-carbon feedstocks

Point source CO_2 (captured from industrial plants) proves cost-effective compared to using DAC CO_2, yet concerns arise about its future availability. Using the UK as an example, if around 70 % of their current industrial CO_2 emissions (~62 Mt) were technically feasible to capture and solely utilised for producing point-source CO_2 electricity-based jet fuel, the resulting capacity (131 TWh) would sufficiently meet the entire current demand for UK aviation (117 TWh). However, factoring in the historical trends of UK industry losses and its decarbonisation efforts via process switching [58], energy efficiency and demand reduction [59], the potential for carbon captured is expected to be much less. This could be limited to specific industries such as cement manufacturing [60], where process emissions are unavoidable. Also, carbon capture and utilisation will likely expand to supply other hard-to-abate sectors like shipping, petrochemicals, in addition to aviation, all of which are on a trajectory of increasing demand [61]. In the future, CO_2 could also originate from BECCS for power and heat generation [62], or hydrogen [63] or fuel production [18]. Similarly for CO_2 from DAC, this carbon could face a conflicting role, as it must also be permanently stored to deliver negative emissions.

Expanding renewable electricity capacity is crucial due to its a dual role: enabling negative emissions through DACCS for the entire energy system and fulfilling both feedstock demands for DAC CO_2-derived hydrocarbons, including electrolytic hydrogen and DAC energy needs. Strategically optimising the use of low-carbon resources (renewables, biomass, low-carbon CO_2) alongside negative emissions necessitates comprehensive energy systems analysis. Moreover, a low-carbon synthetic hydrocarbon-based energy system requires a significant share of renewables, potentially conflicting with sectors more amenable to electrification [64]. Achieving a near [35] or complete [65] transition to renewables power system is technically possible. Practical insights can be gained from existing market models in regions that have made significant strides in renewable integration [66].

While this study focuses on biobased hydrocarbons sourced from biogenic feedstocks that do not compete with food or feed, it is essential to examine their life cycle within more detailed system boundaries. Examining detailed supply chain emissions and implications on biodiversity is essential for setting effective sustainability criteria and low-carbon standards for biobased hydrocarbons, which are yet to be established [4]. A recent work highlights the importance and synergistic effects of combining techno-economic analysis with advanced sustainability methods [67]. Such analysis would complement the results of this work, which primarily provide insights at national and global levels, and enhance the robustness of future investment decisions by incorporating local-level perspectives. This could extend to point source CO_2-derived hydrocarbons, where the overall sustainability of manufacturing fuels and chemicals from industrial gases at scale is yet to be thoroughly determined [68].

4.2. The case for flexible and dynamic operation

Throughout Section 3, reducing electricity prices is emphasised to improve the economic viability of electricity-based hydrocarbons. Feasible business cases rely on shifting to a fully decarbonised power system supported by cheap renewables. As grid electricity costs would include substantial network and balancing costs, one approach would be for plants to invest in dedicated co-located renewable resources. Fuel producers would need to either operate their plants at flexible part-load to match renewable generation variability or would need to deploy on-site storage or purchase grid electricity when renewable generation were low. It would be useful to explore whether such operations have more attractive business cases in some places than the use of grid electricity assumed in this study.

4.3. Subsidies and integration into existing supply chains for co-products

The level of selectivity toward a specific commodity (i.e. minimising the yield of co-products) is extremely influential in the levelised cost calculation. For the purposes of calculating singular commodity production costs, proxies were used for the assumed market price of the co-products. In reality, such prices are subject to individual commodity market developments. Additionally, it is possible that these co-products could receive producer incentives from their respective sectors, potentially positively influencing the business cases of synthetic hydrocarbon plants per product basis and for targeted fuels and chemicals. Legally binding support for low-carbon fuels and chemicals is currently confined to road transport [69]; however, such incentives are also anticipated for other hard-to-abate sectors with price support in discussion for low-carbon jet fuels [4,70].

Given the varying degrees of and limited flexibilities to maximise jet fuel, ethylene and propylene for such technology pathways, a range of different plants may have to be built to be able to produce the required quantities of demand for fuels and chemicals. While the shift toward net-zero aviation is relatively straightforward given the singular product focus, the challenge arises from multiple high-value chemicals with distinct demands that are not interchangeable. Consequently, phasing out existing high-carbon chemical production plants while maintaining a balanced supply-demand relationship could be challenging. For instance, the most economical method of producing ethylene is through methanol-to-olefins technology. Nonetheless, if a specific region with ambitious emission reduction goals experiences substantial demand for BTX aromatics, it might necessitate constructing costly steam crackers within the energy system.

5. Conclusions

This research estimates the current and the future production cost of ethylene, propylene and jet fuel from low-carbon resources from a number of FT or methanol-mediated technologies. It finds that the methanol synthesis pathways are better suited economically in targeting ethylene and propylene production, while FT pathways are more competitive for jet fuel. These findings are sensitive to the future carbon price, and the extent to which policies support business cases of low-carbon co-products. Biobased hydrocarbons appear competitive in the central scenario and may initially drive the market, albeit the investment cost of gasification-based plants and the market for biomass utilisation remain contentious. Rapid transition to a net zero power system is integral for electricity-based hydrocarbons, and DAC CO_2 is set to be important for supplying low-carbon hydrocarbons and/or supporting the counterfactual of negative emissions and the continued use of fossil fuels in hard-to-abate sectors. A system-wide analysis would offer valuable insights into the supply-side implications for achieving net zero targets through low-carbon fuels and chemicals.

Author contribution

Conceptualization and Methodology: SK, PD and IB, Formal analysis and Investigation: SK, Writing – original draft: SK, Writing – review & editing: SK, PD and IB, Funding acquisition: PD.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Seokyoung (Chris) Kim reports financial support was provided by Johnson Matthey Plc. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Seokyoung (Chris) Kim was supported by an EPSRC CASE studentship (grant EP/R513143/1), which was part-funded by Johnson Matthey as the CASE partner. Johnson Matthey did not contribute to or have any influence on the conclusions of this research. Paul Dodds was supported by the “UK-HyRES: Hub for Research Challenges in Hydrogen and Alternative Liquid Fuels” project (EP/X038963/1). Isabela Butnar would like to acknowledge funding from the Natural Environment Research Council (grant NE/V013106/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.115648.

Data availability

Data will be made available on request.

References

[1] Kim S, Dodds PE, Butnar I. Technoeconomic characterisation of low-carbon liquid hydrocarbons production. Energy 2024;294:130810. https://doi.org/10.1016/j.energy.2024.130810.

[2] Brynolf S, Taljegard M, Grahn M, Hansson J. Electrofuels for the transport sector: a review of production costs. Renew Sustain Energy Rev 2018;81:1887–905. https://doi.org/10.1016/j.rser.2017.05.288.

[3] World Economic Forum. Clean skies for tomorrow sustainable aviation fuels as a pathway to net-zero aviation. https://www.weforum.org/reports/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation/; 2020.

[4] Department for Transport. Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate A second consultation on reducing the greenhouse gas emissions of aviation fuel in the UK. 2023.

[5] Dimitriou I, Goldingay H, Bridgwater AV. Techno-economic and uncertainty analysis of Biomass to Liquid (BTL) systems for transport fuel production. Renew Sustain Energy Rev 2018;88:160–75. https://doi.org/10.1016/j.rser.2018.02.023.

[6] Schemme S, Breuer JL, Köller M, Meschede S, Walman F, Samsun RC, et al. H2-based synthetic fuels: a techno-economic comparison of alcohol, ether and hydrocarbon production. Int J Hydrogen Energy 2020;45(8):5395–414. https://doi.org/10.1016/j.ijhydene.2019.05.028.

[7] Wassermann T, Schnuelle C, Kenkel P, Zondervan E. Power-to-Methanol at refineries as a precursor to green jet fuel production: a simulation and assessment study. Computer Aided Chemical Engineering 2020;48:1453–8. https://doi.org/10.1016/B978-0-12-823377-1.50243-3.

[8] Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T. Power-to-Liquids as renewable fuel option for aviation: a review. Chem Ing Tech 2018;90(1–2):127–40. https://doi.org/10.1002/cite.201700129.

[9] ExxonMobil. ExxonMobil methanol to jet technology to provide new route for sustainable aviation fuel production 2023. 2023. Available from: https://www.exxonmobilchemical.com/en/resources/library/library-detail/101116/exxonmobil_sustainable_aviation_fuel_production_en. [Accessed 1 June 2023].

[10] Gonzalez-Garay A, Heuberger-Austin C, Fu X, Klokkenburg M, Zhang D, van der Made A, Shah N. Unravelling the potential of sustainable aviation fuels to decarbonise the aviation sector. Energy Environ Sci 2022;15(8):3291–309. https://doi.org/10.1039/D1EE03437E.

[11] IRENA and Methanol Institute. Innovation outlook: renewable methanol. https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol; 2021.

[12] Li HR, Zhang SY, Zhou J, Wang ZY, Zhao XB, Qiu T. Toward carbon-neutral ethylene production: assessment of the application potential of bio-ethylene production pathways in China. Biofuels Bioproducts & Biorefining-Biofpr 2022;16(6):1568–82. https://doi.org/10.1002/bbb.2406.

[13] Nyhus AH, Yliruka M, Shah N, Chachuat B. Green ethylene production in the UK by 2035: a techno-economic assessment. Energy Environ Sci 2024;17(5):1931–49. https://doi.org/10.1039/D3EE03064D.

[14] Markowitsch C, Lehner M, Maly M. Evaluation of process structures and reactor technologies of an integrated power-to-liquid plant at a cement factory. J CO2 Util 2023;70. https://doi.org/10.1016/j.jcou.2023.102449.

[15] Dray L, Schäfer AW, Grobler C, Falter C, Allroggen F, Stettler MEJ, Barrett SRH. Cost and emissions pathways towards net-zero climate impacts in aviation. Nat Clim Change 2022;12(10):956–62. https://doi.org/10.1038/s41558-022-01485-4.

[16] Lopez G, Keiner D, Fasihi M, Koiranen T, Breyer C. From fossil to green chemicals: sustainable pathways and new carbon feedstocks for the global chemical industry. Energy Environ Sci 2023;16(7):2879–909. https://doi.org/10.1039/D3EE00478C.

[17] Zennaro R, Ricci M, Bua L, Querci C, Carnelli L, d'Arminio Monforte A. Syngas: the basis of Fischer–Tropsch. Greener Fischer-Tropsch Processes for Fuels and Feedstocks 2013:17–51.

[18] Fernanda Rojas Michaga M, Michailos S, Akram M, Cardozo E, Hughes KJ, Ingham D, Pourkashanian M. Bioenergy with carbon capture and storage (BECCS) potential in jet fuel production from forestry residues: a combined Techno-Economic and Life Cycle Assessment approach. Energy Convers Manag 2022;255:115346. https://doi.org/10.1016/j.enconman.2022.115346.

[19] Mbatha S, Everson RC, Musyoka NM, Langmi HW, Lanzini A, Brilman W. Power-to-methanol process: a review of electrolysis, methanol catalysts, kinetics, reactor designs and modelling, process integration, optimisation, and techno-economics. Sustain Energy Fuels 2021;5(14):3490–569. https://doi.org/10.1039/D1SE00635E.

[20] Johnson Matthey. Synthesis technology 2023 [Available from: https://matthey.com/products-and-markets/chemicals/synthesis. [Accessed 1 June 2023].

[21] de Klerk A, Li Y-W, Zennaro R, Fischer–Tropsch Technology. Greener Fischer-Tropsch processes for fuels and feedstocks. 2013. p. 53–79.

[22] Pearson R, Coe A, Paterson J. Innovation in fischer-tropsch: a sustainable approach to fuels production. Johnson Matthey Technology Review 2021;65:395. https://doi.org/10.1595/205651321X16143384043486.

[23] Menges M, Kraushaar-Czarnetzki B. Kinetics of methanol to olefins over AlPO4-bound ZSM-5 extrudates in a two-stage unit with dimethyl ether pre-reactor. Microporous Mesoporous Mater 2012;164:172–81. https://doi.org/10.1016/j.micromeso.2012.07.012.

[24] Ye M, Tian P, Liu Z. DMTO: a sustainable methanol-to-olefins technology. Engineering 2021;7(1):17–21. https://doi.org/10.1016/j.eng.2020.12.001.

[25] Koempel H, Liebner W. Lurgi's methanol to propylene (MTP®) report on a successful commercialisation. Stud Surf Sci Catal 2007;167:261–7. https://doi.org/10.1016/S0167-2991(07)80142-X.

[26] Huang X, Li H, Li H, Xiao W-D. Modeling and analysis of the Lurgi-type methanol to propylene process: optimization of olefin recycle. AIChE J 2017;63(1):306–13. https://doi.org/10.1002/aic.15565.

[27] Liu Z, Ye M. DMTO and beyond: DICP's sustainable innovations in technologies for on-purpose production of light olefins from methanol. 2016.

[28] Fuchs C, Arnold U, Sauer J. (Co-)Oligomerization of olefins to hydrocarbon fuels: influence of feed composition and pressure. Chem Ing Tech 2023;95(5):651–7. https://doi.org/10.1002/cite.202200209.

[29] IEA. The future of petrochemicals. https://iea.blob.core.windows.net/assets/bee4ef3a-8876-4566-98cf-7a130c013805/The_Future_of_Petrochemicals.pdf; 2018.

[30] Griffin P. Radical Change in energy intensive UK industry. of Bath: University; 2015. https://researchportal.bath.ac.uk/en/studentTheses/radical-change-in-energy-intensive-uk-industry.

[31] Haarlemmer G, Boissonnet G, Peduzzi E, Setier P-A. Investment and production costs of synthetic fuels – a literature survey. Energy 2014;66:667–76. https://doi.org/10.1016/j.energy.2014.01.093.

[32] Department for Business Energy and Industrial Strategy. Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal. Data tables 1 to 19: supporting the toolkit and the guidance. 2023.

[33] Drummond P, Grubb M, Barazza E. Delivering competitive industrial electricity prices in an era of transition. https://www.aldersgategroup.org.uk/content/uploads/2022/03/DELIVERING-COMPETITIVE-INDUSTRIAL-ELECTRICITY-PRICES-IN-AN-ERA-OF-TRANSITION-policy-briefing.pdf; 2021.

[34] International Energy Agency. Indexed quarterly average wholesale prices for selected regions, 2019-2024. Paris: IEA; 2023 [Available from: https://www.iea.org/data-and-statistics/charts/indexed-quarterly-average-wholesale-prices-for-selected-regions-2019-2024. [Accessed 9 August 2023].

[35] Price J, Keppo I, Dodds PE. The role of new nuclear power in the UK's net-zero emissions energy system. Energy 2023;262:125450. https://doi.org/10.1016/j.energy.2022.125450.

[36] CCC. The sixth carbon budget the UK's path to net zero. https://www.theccc.org.uk/publication/sixth-carbon-budget/; 2020.

[37] Alberici S, Noothout P, Mir GUR, Stork M, Wiersma F. Assessing the potential OF CO2 utilisation in the UK. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/799293/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2_1_.pdf; 2017.

[38] International Energy Agency. Technology perspectives energy special report on carbon capture utilisation and storage CCUS in clean energy transitions. https://www.iea.org/reports/ccus-in-clean-energy-transitions; 2020.

[39] Leonzio G, Fennell PS, Shah N. A comparative study of different sorbents in the context of direct air capture (DAC): evaluation of key performance indicators and comparisons. Appl Sci 2022;12(5). https://doi.org/10.3390/app12052618.

[40] Marinič D, Likozar B. Direct air capture multiscale modelling: from capture material optimization to process simulations. J Clean Prod 2023;408:137185. https://doi.org/10.1016/j.jclepro.2023.137185.

[41] Drax. The UK's largest renewable power station 2023 [Available from: https://www.drax.com/uk/about-us/our-sites-and-businesses/drax-power-station/. [Accessed 21 July 2023].

[42] Ricardo Energy & Environment. Global biomass markets. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/795029/Global_Biomass_Markets_Final_report.pdf; 2014.

[43] Peacock M, Paterson J, Reed L, Davies S, Carter S, Coe A, Clarkson J. Innovation in fischer–tropsch: developing fundamental understanding to support commercial opportunities. Top Catal 2020;63(3):328–39. https://doi.org/10.1007/s11244-020-01239-6.

[44] Nizami M, Slamet Purwanto WW. Solar PV based power-to-methanol via direct CO2 hydrogenation and H2O electrolysis: techno-economic and environmental assessment. J CO2 Util 2022;65. https://doi.org/10.1016/j.jcou.2022.102253.

[45] Sollai S, Porcu A, Tola V, Ferrara F, Pettinau A. Renewable methanol production from green hydrogen and captured CO2: a techno-economic assessment. J CO2 Util 2023;68:102345. https://doi.org/10.1016/j.jcou.2022.102345.

[46] Department for Business Energy & Industrial Strategy. Plans unveiled to decarbonise UK power system by 2035. 2021.

[47] Department for Business Energy and Industrial Strategy. Hydrogen production costs 2021. 2021.

[48] International Energy Agency. IEA G20 hydrogen report: assumptions. https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf; 2020.

[49] Niziolek AM, Onel O, Hasan MMF, Floudas CA. Municipal solid waste to liquid transportation fuels – Part II: process synthesis and global optimization strategies. Comput Chem Eng 2015;74:184–203. https://doi.org/10.1016/j.compchemeng.2014.10.007.

[50] Young J, McQueen N, Charalambous C, Foteinis S, Hawrot O, Ojeda M, et al. The cost of direct air capture and storage can be reduced via strategic deployment but is unlikely to fall below stated cost targets. One Earth 2023;6(7):899–917. https://doi.org/10.1016/j.oneear.2023.06.004.

[51] Forman GS, Divita VB, Han J, Cai H, Elgowainy A, Wang M. U.S. Refinery efficiency: impacts analysis and implications for fuel carbon policy implementation. Environmental Science & Technology 2014;48(13):7625–33. https://doi.org/10.1021/es501035a.

[52] International Energy Agency. Emissions from oil and gas operations in net zero transitions. https://www.iea.org/reports/emissions-from-oil-and-gas-operations-in-net-zero-transitions; 2023 May 2023.

[53] OCI. Profiling supply chain emissions oil climate index plus gas [Available from: https://ociplus.rmi.org/supply-chain?sortField=upstream&gwp=1. [Accessed 28 August 2023].

[54] Environmental Assessment and Optimization group. OPGEE: the oil production greenhouse gas emissions estimator. Stanford University; 2023 [Available from: https://eao.stanford.edu/research-project/opgee-oil-production-greenhouse-gas-emissions-estimator#:%7E:text=The%20Oil%20Production%20Greenhouse%20gas%20Emissions%20Estimator%20(OPGEE)%20is%20an,and%20transport%20of%20crude%20petroleum. [Accessed 28 August 2023].

[55] Voigt C, Kleine J, Sauer D, Moore RH, Bräuer T, Le Clercq P, et al. Cleaner burning aviation fuels can reduce contrail cloudiness. Communications Earth & Environment 2021;2(1):114. https://doi.org/10.1038/s43247-021-00174-y.

[56] Beyersdorf AJ, Timko MT, Ziemba LD, Bulzan D, Corporan E, Herndon SC, et al. Reductions in aircraft particulate emissions due to the use of Fischer–Tropsch fuels. Atmos Chem Phys 2014;14(1):11–23. https://doi.org/10.5194/acp-14-11-2014.

[57] Seymour K, Held M, Stolz B, Georges G, Boulouchos K. Future costs of power-to-liquid sustainable aviation fuels produced from hybrid solar PV-wind plants in Europe. Sustain Energy Fuels 2024;8(4):811–25. https://doi.org/10.1039/D3SE00978E.

[58] DESNZ. UK hydrogen strategy. Department for Energy Security and Net Zero; 2021. https://www.gov.uk/government/publications/uk-hydrogen-strategy.

[59] UK Government Office for Science. Net zero Society: scenarios and pathways. 2023.

[60] Hanson. Flintshire cement work's carbon capture plan UK. Hanson Heidelberg Cement Group; 2023 [Available from: https://www.hanson.co.uk/en. [Accessed 10 August 2023].

[61] IEA. Net zero by 2050. Paris: IEA; 2021. https://www.iea.org/reports/net-zero-by-2050.

[62] Bui M, Zhang D, Fajardy M, Mac Dowell N. Delivering carbon negative electricity, heat and hydrogen with BECCS – comparing the options. Int J Hydrogen Energy 2021;46(29):15298–321. https://doi.org/10.1016/j.ijhydene.2021.02.042.

[63] Rosa L, Mazzotti M. Potential for hydrogen production from sustainable biomass with carbon capture and storage. Renew Sustain Energy Rev 2022;157:112123. https://doi.org/10.1016/j.rser.2022.112123.

[64] Ueckerdt F, Bauer C, Dirnaichner A, Everall J, Sacchi R, Luderer G. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat Clim Change 2021;11(5):384–93. https://doi.org/10.1038/s41558-021-01032-7.

[65] Denholm P, Arent DJ, Baldwin SF, Bilello DE, Brinkman GL, Cochran JM, et al. The challenges of achieving a 100% renewable electricity system in the United States. Joule 2021;5(6):1331–52. https://doi.org/10.1016/j.joule.2021.03.028.

[66] Grubb M, Newbery D. UK electricity market reform and the energy transition: emerging lessons. Energy J 2018;39(6):1–26. https://doi.org/10.5547/01956574.39.6.mgru.

[67] Aghbashlo M, Hosseinzadeh-Bandbafha H, Shahbeik H, Tabatabaei M. The role of sustainability assessment tools in realizing bioenergy and bioproduct systems. Biofuel Research Journal 2022;9(3):1697–706. https://doi.org/10.18331/brj2022.9.3.5.

[68] Innovate UKKTN. Industrial Gases to Chemicals: collaborating to transform foundation industries towards circularity. https://iuk.ktn-uk.org/perspectives/industrial-gases-to-chemicals-collaborating-to-transform-foundation-industries-towards-circularity/#:~:text=To%20further%20support%20and%20accelerate,Net%20Zero%20through%20circular%20innovation; 2023.

[69] Department for Transport. Renewable transport fuel obligation [Available from: https://www.gov.uk/guidance/renewable-transport-fuels-obligation. [Accessed 10 August 2023].

[70] European Commission. ReFuelEU Aviation – sustainable aviation fuels [Available from: https://commission.europa.eu/document/b94c33cd-7249-4b4e-9c0d-5a0f8aed6b1d_en; 2021 [Last accessed.