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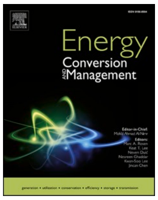

Research Paper

Fuel from air: A techno-economic assessment of e-fuels for low-carbon aviation in China

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ABSTRACT

Aviation remains one of the most challenging sectors to achieve low carbon emissions due to its heavy reliance on fossil fuels and the lack of cost-competitive alternatives. This study evaluates the potential of Direct Air Capture (DAC)-based e-fuels to meet China's aviation fuel demand by 2050. The research assesses e-fuel production costs and resource requirements under diverse scenarios, incorporating spatio-temporal variations in electricity, water, transportation, and policies. Results show that DAC capital costs and the energy market are the primary determinants. Liquid absorbent DAC (L-DAC), with lower capital costs but higher resource demands, is suitable for resource-abundant regions, while solid absorbent DAC (S-DAC), benefiting from higher learning rates and lower resource requirements, is optimal for water-scarce, high-demand regions like Beijing and Shanghai. By 2050, China could produce 102 Mt of e-fuels, meeting 84% of its demand, requiring 3457 TWh of renewable electricity and 597 billion liters of water, 78% of which would come from desalination. E-fuel costs range from \$3176/ton (S-DAC) to \$3208/ton (L-DAC), remaining 2.5–4 times higher than fossil jet fuels. Achieving cost parity requires low electricity prices (~\$5/GJ), high DAC learning rates (\$80–50/ton), and strong policy incentives. This could reduce e-fuel costs to \$900–1000/ton. The study also evaluates an alternative pathway involving Direct Air Capture with Carbon Storage paired with fossil fuel utilization. While this route offers cost and energy efficiency, it may raise long-term sustainability concerns. These findings underscore the potential of e-fuels for net-zero aviation targets, highlighting the urgency of supportive policies to scale their deployment effectively.

1. Introduction

1.1. Background

Maintaining the earth's mean temperature at 1.5 °C above pre-industrial levels requires a global emission reduction of 88–95 % by 2050, compared to 2020 levels, necessitating drastic reductions in GHG emissions to achieve net-zero targets [1]. However, sectors like aviation and heavy industry remain difficult to achieve low emissions due to limited competitive substitutes. Aviation, heavily reliant on carbon-intensive Jet A-1 kerosene, contributes 2.5 % of global carbon emissions and 3.5 % of non-carbon emissions [2]. Net-zero roadmaps from the International Energy Agency (IEA) and International Air Transport Association (IATA) project that aviation will continue to be a net emitter. These roadmaps highlight the critical role of Sustainable Aviation Fuels (SAFs), expected to meet 80 % of aviation fuel demand by 2050, positioning SAFs as central to achieving in-sector emission reductions [3].

Sustainable Aviation Fuels (SAF) represent low or zero emission fuel solutions to further de-fossilize the aviation sector [4]. SAF should have good combustion properties and high energy density. Fuels that come under this category are hydrogen, biofuels, and artificial hydrocarbons. In comparison to hydrogen, biofuels and artificial hydrocarbons are more favourable options as they require fewer or zero changes in the current aviation infrastructure [5]. One of the upsides of utilising direct to use SAFs is neither do they require engine or system modifications in the aircraft at certain blending rate, nor new or dedicated re-fueling infrastructure [6,7]. Whilst using SAF as an aviation fuel still generates emissions, using low carbon inputs in the production process can reduce life cycle carbon emissions by 50 % to 100 % [8,9]. As per the

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ICAO sustainability criterion, fuels (biofuels or artificial hydrocarbons) that result in the reduction of net greenhouse gas emissions by 10 % from the baseline on a life cycle basis can be regarded as sustainable aviation fuels [10]. Currently, there are three broad SAF production pathways: hydro-processed esters and fatty acids (HEFA), gasification Fischer-Tropsch (G/FT), and alcohol-to-jet. These pathways are well-developed and predominately rely on bio-based feedstocks. The cost of HEFA is in the range 825–1775 $/t [11,12], for G/FT in range 1188–3127 $/t [13], and for alcohol-to-jet is in range 1387–3000 $/t [14] depending upon the type of feedstock used. Despite being technologically matured, bio-fuels encounter significant challenges related to feedstock availability, land demand, and their competition with food crops [15].

Electricity-based SAF or e-fuels are another category that can be synthesized by using renewable electricity, water and carbon (CO_2) and results in nearly zero emission intensity [16]. Green e-fuels are produced by using hydrogen (from a renewable energy-based electrolysis process) and CO_2 (captured through direct air capture (DAC) plants as feedstocks. These feedstocks are then synthesised to produce syngas in reversed water gas shift reaction (rWGS) accompanied by Fischer–Tropsch (FT) reaction to produce e-fuels [17]. In comparison to bio-fuels, e-fuels present lower barriers related to resource and land availability constraints; however, they currently possess a major cost-competitiveness challenge w.r.t fossil jet fuel [15]. Given the importance of e-fuels, this study focuses on evaluating the DAC-based e-fuel production pathways, providing its in-depth techno-economic assessment considering the ecological parameters, infrastructure and technology development, and policy measures to accelerate the development of e-fuels in China.

1.2. Literature review

Currently, power-to-fuel technology presents a significant cost challenge for scaling as highlighted in the McKinsey's report with their prices ranging between $1550–5600 per ton [18]. Therefore, the cost of production of e-fuels is much higher than the fossil-based jet fuels prices, which normally lie in the range of 500 to 1125 $/t [19]. E-fuels need CO_2 as a feedstock, which requires cost-intensive technologies like carbon capture, utilization, and DACs, making them unlikely to compete with fossil jet fuel prices in the near term [20]. Policy support is important to accelerate the deployment of e-fuels. The EU Commission has mandated the use of advanced biofuels and synthetic aviation fuel for aircraft as part of ReFuelEU Aviation initiative, which is coherent with the Fit-for-55 package and the revision of the Renewable Energy Directive II [21].

Several recent research studies conducted techno-economic modeling of e-fuels to analyze their production potential and role in decarbonizing the aviation sector. Vardon et al. [22] and the US Energy Information Administration (EIA) [23] recommend e-fuels along with other bio-based SAFs as an alternative and less carbon-intensive fuel to meet the growing demand of the aviation sector, which is projected to be double by 2050. Bergero et al. [24] and Sacchi et al. [25] further discuss the pathways to ensure low emissions in the aviation sector through e-fuels and carbon reduction techniques. These studies emphasize that achieving carbon–neutral aviation requires not only increased e-fuel production but also a substantial reduction in aviation demand. Sacchi et al. [25] specifically highlight that deploying DAC with fossil jet fuels places significant pressure on natural resources due to the limited availability of geological storage sites.

Gössling et al. [26] highlight the need for renewable-based e-fuels in the aviation sector under different demand and carbon price scenarios. Their findings indicate that achieving near-zero aviation emissions by 2050 requires a blending mandate for synthetic fuels and a competitive carbon price of around $800/ton CO_2. The International Energy Agency's (IEA) Net Zero Emissions (NZE) scenario supports the high carbon prices by projecting it in the range of $250/ton CO_2 in developed economies and $200/ton CO_2 in developing economies by 2050 [27].

A techno-economic investigation on the role of carbon capture storage and utilization (CCS-U) and direct air capture (DAC) to synthesize the e-fuels is presented in [28]. This study highlights that DAC and CCS-U based e-fuels will be cost-competitive with fossil fuels under high carbon prices and high learning rates and have the potential to reduce emissions by 80 %. Moreover, it suggests that point source carbon capture technology will be a more cost-effective alternative than DAC in 2050. Additionally, Vedant et al. [29] investigate the climate impact of e-fuels in the European aviation sector, emphasizing that e-fuels have a more favorable impact when carbon feedstock is sourced from biogenic origins. In contrast, the effectiveness of DAC-sourced CO_2 depends heavily on the carbon intensity of the electricity used in the process. The role of hydrogen and CO_2 in e-fuel production is discussed in [30] and validates its techno-economic assessment through a UK-based case study. This study highlights that the electrical energy requirement is the bottleneck in producing cost-effective, large-scale e-fuels. Paulsen et al. present the techno-economic study of e-fuels produced using high-temperature direct air capture (HT DAC) and identify hydrogen cost as the critical factor in the overall process to ensure the e-fuel's economic viability [31] and highlight that the e-fuel cost will be in the range 4000 to 7740 $/ton. To support low-emission land transportation, D'Adamo et al. [32] demonstrate the techno-economic feasibility of e-fuel production in Italy and highlight that the current production cost of e-fuels is at least twice that of fossil fuel and will be around 3500 – 4000 $/ton. The techno-economic production potential of DAC and alkaline electrolyzer-based e-fuel development in Egypt is proposed in the [33]. The study highlights that Egypt has the potential to fulfil Europe's 10 % fuel and chemical demand and has the potential to contribute 5 % of the global CO_2 removal capacity; however, finding the optimal locations of setting up different types of DACs and electrolysers facilities based on the feedstock availability is not thoroughly covered. Further, Sendi et al. [34] present the geospatial technoeconomic analysis of the optimal mix of different energy sources, including fossil and renewable energy sources, to operate solid DACs. However, the carbon capture and utilization aspect is not explored in this study. An informative techno-economic analysis is conducted in Gray et al. [35] to highlight the two pathways, namely, P-to-X and using only DACs to support the emission aviation sector. This research highlights that the DAC scenario can reduce 9.8 times more emissions than P-to-X pathways and will be more cost-effective than the former one; however, it raises certain concerns on the long-term usability of DACs. Similarly, Gonzalez et al. [36] explore the potential of solar power-based artificial jet fuels produced from FT and methanol-to-jet processes for Spain's aviation demand. This research demonstrates that SAF can reduce emissions by 25 % but would cost 8 to 10 times more than the current fossil-based jet fuel price.

1.3. Contribution and aim of the study

Most studies available in the literature adopt a holistic, top-down approach, often overlooking region-specific constraints and ecological parameters. Critical factors such as the spatial and temporal variability of renewable energy and water availability are insufficiently addressed. While electricity is often considered a critical factor in e-fuel development, another essential resource vector, water, remains less explored, particularly in its spatial and temporal context. Furthermore, aspects such as the transportation infrastructure, policy parameters, and learning pathways of key technologies (DACs) are not comprehensively integrated into existing studies. In addition, since DACs are cost and energy-intensive, determining their optimal types and locations must be included in the techno-economic assessment to achieve optimal results.

Thus, to bridge these research gaps, this study focuses on exploring the e-fuels production potential and evaluating its entire value chain, i.e., from 'well-to-tank' at the supply chain level under diverse sustainability and economic scenarios within the 2020–2050 timeframe. These scenarios include spatial and temporal variations in feedstock (renewable energy and water) availability, aviation demand, techno-economic data of employed technologies, and policy measures like carbon tax and fossil fuel price. Another key contribution of this work is the inclusion of CO_2 transportation pipelines to evaluate the impact of network expansion on e-fuel production. This infrastructure modeling facilitates the identification of optimal locations for DAC plants.

The primary objective of this study is to evaluate the impact of ecosystem factors (renewable energy and water availability), techno-economic factors (transportation network expansion, technology scale-up, and energy prices), and policy measures on e-fuel production, with a focus on minimizing overall supply chain costs. The research specifically targets China, given its rapidly growing aviation sector and significant aviation fuel demand. By providing a holistic analysis of technological, economic, and policy-related challenges, the study aims to identify essential support mechanisms and optimal production pathways to accelerate the adoption of e-fuels. Additionally, it offers insights into the techno-economic potential, projected costs, and bottlenecks of e-fuel production during the 2020–2050 period while also comparing e-fuels with the 'DAC-only with fossil fuels' pathway to highlight alternative decarbonization strategies.

The outline of the paper is as follows: Section 2 describes the methodology, highlighting the modeling approach, model setup, spatio-temporal distribution of different feedstocks, techno-economic parameters of the key technology used, and scenario definitions. Section 3 presents the results from the modelling framework. Section 4 discusses the key implications of the results, and finally, section 5 concludes the research, showing the key findings and outlining potential directions for future research.

2. Methodology

This research focuses on e-fuels production for the aviation industry that are produced through renewable energy-based direct air capture (DAC) and electrolyzer (H_2) plants as picturised in Fig. 1. DAC captures atmospheric CO_2 using electricity from renewable energy sources (RES), and H_2 plants produce required hydrogen utilizing ground water or sea water and RES. The mixture of the two is then transformed into e-fuel through rWGS and (FT) reaction. In the subsequent subsections, the model setup to simulate the entire supply chain, spatial distribution of resource availability, in-depth discussion on DAC technologies, CO_2 transportation along with other techno-economic parameters, and scenario definition are discussed.

2.1. Model setup

To analyse the techno-economic feasibility of e-fuels, this research uses the BeWhere Model, a spatially explicit renewable energy optimization tool developed by IIASA, Austria [37]. The current model setup builds upon the core version of the model [38,39]. BeWhere is a mixed integer linear programming (MILP), partial equilibrium model that assesses the least-cost pathways to achieve low or zero emission energy systems. It has been widely employed in previous studies, including the evaluation of renewable fuel production for the marine sector [40], power-to-gas and power-to-liquid technologies [41], bio energy assessments [42], supply chain assessment [43] and the decarbonization of steel production in Europe [44]. The model is written in General Algebric Modelling System (GAMS) and uses CPLEX solver.

The complete supply chain of e-fuel production is shown in Fig. 2 and the model is revamped to integrate the highlighted e-fuels framework along with the CO_2 pipeline transportation network. Renewable energy and water are first transported through the existing transmission and pipeline network system to the electrolysis and DAC facilities for the first-stage conversion. The produced CO_2 is then used along with hydrogen to produce e-fuels on site, or the CO_2 can be transported to the other demand points. Further, the generated e-fuels are also allowed to be transported to other airports through already existing pipeline networks.

Being spatially explicit in nature, the optimization model minimizes the cost function while considering the cost and emissions at each node of the supply chain of e-fuel production under diverse scenarios within the 2020–2050 timeframe. The overall cost includes four main components: cost of e-fuel production, carbon emission cost, fossil fuel cost, and subsidies as illustrated in eq. (1).

$$\min\left(COST_{efuels_{sc}} + COST_{fossilfuels} + \left[\left(EC_{efuels_{sc}} + EC_{fossilfuels}\right) {}^{*}C_p\right] - Subsidies\right) \tag{1}$$

The e-fuel cost ($COST_{efuels_{sc}}$) represents the entire supply chain cost to generate e-fuels. It incorporates feedstock input costs, calculated as the product of resource consumption and their respective industrial market prices. This further includes renewable electricity, ground water, desalination prices for industrial use); Capital and operating cost of different technologies involved such as DACs, electrolysers, and FT reactors including their dynamic learning rates; Transportation cost of resources and intermediary products (CO_2) and end products (e-fuel) including the annualised network expansion cost. The second component ($COST_{fossilfuels}$) includes the fossil jet fuel prices as the model is competing with against it. The model also quantifies the carbon emissions for each section of the supply chain, including the emission captured by DACs and emissions emitted by fossil fuels and e-fuels; thus, the third component represents the Emission Cost (EC) reflects the net carbon emission cost by multiplying net emissions with carbon prices (C_p). The fourth component ($Subsidies$) highlights the subsidies based on the IRA

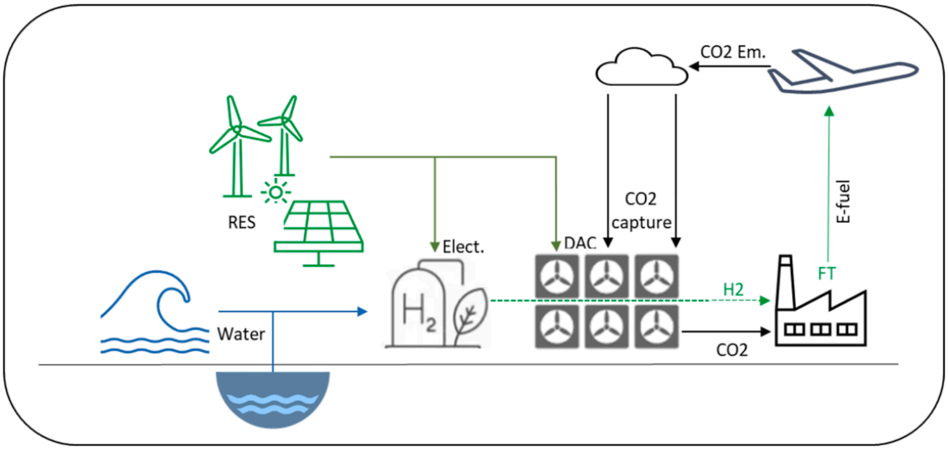


Fig. 1. Graphical picturisation of the e-fuel production.

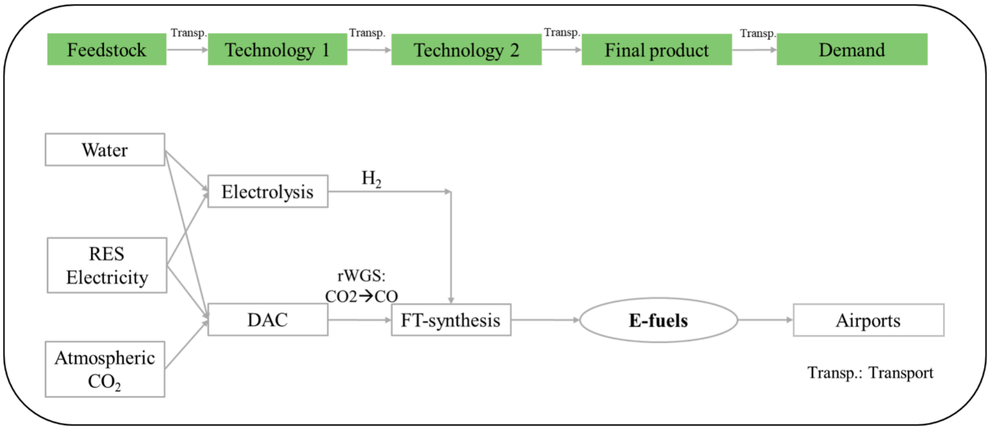


Fig. 2. Model structure of e-fuel production supply chain.

incentive policy for DACs.

To model the transportation network between different nodes, a network analysis is conducted to assess transportation distances from the facility locations to the demand sites. This distance is used to identify the optimal transportation costs and emissions. The main objective of the model is to identify the optimal type and location of DAC plants and explore the production potential of e-fuels based on infrastructure, renewable energy, and water availability, with the goal of minimizing the overall supply chain cost and emissions of the entire value chain.

This study considers the following assumption to model the discussed e-fuel supply chain model. Assumptions are: 1.) e-fuel plants can access seawater within a maximum distance of 200 km from the coastline 2.) e-fuels are processed and produced at the airports (demand location) 3.) DAC facility can only be positioned near or at the demand locations; 4.) all the airports have electrolyzer plant and FT synthesis plants to facilitate on-site production; 5.) once a production plant is set up in a selected year, it stays up for the following years. Plant capacity expansion is feasible at a maximum 20 % increase in the next year. 6.) All the demand locations have access to electricity, so no new transmission lines are constructed, and the transmission cost of electricity is assumed to be negligible.

2.2. Resource availability

As mentioned, e-fuels are energy and water-intensive; this section identifies the spatial locations and availability of groundwater and renewable energy plants in China. In the model, the entire studied region of China is divided into 1258 grid cells with a spatial resolution of 1° (approximately 100*100 km). The spatial data sets and techno-economic parameters of the water, renewable electricity, and aviation demand are given in Appendix A.

2.3. Direct air capture and CO_2 availability

In this study, Direct Air Capture (DAC) technology is used to ensure the availability of CO_2 as feedstock. DAC offers a promising solution for removing CO_2 directly from the atmosphere. From an energy system perspective, DAC technologies can be classified into high-temperature aqueous solutions (HT DAC) and low-temperature solid sorbent (LT DAC) systems (Fasihi et al., 2019). In the DAC process, CO_2 is captured by a sorbent and subsequently released as high-purity CO_2 during sorbent regeneration, which can then be securely stored or used directly for other processes [45]. Designing a DAC-fuel plant requires engineers to choose a capture media of either solid sorbents or aqueous basic solutions [46]. Each offers distinct advantages, its own challenges, and a range of costs depending on the specific material selection. Some studies have favored solid sorbents, citing avoided heat loss and lower required energy input due to the lower heat of adsorption [46]. Alternatively, aqueous sorbents can provide faster sorption kinetics and require little maintenance but are much more energy intensive due to the high temperatures necessary for calcination [45]. Several companies are pioneering the use of DAC technologies: Carbon Engineering utilizes HT DAC, while Climeworks, Global Thermostat, Antecy, Hydrocell, Infinitree, and Skytree apply LT DAC [47].

DAC plays a crucial role in sector coupling, effectively integrating high-integrity renewable fuel production with a renewable electricity-based energy system. However, currently, the cost of DAC technology is uncertain as this technology is yet to be matured at the economy of scale, i.e., 1 million tons (Mt) CO_2/year and over. Capture cost estimates reported in the literature are wide, typically ranging anywhere from USD 200/t to USD 1000/ton CO_2 [48]. Ref. [47] estimated that with plant capacity over 1Mt CO_2, S-DAC cost ranges from 730 $/ton to 200 $/ton CO_2 (2050) while the L-DAC cost varies from 815 $/ton to 220 $/ton CO_2 (2050) while considering the installed capacity growth of DAC technology from 3 Mt (2020) to more than 15,000 Mt CO_2 in 2050. Another study predicted the cost of S-DAC 760 $/ton CO_2 to be subjected to plant capacity over 1 Mt/year. In study [49], the detailed cost estimation of the two mentioned DAC technologies has been analyzed for the first megaton-scale direct air capture plant. According to the report, the first plant cost of S-DAC is in the range of 1711 to 850 $/ton CO_2 while the cost of L-DAC varies from 1100 to 550 $/ton CO_2 and concludes S-DAC cost will be higher than L-DAC technology. A similar trend is followed by [48], and estimates the levelized cost of S-DAC and L-DAC to be 540 and 350 $/ton CO_2, respectively. According to [48,50], currently L-DAC, due to its comparative mature technology than S-DAC, has a lower CAPEX cost. However, due to the modular architecture of S-DAC technology, its learning rate will be higher than L-DAC. Based on the literature [48,49,50], the learning rate of S-DAC will be 15 % to 20 % while L-DAC will persist with a learning rate of 10 % to 12.5 %, thus, S-DAC cost will surpass the L-DAC and become cost-effective. This study considers the four learning rates, i.e., 10 %, 12.5 %, 15 %, and 20 % for both DAC technologies and estimates its impact on e-fuel production cost.

Further, DAC technology is water and energy intensive, and the requirement varies with the technology. Since the S-DAC works at low temperatures (100 °C), the heat requirement is often compensated by waste heat [48] or heat pumps [51]. The electrical and heating requirement of S-DAC is approximately 250–489 kWh_{el} to 1500–1750 kWh_{th}, respectively [48,51]. The high temperature requirement (800–1000 °C) of L-DAC cannot be fulfilled with waste heat processes and requires heating through natural gas systems [48]. However, a fully electrified L-DAC system with a net electrical requirement of 1500 kWh for heating and electricity is configured by Carbon Engineering, as reported by [47]. Due to the physical nature and properties of absorbents, L-DAC is more water intensive than S-DAC [52]. In L-DAC, water is required to replenish the absorbents, which are lost due to high heat under continuous capture and regenerative cycles. Water requirement for solid DAC is from zero to 1 ton of water for 1 ton of CO_2 [47,48 52].

This study assesses the two DAC technologies, i.e., low-temperature solid absorbent (S-DAC) and high-temperature liquid absorbent (L-DAC), based on their techno-economic parameters and determines their optimal locations to be set up. In this analysis, atmospheric CO_2 concentration is assumed to be 1 Mt per grid, with DAC plants strategically located adjacent to airports to facilitate efficient CO_2 capture and utilization.

Given the cost uncertainty of DAC technology, this study applies learning rates of 10 %, 12.5 %, 15 %, and 20 % for high, mid, low, and ambitious scenarios, respectively, as derived from the literature. The cost reduction projections for DAC technology from 2020 to 2050 are estimated using the standard learning rate model (2) [49] for the nth DAC plant of 1 Mt capacity:

$$\text{Cost of capture for } n^{th} \text{ DAC plant} = C_0 * \left[(1 - \text{learning rate})^{(\ln(N)/\ln\ (2))}\right] \tag{2}$$

where C_0 stands for the base first plant capital cost ($/t$CO_2$/y). N is the cumulative DAC plant capacities installed over the years relative to the base capacity. The base capital costs for each DAC technology and annual capacity scale-up projections are derived from IEA [48] and [49] as presented in Table 1. The operation and maintenance costs are assumed to be 4 % of the capital cost. Additionally, the cost of low-grade heating at $1.8/GJ is incorporated into the S-DAC cost to account for the associated heat energy expenses.

Apart from DACs, electrolysers, reverse water gas for CO2 conversion, and Fischer–Tropsch −synthesis technologies are required to produce e-fuels. Their techno-economic parameters, along with efficiencies, mass-energy balances, and emissions factors of the full value chain, are presented in Appendix A.

2.4. CO_2 transportation

The transportation network is needed to find the optimal locations of high-cost technology units such as DACs (Direct Air Capture) to minimize the overall cost of the e-fuel network chain. To do so, this study develops a pipeline transportation network for all the feedstocks (electricity, water, and CO_2) and end product (e-fuel). Pipeline transportation is considered to be safe and well-regulated, option [53,54] that is favorable for big volumes of CO_2 with annual transportation capacity of more than 10 Mt and distances in the range of 100–1000 km [47].

Currently, China lacks dedicated infrastructure for CO_2 transportation. The existing pipeline infrastructure for fossil fuel transportation is presented in Fig. 3. Based on this existing network, multiple scenarios have been developed to analyse the role of CO_2 transportation in supporting e-fuel production. In the first scenario [S1: PPL-1], a new, dedicated pipeline infrastructure is proposed for CO_2 transport. This scenario includes the connection of the airports having the current (2022) demand of more than 7 PJ (or 0.16 Mt) via dedicated CO2 pipelines by 2030, covering the overall distance of 4492 km. The second scenario [S2: PPL-2] extends S1 by assuming that all remaining airports are connected through dedicated CO_2 pipelines over the subsequent decade, ending in 2040. Thus, in scenario S2, an additional 32,896 km of new pipeline construction is required. The third scenario [S3: PPL-3] examines the fossil phaseout approach, utilizing existing fossil fuel pipeline infrastructure for CO_2 transport through retrofitting. However, as the existing pipeline infrastructure does not cover all airports, the remaining airports will be connected by 2040, requiring the construction of an additional 4,968 km of new pipelines.

Table 1

Projected DAC technology capital cost ($/t$CO_2$/y).

S-DAC							
	Base	2025	2030	2035	2040	2045	2050
DAC Cap./y	1 Mt	43 Mt	85 Mt	353 Mt	620 Mt	800 Mt	980 Mt
LR:10 %	1711	976.6	870.9	701.6	643.9	619.4	600.6
LR:12.5 %	1155	567.5	490.8	373.2	334.7	318.7	306.4
LR:15 %	850	357.9	299.9	214.9	18.,2	177.3	169.1
LR:20 %	850	205	161.2	102.0	85	78.3	73.4
L-DAC							
	Base	2025	2030	2035	2040	2045	2050
LR:10 %	1106	631.3	563.0	453.5	416.2	400.4	388.2
LR:12.5 %	675	331.6	286.8	218.1	195.6	186.2	179.1
LR:15 %	525	221.1	185.3	132.7	116.3	109.5	104.4
LR:20 %	525	126.9	99.5	63.0	52.5	48.4	45.3

The construction cost for a pipeline is a function of the length and capacity. Here, the cost of constructing a dedicated pipeline to transport 1 ton of CO_2 for 1 km is 0,13 $ [53]. Based on this, the investment cost for deploying dedicated CO_2 transportation is calculated for all scenarios and is highlighted in Table 2. In addition, this study also includes the *retro*-fitting cost of existing pipelines for CO_2 transportation and is assumed to be 52 % less than the cost of the new pipeline [55,56]. These cost parameters are annualized with an assumption of 40 years of project life and 8 % interest. The operational and maintenance cost is assumed to be 3 % of the CAPEX cost. Since the pipelines are used to transport all the feedstocks and e-fuel, the emissions related to the transportation are assumed to be negligible.

In addition, it is assumed that all the airports are connected to electrical and water networks, and their associated costs are highlighted in Table A4. The electricity transportation cost is assumed to be negligible in this study.

2.5. Scenario definitions

This research assesses the role of (a) ecosystem resource availability, (b) techno-economics of various technology scales, energy prices, and transportation networks, and (c) policy measures (such as carbon tax and fossil fuel pricing) in the production of e-fuels. The objective is to minimize the overall supply chain cost of e-fuels, which is the summation of feedstock cost, operational and capital cost of different technologies, and transportation cost.

To achieve this, multiple scenarios are modeled to comprehensively assess the interplay of these factors. Water and electricity availability are examined through two distinct scenarios, RES1 and RES2, with their definitions detailed in Table 3. In addition, CO_2 transportation (section 2.4) and technology learning rates scenarios (Table 1 and Table A1) are considered to comprehensively assess the e-fuels production potential and cost. Carbon cost scenarios are also incorporated to restrict the consumption of fossil fuels and facilitate the advancements of e-fuel production, highlighted in Table 4.

Finally, to evaluate the combined impact of CO_2 transportation systems and resource availability on e-fuel production and its associated supply chain costs, five hybrid scenarios are developed.

a. Baseline Scenario (S1): highlights the limited availability of resources (water and renewable electricity) and infrastructure [RES-1 + PPL-1].
b. Moderate Scenario (S2): highlights the limited availability of resources (water and renewable electricity) while covering all the airports with dedicated CO_2 pipelines [RES-1 + PPL-2].
c. Transition Scenario (S3): highlights the limited resource availability and the use of existing pipeline infrastructure considering fossils are phased out [RES-1 + PPL-3].
d. Transitional Expansion Scenario (S4): explores the maximum production potential of e-fuels under high resource availability and phaseout of fossil pipeline infrastructure [RES-2 + PPL-3].

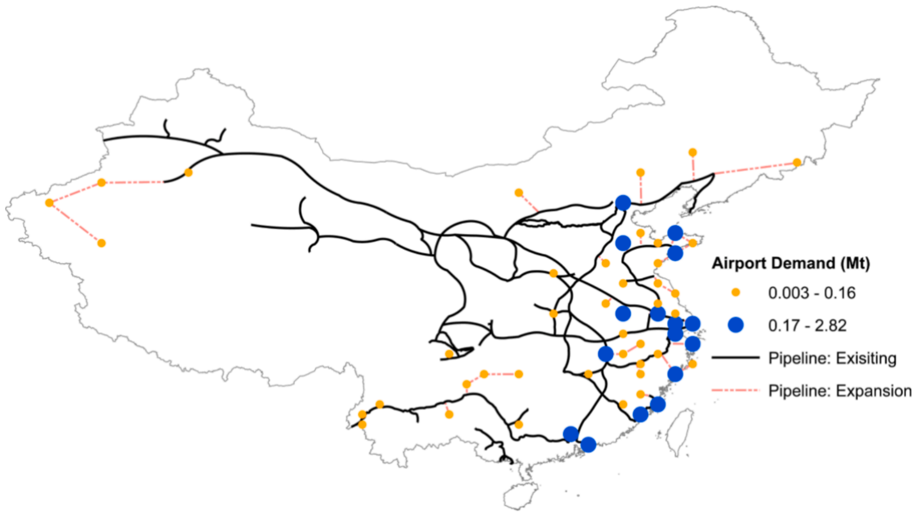


Fig. 3. CO_2 transportation pipeline connecting all airports.

Table 2
CO_2 pipeline investment cost.

	Existing Infrastructure (Km)	New Infrastructure (Km)	Investment Cost ($/ton$CO_2$)
S1: PPL-1	0	5152	705
S2: PPL-2	5152	32236.5	4415
S3: PPL-3	31,076	6312	864

Table 3
Resource availability scenarios.

No.	Scenario	Definition
1	RES1	(Conservative Scenario) This scenario is developed to meet jet fuel demand through e-fuel in a conservative scenario, i.e., under limited resource availability. Here, groundwater availability share is 5 %, desalination plants are allowed with a plant capacity of 40 k ML per year, and renewable electricity availability is 8500 TWh.
2	RES2	(Ambitious Scenario) This scenario is developed to meet maximum aviation demand through e-fuel. Here, the groundwater availability share is increased to 10 %, the desalination plant capacity is doubled to 80 k ML per year, and renewable electricity availability is more than 8500 TWh.

e. Ambitious Expansion Scenario (S5): explores the maximum production potential of e-fuels under high availability of resources and full dedicated CO_2 pipeline coverage [RES2 + PPL-2]:

3. Simulation results

Based on the mentioned scenarios, the subsequent section presents the results and discussions and highlights the critical ecological factors, role of infrastructure, technological learning rates, policies, and subsidies in advancing the production of e-fuels in China. Further, the spatial distribution maps of e-fuel production and optimal locations of DAC facilities under different scenarios are highlighted.

3.1. Impact of net resource availability and transportation infrastructure

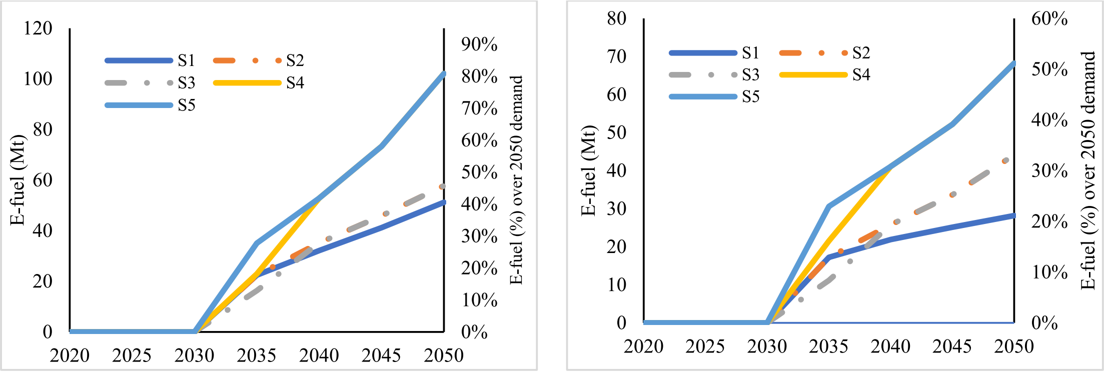
Renewable electricity availability and water availability have a direct correlation with e-fuel production. In addition, the two considered direct air capture technologies, due to their different energy efficiencies and mass energy balances, also influence e-fuel production. Fig. 4 highlights the e-fuel production potential under different scenarios for two DAC technologies. Here, it is important to note that the BeWhere model allows e-fuel production to commence once its overall supply chain cost becomes less than fossil-based jet fuel prices. Fig. 4 shows that, under an extreme carbon tax scenario and high fossil fuel price factors, e-fuel commence in 2035 for medium learning rate (i.e., 12.5 %) of DAC technologies. Here, the carbon tax and fossil fuel factors are not directly considered in calculating the e-fuel cost. The calculated e-fuel cost is the summation of feedstock cost, technology operational and capital cost, transportation and other infrastructure cost.

In baseline scenario (S1), e-fuels meet 41 % of the 2050 demand in case of S-DAC technology (Fig. 4 a). While, under same scenario and assumptions, L-DAC technology accounts for 23 % e-fuel production over 2050 demand (Fig. 4 b). This is due to the fact that L-DAC technology is highly energy intensive than S-DAC, however, the former has less capital cost. Thus, S-DAC technology results in higher e-fuel production and encounters higher generation cost, as shown in Fig. 5.

With the expansion of the pipeline networks, CO_2 can be transported to other demand locations and therefore, under the scenarios S2 and S3, e-fuel production increases to 47 % and 36 % under S-DAC and LDAC technology, respectively. As this study assumes that all the airports will be connected with pipelines by 2040, it results in higher transportation costs for the years 2040 to 2050 (Fig. 5). Therefore, the approximated expansion cost is increased from 273 M$ in year 2035 to 3029 M$ in year 2040 for scenario S2. However, transitional scenario (S3) results in an expansion cost of 1966 M$ in year 2040, due to the use of existing

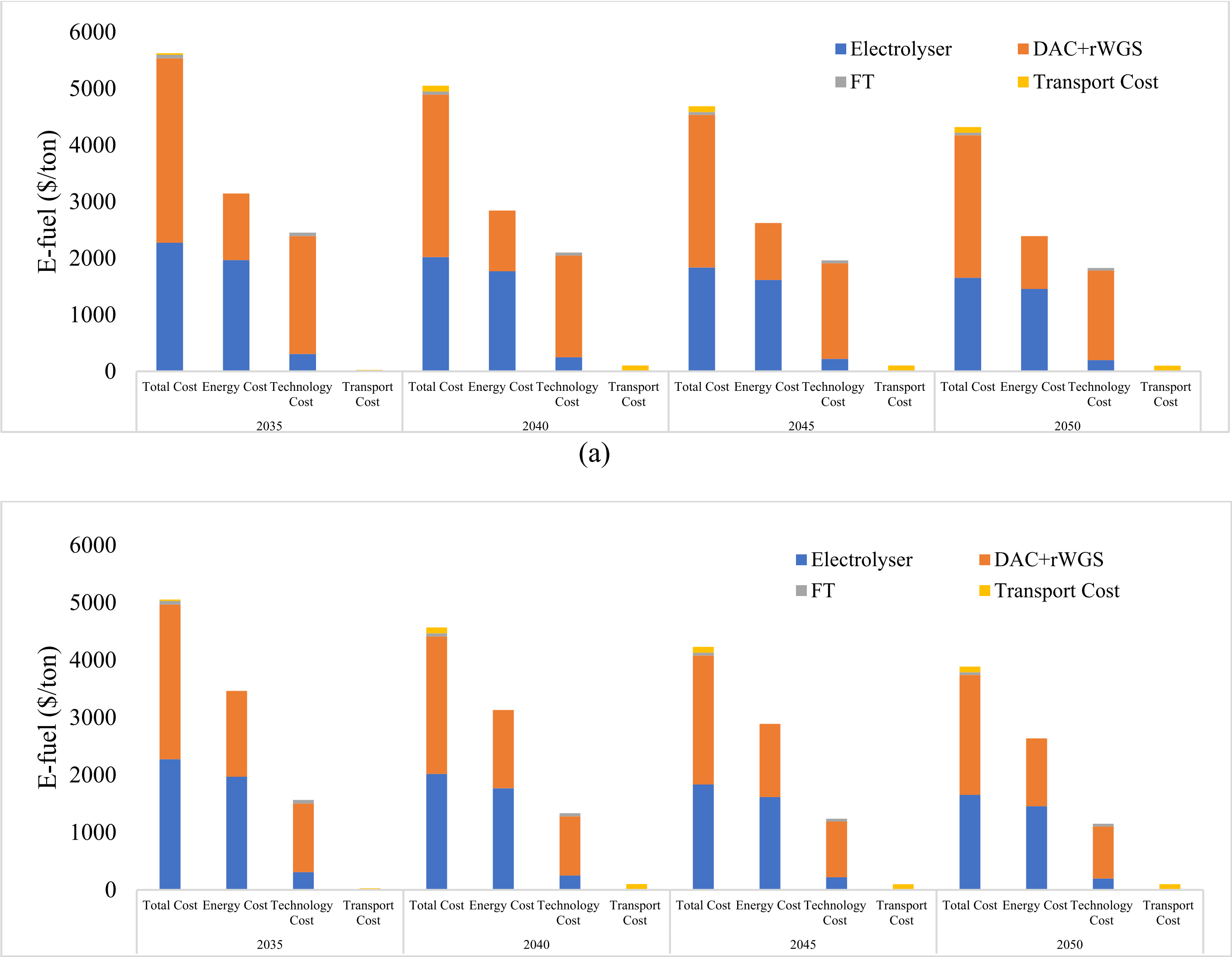
Table 4
Carbon price ($/ton$CO_2$) scenarios.

No.	Definition	2020	2025	2030	2035	2040	2045	2050
1	Base	10	12.4	18.6	22.5	26.4	30.4	34.3
2	Extreme	100	150	200	250	300	400	500
3	Aggressive	300	330	460	500	580	650	700



(a) (b)

Fig. 4. E-Fuel production potential under (a) S-DAC and (b) L-DAC production pathways (Assumptions: high FF price factor; extreme carbon tax, desalination allowed, medium DAC cost (LR12.5%), RES-2, PPL-2 and electricity price reduction-1% annually).



(a)

(b)

Fig. 5. E-fuel levelized cost breakdown of (a) S-DAC and (b) L-DAC production pathways. (Assumptions: high FF price factor; extreme carbon tax, desalination allowed, medium DAC cost (LR12.5%), RES-2, PPL-2, and electricity price reduction-1% annually).

pipelines.

With increased resource availability, scenarios S4 and S5 demonstrate that S-DAC-based e-fuel production could reach 102 Mt or 4,440 PJ, meeting up to 84 % of the demand by 2050. In comparison, the L-DAC-based pathway is projected to fulfill approximately 56 % of the demand. Finally, the estimated cost of e-fuel in 2050 is anticipated to be around $4319 per ton for S-DAC-based e-fuel (Fig. 5 a) and $3885 per ton for L-DAC-based e-fuel (Fig. 5 b), assuming a medium learning rate (12.5 %) for two DAC technologies for the ambitious expansion (S5).

As illustrated, energy cost plays a larger role in the overall cost breakdown in e-fuel production than the technology cost. For a given year, energy costs contribute approximately 56 % to the levelized cost of e-fuel production via the S-DAC pathway, while technology costs account for 42 %. In the L-DAC production pathway, the share of energy costs in the levelized cost rises to 68 %, with technology costs decreasing to 29 %. Additionally, transportation costs make up only 2.5 % of the levelized cost. The cost distribution highlights that the energy cost and DAC technology cost are the two main factors that significantly impact the overall e-fuel production costs. These factors play a crucial role in determining the choice of technology over the long term. Energy costs are mainly influenced by electricity and water prices, efficiency, and mass-energy balances, while DAC technology costs depend on learning rates and deployment levels. As a result, L-DAC plants are more likely to be located in areas with abundant and affordable resources, while S-DAC plants may be more suitable for regions where resources are either scarce or come at a higher cost.

3.2. Impact of DAC learning rates and energy cost

Fig. 6 highlights the e-fuel cost w.r.t two deployed DAC technologies. Under the S-DAC production pathway, the cost of e-fuel in 2050 is higher than that of the L-DAC pathway, under the 10 % learning rate scenario. This is due to the higher capital expenditure associated with S-DAC technology. Further, it can be noticed that, for higher learning rates (15 % and 20 %), e-fuels start producing 5 years earlier than low learning rates (10 % and 12.5 %).

However, as both DAC technologies scale up and their capital costs decrease over time, the cost disparity between the two production pathways diminishes. By 2050, both S-DAC- and L-DAC-based e-fuels have comparable costs, as highlighted in Fig. 7. This shift is attributed to the fact that, once the technology costs converge, the cost of energy, i.e., feedstock (water and electricity), becomes a more significant factor. Under the high learning rate, e-fuel cost is 3176 $/ton and 3208 $/ton in case of S-DAC and L-DAC, respectively (Fig. 7).

As highlighted in section 3.1, energy cost plays a key role in the e-fuel production cost. The impact of electricity prices on e-fuel production cost is highlighted in Fig. 7. For the electricity price of 9.8 $/GJ in 2050 (assuming 3 % annual decrease in the electricity price), e-fuel cost varies between 4772 $/ton to 2073 $/ton under low (10 %) and high learning (20 %) rates of S-DAC technology whereas for L-DAC, it varies between 3750 $/ton to 2015 $/ton over the same learning rates. With the further decrease in the electricity prices to 5 $/GJ in 2050, assuming 5 % annual decrease in the electricity price, e-fuel prices would vary between 1466 $/ton to 1358 $/ton for S-DAC and L-DAC pathways, respectively, considering 20 % learning rates. This indicates that with low electricity prices (approx. 5 $/GJ), which may be achievable due to high deployment of solar and wind technologies in China's energy system [57], and high learning rate of DAC (80$/ton to 50 $/ton) and electrolysers (5 $/GJ to 3 $/GJ), e-fuels become cost comparable with fossil jet fuels.

Further, China currently has no subsidy to incentivize DAC technologies. Thus, to assess the impact of such policy on e-fuel cost, this study considers the US IRA incentives scheme as the subsidy. It provides an incentive of 130 $ per ton of CO_2 to the DAC plant, having the capacity of capturing 1000 tons of CO_2 per year [58]. With these incentives, e-fuel cost may further reduce and lies between 1000 $/ton to 900 $/ton, depending upon the electricity prices, technology costs, and learning rates. This analysis highlights that no single parameter can independently drive a significant reduction in e-fuel costs. Instead, it is the interplay of multiple factors, such as technology costs, learning rates, efficiencies, and energy costs, that collectively determine the trajectory of e-fuel costs over time.

3.3. Impact of water availability

DAC-based e-fuel production is a water-intensive process. To meet around 80 % of the aviation demand over 2050, a significant amount of ground water is required, as presented in Fig. 8. These scenarios assume that desalination is not permitted. With S-DAC technology, a 70 % share of groundwater availability would only suffice to meet approximately 40 % of aviation fuel demand by 2050 (Fig. 8 a). In contrast, under similar water availability conditions, the L-DAC technology would meet 31 % of the e-fuel demand by 2050 (Fig. 8 b).

Besides DAC technology, electrolysis is also highly dependent on water availability. Given that China's aviation demand is concentrated in Shanghai, Beijing, and Guangdong (approximately 57 %), which are water-scarce regions, the implementation of desalination plants is crucial for e-fuel production in these cities. With desalination plants and S-DAC technology, e-fuel production can meet up to 80 % of aviation demand in 2050 (Fig. 4 a). Under this technological pathway, the desalination water requirement in 2050 will be 44 % of China's current desalination capacity. The current desalination capacity is 2.9 ML/day according to China's latest 'five-year plan' from 2021 to 2025 [59]. However, with L-DAC deployment, the de-salinated water requirement will be equivalent to the current desalination capacity of China.

Fig. 9 highlights the comparison of water intensity for e-fuel production under two DAC technologies deployment. To produce 1 ton of e-fuels, around 20,425 L of water is needed through L-DAC, whereas S-DAC technology reduces the water requirement by 70 % and has a water intensity of 5,857 ML water per ton of e-fuel. In terms of litres of water per gallon of e-fuels, the water intensity for S-DAC is 17 L per gallon of e-

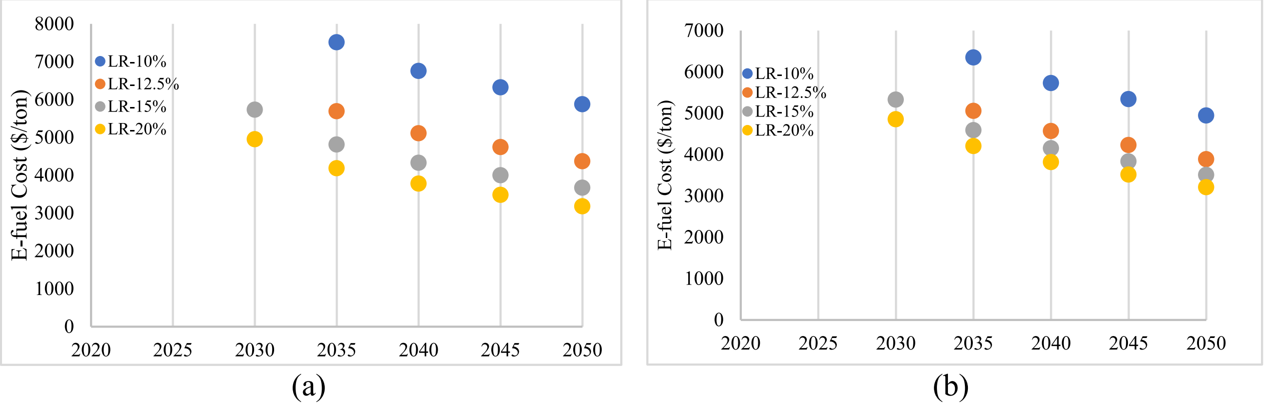
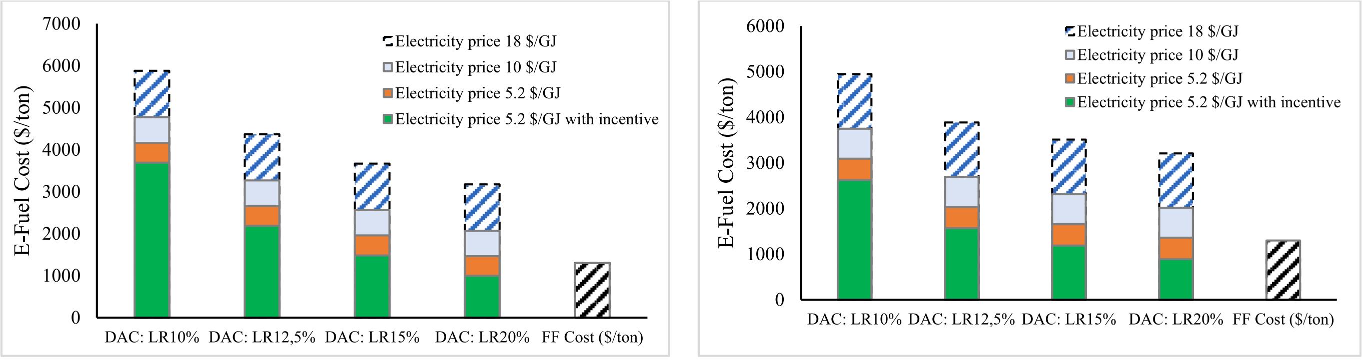
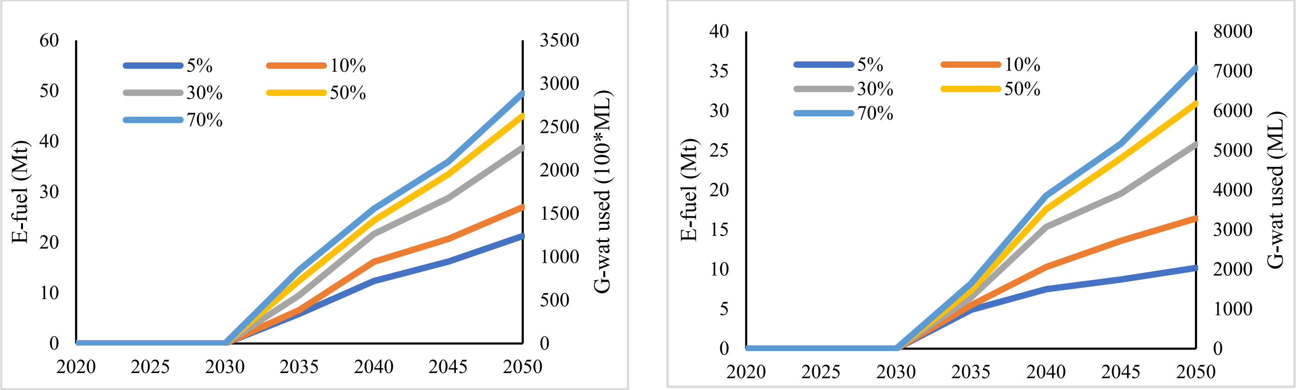


Fig. 6. E-Fuel cost projections over the simulation years under different DAC technologies. (Assumptions: high FF price factor; extreme carbon tax, desalination allowed, RES-2, PPL-2 and electricity price reduction-1% annually).



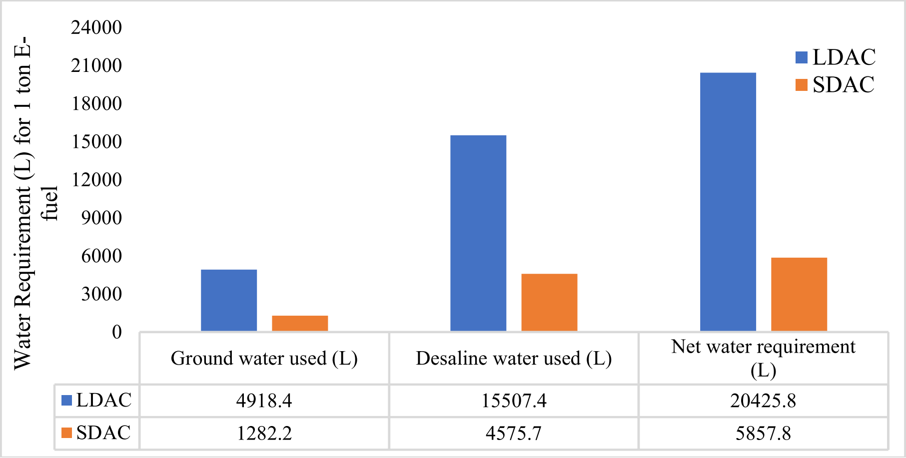
(a) (b)

Fig. 7. Impact of learning rates and energy prices on e-fuel cost for (a) S-DAC and (b) L-DAC production pathways. (Assumptions: high FF price factor; extreme carbon tax, desalination allowed, RES-2, PPL-2).



(a) (b)

Fig. 8. Impact of groundwater availability on e-fuel production for (a) S-DAC and (b) L-DAC pathways. Assumptions: high FF price factor; extreme carbon tax, no desalination allowed, medium DAC cost (LR12.5%), PPL-2 and electricity price reduction-1% annually).



	Ground water used (L)	Desaline water used (L)	Net water requirement (L)
LDAC	4918.4	15507.4	20425.8
SDAC	1282.2	4575.7	5857.8

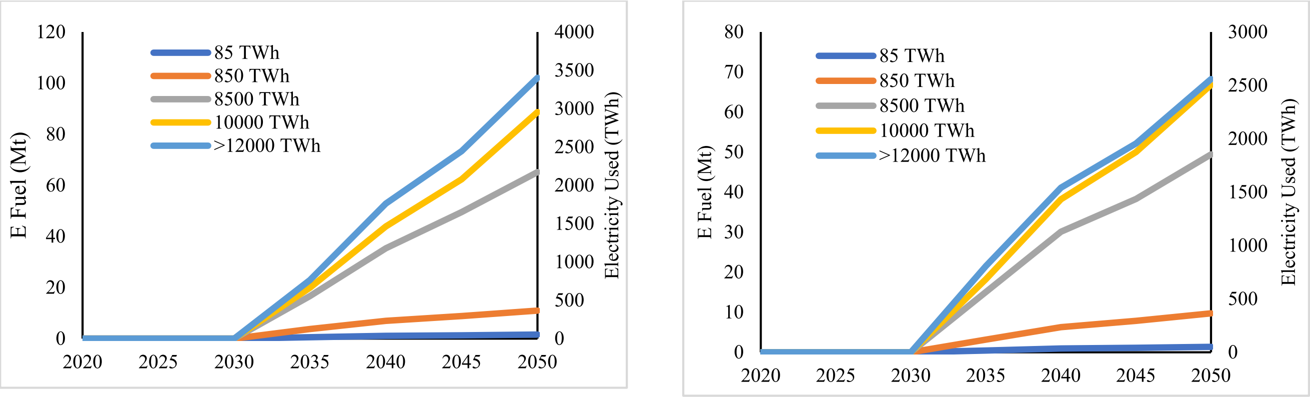
Fig. 9. Water requirement to produce 1 ton of e-fuel.

fuel, while for L-DAC pathways, water intensity is 60 L per gallon of e-fuel.

3.4. Impact of renewable electricity

The impact of electricity availability on e-fuel production is highlighted in Fig. 10. It can be noticed that water is a limiting factor for e-fuel production under the L-DAC pathway, given that by increasing of 20 % the electricity availability, e-fuel production does not increase substantially. Thus, L-DAC-based e-fuels can only meet 56 % of the aviation demand over 2050. To increase the e-fuel production under L-DAC pathways, water availability needs to increase further.

In the case of S-DAC-based e-fuel production, an increase in electricity availability results in a corresponding increase in e-fuel



(a) (b)

Fig. 10. Impact of renewable electricity availability on e-fuel production for (a) S-DAC and (b) L-DAC pathways. (Assumptions: high FF price factor; extreme carbon tax, desalination allowed, medium DAC cost (LR12.5%), PPL-2 and electricity price reduction-1% annually).

production (Fig. 10 a). This indicates that electricity is the key deciding factor for S-DAC-based e-fuel production pathways. The S-DAC production pathway is projected to produce 102 million tonnes (Mt) or 4400 PJ of e-fuel by 2050. This production requires 3457 TWh of renewable electricity, which constitutes approximately 10 % of China's projected renewable energy potential of 115 EJ in 2050 [60] and is 1.2 times more than the current installation (2023) of renewable energy in China [61]. This results in an overall electrical intensity of 33.8 MWh per tonne, which is equivalent to 0.1 MWh per gallon of e-fuel. In the case of L-DAC-based e-fuel production, the overall electrical intensity is calculated to be 37 MWh per tonne, or 0.11 MWh per gallon of e-fuel.

3.5. Impact on emissions

The impact of e-fuels on carbon emissions from the aviation sector is highlighted in Fig. 11. Under the extreme carbon and fossil fuel price factors and with the ambitious learning rate of DAC technologies, S-DAC based e-fuels will enter the aviation market in 2030. This is because the model allows the e-fuels to commence once the e-fuel cost becomes comparable with fossil jet fuel. Thus, from 2030, carbon emissions will start reducing drastically. S-DAC-based e-fuels can meet 84 % of the demand under high resource availability, and the remaining demand is fulfilled by fossil fuels. Thus, this pathway results in a 97 % reduction in carbon emissions from the fossil fuel usage pathway. E-fuels and fossil jet fuel have equivalent combustion emissions. However, by using carbon captured from the atmosphere and renewable electricity for their production, the overall lifecycle emissions of e-fuels are less than those of fossil fuels. This study found that the emission intensity of DAC-based e-fuels is approximately zero as compared to fossil fuels having a CO_2 emission intensity of 95 gCO_2/MJ.

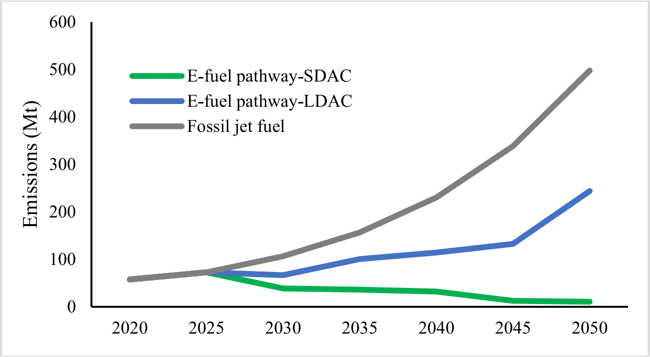


Fig. 11. Net CO_2 emissions from aviation sector under (a) continued use of fossil fuels, (b) S-DAC pathway meeting 80% demand, and (c) L-DAC pathway meeting 56% of the demand from e-fuels. (Assumptions: high FF price factor; extreme carbon tax, desalination allowed, low DAC cost (LR20%), RES-2, PPL-2, and electricity price reduction-1% annually).

3.6. Spatial distribution of e-fuels production and DAC plants

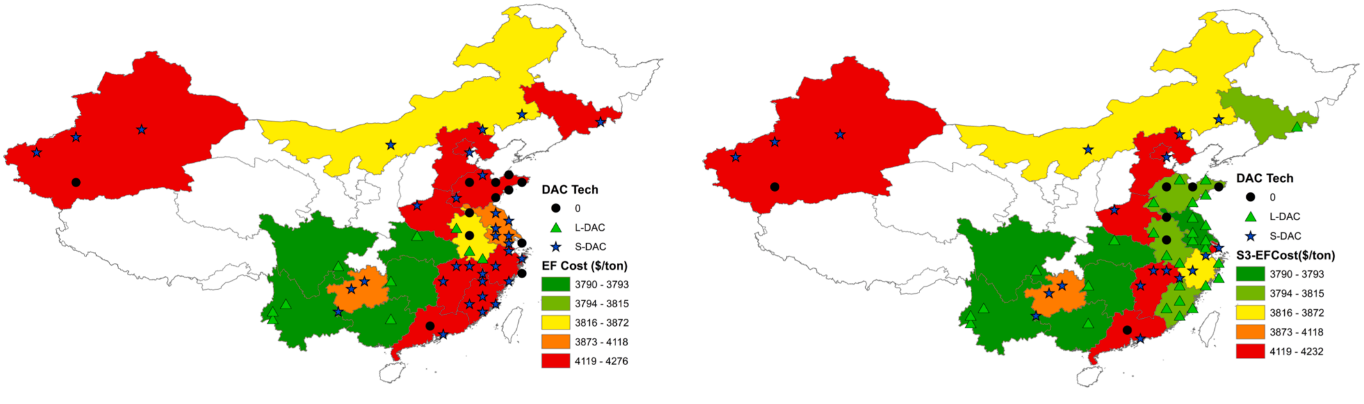
As mentioned in section 3.3, desalination plants are crucial since water availability is the limiting factor in e-fuel production. Fig. 12 and Fig. 13 illustrate the optimal distribution of DAC facilities, e-fuel cost, and production potential for scenarios with and without desalination plants in the final year of simulation (2050).

In the no desalination scenario, airports in coastal areas primarily opt for S-DAC plants (Fig. 12 a). As a result, provinces such as Fujian, Zhejiang, Anhui, Jiangsu, and Shandong experience higher e-fuel costs compared to the desalination-allowed scenario (Fig. 12 b). In this scenario, there are 34 sites with S-DAC plants, 10 sites with L-DAC plants, and 12 locations with no DAC facilities. The corresponding e-fuel distribution is shown in Fig. 13 a. In regions like Beijing, Shanghai, and Guangdong, e-fuel production is negligible due to water scarcity and high demand. At sites with no DAC facilities, e-fuels are transported to meet demand.

In the desalination-allowed scenario, the number of L-DAC plants increases due to their lower capital cost. This scenario features 30 L-DAC plants, 19 S-DAC plants, and 7 sites without DAC facilities. S-DAC technology, with its lower energy and water requirements, is deployed in locations with high demand and low resource availability, such as Beijing, Shanghai, and Guangdong (Fig. 12 b).

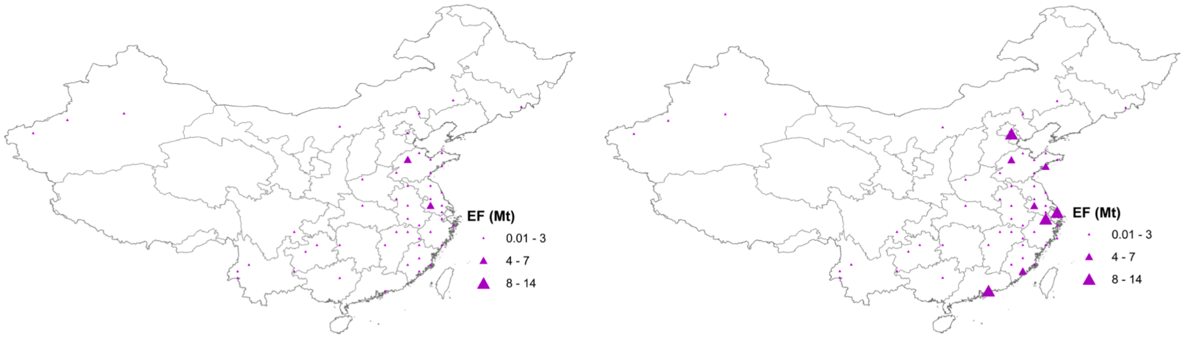
Since electricity and water costs are uniform across China, the optimal locations for e-fuel production are determined primarily based on feedstock availability. To evaluate this, a scenario is developed in which the availability of electricity and water is limited to 1 %. Under this scenario, provinces capable of generating maximum e-fuels are considered as favourable locations for e-fuel production. Fig. 14 highlights that provinces such as Jiangsu and Shandong are in mapped in green colour under both DAC technology pathways, followed by Anhui. This is attributed to the high availability of water and green electricity. Additionally, the province of Neil Mongol is favourable in the case of the S-DAC production pathway due to its high wind energy availability.

Fig. 15 shows the optimal placement of DAC and the corresponding e-fuel cost under different learning rates of DAC cost. These simulation results are for the final year of simulation, i.e., 2050. Under ambitious learning rates for DAC, S-DAC facilities are established throughout China due to their low energy and water requirements (Fig. 15 a). In this scenario (S1), as the technology cost reaches its lowest point, the cost of



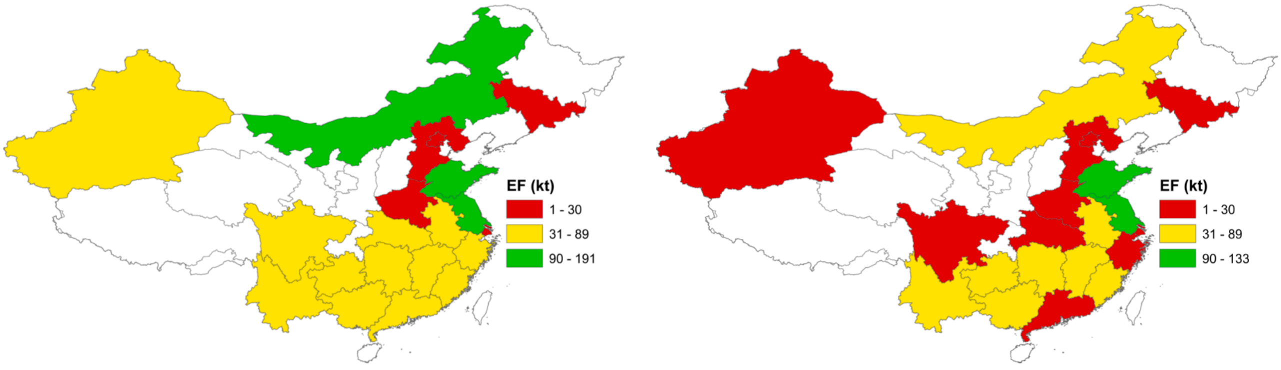
(a) (b)

Fig. 12. Spatial distribution of DAC plants and e-fuel cost under (a) without desalination plants and (b) with desalination plants scenarios. (Assumptions: high FF price factor; extreme carbon tax, med DAC cost (LR12.5%), RES-2, PPL-2 and electricity price reduction-1% annually).



(a) (b)

Fig. 13. Spatial distribution of e-fuel production under (a) without desalination plants and (b) with desalination plants scenarios. (Assumptions: high FF price factor; extreme carbon tax, med DAC cost (LR12.5%), RES-2, PPL-2 and electricity price reduction-1% annually).

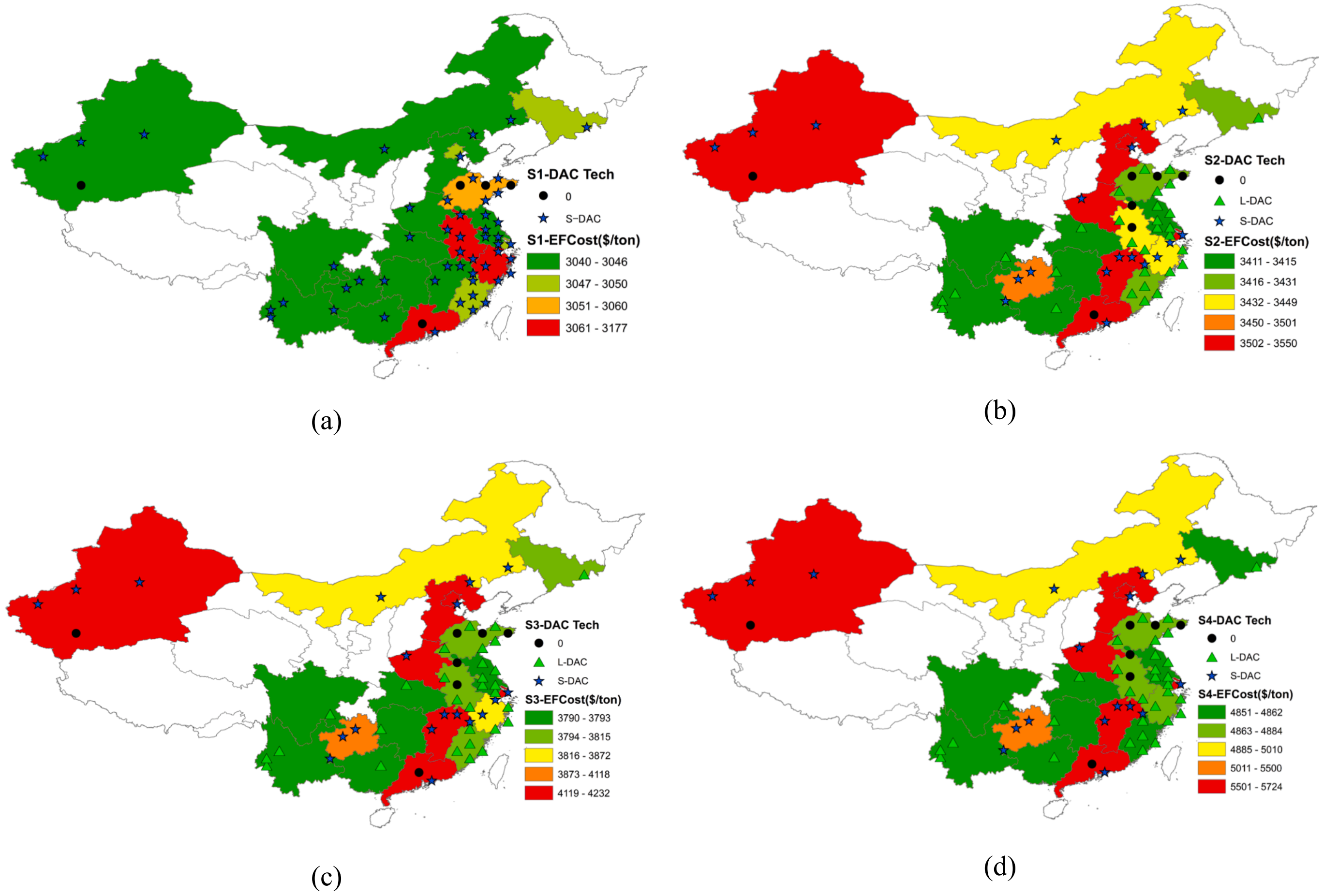


(a) (b)

Fig. 14. Favorable locations of e-fuel production under limited resource availability using (a) S-DAC and (b) L-DAC technology. (Assumptions: high FF price factor; extreme carbon tax, med DAC cost (LR12.5%), PPL-2 and electricity price reduction-1% annually) kt: kilo-ton.

feedstocks becomes the prominent and deciding factor compared to the plant setup cost. In this scenario, a total of 51 S-DAC plants are established, while remaining airports either use fossil fuels or have e-fuels transported to them.

Under the 15 % learning rate scenario (S2), the number of S-DAC plants decreases to 19, while the number of L-DAC plants increases to 30. L-DAC plants are primarily located in coastal areas due to the access of de-saline water (Fig. 15 b). Notably, despite the availability of desalination plants in Beijing, Shanghai, and Guangdong, S-DAC plants are established in these cities; otherwise with L-DAC, they have high de-saline water demand. Locations with S-DAC plants have higher e-fuel production costs compared to sites with L-DAC plants, owing to the differences in technology costs. A similar trend is observed in the S3 scenario (Fig. 15 c), where the number of S-DAC and L-DAC plants are 19



(a) (b)

(c) (d)

Fig. 15. Optimal placement of DAC and corresponding e-fuel cost under different DAC learning rates (a) S1: LR-20% (b) S2: LR-15% (c) S3: LR-12.5% (d) S4: LR-10%. (Assumptions: high FF price factor; extreme carbon tax, RES-2, PPL-2 and electricity price reduction-1% annually).

and 30, respectively. Under a higher DAC technology cost scenario (S4), the number of L-DAC plants increases to 32, and S-DAC facilities decrease to 17 (Fig. 15 d). The shift in the number of L-DAC and S-DAC facilities is due to their capital cost.

4. Discussion and broader implications

The results presented so far highlight that even under ambitious expansion scenarios with high learning rates and low energy costs, e-fuels remain significantly expensive than fossil jet fuels in the absence of incentives. This section evaluates alternative low-emission strategies, examines key policy measures to support e-fuel deployment, and discusses the broader implications of the findings.

4.1. Direct air capture with carbon storage (DACCS) as an alternative strategy

To explore other cost-effective alternatives to ensure a low-emission aviation sector, this study compares the 2050 abatement cost of e-fuels with the cost resulting from an alternative DACCS scenario (Fig. 16). This pathway combines a continued use of fossil jet fuel with DACCS to remove the carbon emitted in burning the fossil jet fuel. The cost of CO_2 storage is considered as 10 $/ton [51].

Producing 102 Mt of e-fuels requires approximately 3457 TWh of electricity, 597 billion liters of water, and 497 Mt of CO_2. In contrast, capturing the same amount of CO_2 via the 'DACCS' pathway consumes only 165 TWh of electricity and 3 billion liters of water. This demonstrates that the overall electricity and water demand for this route is approximately 20 and 188 times lower, respectively, than that of the e-fuel route. Thus highlighting the potential of the 'DACCS' pathway as an energy-efficient and cost-effective alternative.

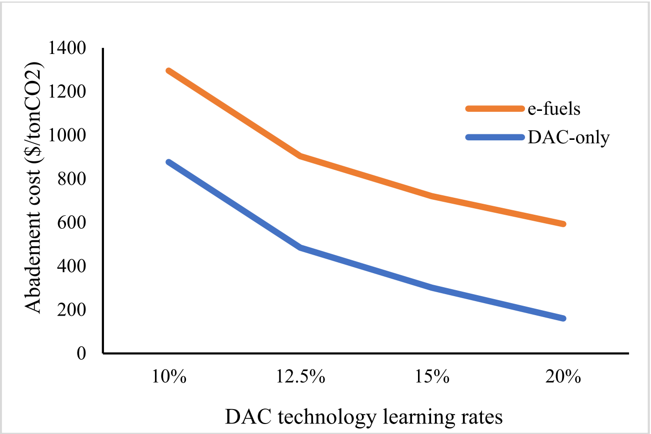


Fig. 16. Carbon abatement costs for e-fuels and 'DAC-only' pathways in 2050 under varying DAC technology learning rates. (Assumptions: high FF price factor; extreme carbon tax, RES-2, PPL-2 and electricity price reduction-1% annually).

However, relying on fossil fuels with DACCS presents significant sustainability concerns. The dependence on international trade to meet energy demands limits the viability of this route as a long-term solution. Furthermore, the limited availability and uneven distribution of natural CO_2 storage sites may exert additional pressure on natural ecosystems

[25], creating logistical challenges for the efficient and sustainable storage of captured CO_2 [35]. Additionally, as intermittent renewable energy deployment grows, e-fuel production can offer ancillary services, such as grid balancing, while enhancing renewable integration across multiple sectors. There is a need to optimally balance both pathways to address immediate decarbonization needs while building a robust and sustainable energy transition for the future. Another critical consideration in continued fossil jet fuel use is the emission of non-carbon pollutants during combustion, such as NO_x, water vapors, sulfates, and other volatile organic compounds [62]. To maintain air quality, DACCS systems need to be retrofitted with special scrubbers (amine based) and chemicals that remove non-CO2 pollutants, or be significantly oversized to ensure equivalent carbon emission capture [63]. In contrast, using e-fuels or blending them with fossil fuels results in significantly lower non-CO_2 pollutants, up to 50 to 70 % [64]. Finally, achieving substantial reductions in both CO_2 and non-CO_2 emissions ultimately requires a transition toward hydrogen-powered aircraft or, in parallel, by managing demand by alternate high-speed modes [65].

4.2. Policy and pathways to scale up e-fuels

China currently lacks dedicated incentive policies and a structured roadmap to scale up e-fuels and enhance their cost competitiveness, unlike the U.S. Inflation Reduction Act (IRA). Leveraging such incentives, along with its vast reserves of critical raw materials and abundant renewable energy potential, a well-designed policy framework could position China as a strategic global exporter of e-fuels. This study assesses the importance of different policy factors that could accelerate the e-fuel development. The impact of carbon price and the learning rates of two DAC technologies on the availability of e-fuels is presented in Fig. 17. Three carbon cost scenarios (base, aggressive, and extreme) and DAC cost scenarios are assessed, as highlighted in Table 4 and Table 1, respectively. For the base carbon tax and at a low fossil fuel factor of 1.2, e-fuels will not be commenced until 2050 due to their high cost. Under DAC learning rates of 12.5 %, L-DAC based e-fuels commence 5 years earlier than S-DAC based e-fuels. Similarly, increasing the carbon tax from the base scenario to the extreme scenario will commence e-fuels production 10 years earlier. Thus, policy support is needed to accelerate e-fuel production.

Finally, the pathways to support the scaling of e-fuels are summarized in Fig. 18. Scenarios S1 to S3 highlight the critical role of policy measures in enabling e-fuels to enter the market by 2035. In these three scenarios, limited feedstock supply and infrastructure are considered. S4 highlights the impact of DAC technology scale-up, demonstrating that reduced DAC costs could accelerate e-fuel market entry. Scenario S5

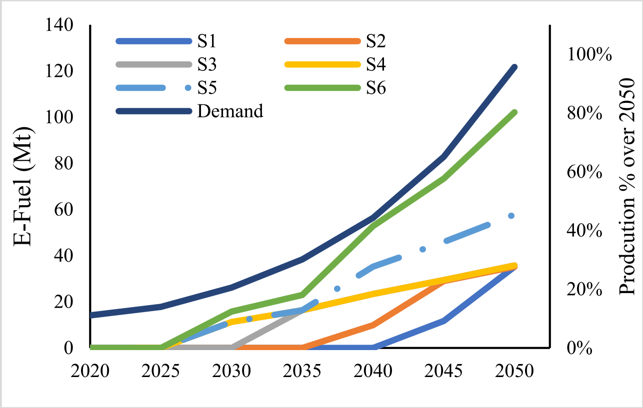


Fig. 18. E-fuel production pathways under policy, infrastructure, and feedstock availability scenarios. (Scenario definition: S1- FF price factor-1.2, aggressive CT, RES1, PPL-1, DAC LR-12.5%; S2- FF price factor-1.2, extreme CT, RES1, PPL-1, DAC LR-12.5%; S3- FF price factor-1.8, extreme CT, RES1, PPL-1, DAC LR-12.5%; S4- FF price factor-1.8, extreme CT, RES1, PPL-1, DAC LR-15%, S5- FF price factor-1.8, extreme CT, RES1, PPL-2, DAC LR-20%; S6- FF price factor-1.8, extreme CT, RES2, PPL-2, DAC LR-20%.) (Assumptions: desalination allowed and electricity price reduction −1 % annually).

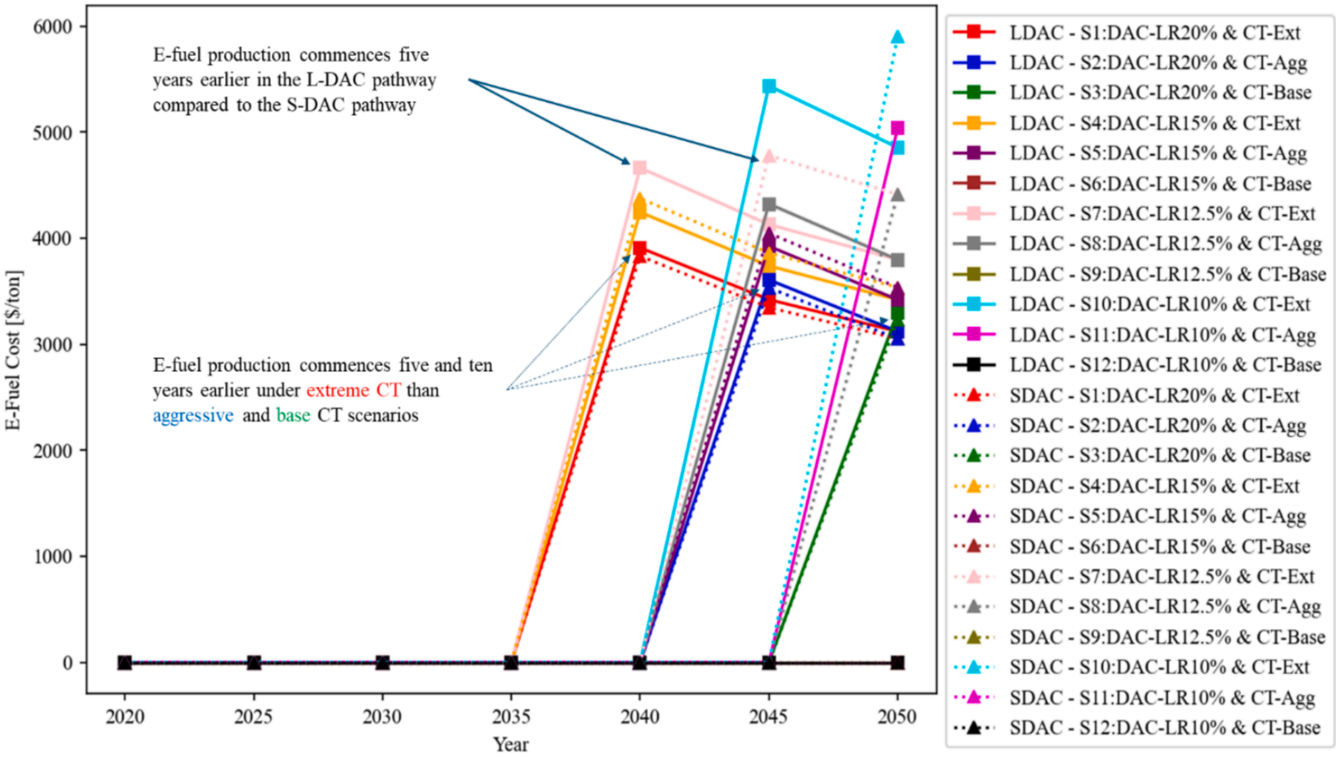


Fig. 17. E-fuel production under different carbon tax and DAC cost scenarios(Assumptions: high FF price factor; desalination allowed, RES-2, PPL-2 and electricity price reduction-1% annually).

illustrates that extending the CO_2 pipeline network increases e-fuel production from 41 % to 47 %. Furthermore, S5 shows that with enhanced feedstock availability, e-fuels could meet up to 84 % of aviation demand by 2050.

4.3. Role of green hydrogen as a sustainable energy source

Hydrogen is one of the key energy vectors that directly influence the cost-competitiveness and scalability of e-fuels. As highlighted in Fig. 7 that once the technologies are matured and the capital cost of technologies reached at their optimal level, the energy cost becomes the prominent factor in the e-fuel cost. Further, the majority of the energy cost is associated with the green hydrogen production (Fig. 5), so scalable and low-cost green hydrogen availability is the key to ensuring the economic viability of the e-fuels. In China, currently, the AECs are the main source of hydrogen production due to their domestic manufacturing. The critical materials to manufacture PEMs are not readily available in China, thus, the reported capacity of alkaline technology is 10 times more than the PEMs. This reliance on AECs reduces dependence on foreign supply chains but also presents challenges in efficiency and operational flexibility [57].

Moreover, the feasibility of large-scale green hydrogen production from water electrolysis remains constrained by renewable energy and water availability. As demonstrated in this study, meeting 84 % of the projected 2050 aviation fuel demand would require approximately 597 billion liters of water, with over 98 % allocated to hydrogen production when employing S-DAC technology. Furthermore, out of the total water usage, 78 % of the water requirement is met through seawater desalination. Consequently, the availability of low-cost renewable energy and sustainable water resources poses a significant challenge, particularly in water-scarce or landlocked regions where desalination may not be a viable option. From a geopolitical perspective, ensuring the availability of critical materials, secure water availability, and renewable energy infrastructure is critical for long-term e-fuel sustainability. China's geographical advantage, abundant renewable energy, and seawater access position it as a potential export hub for e-fuels, reducing reliance on fossil imports while supporting global e-fuel trade. Looking into these constraints, the sustainable strategy should be employed to optimally utilize the green hydrogen as it is a flexible and versatile energy source that could be used in multiple sectors (heat, power, transportation, industries) to contribute to developing low-emission systems [67].

4.4. Comparison with existing literature

Due to significant variations in assumptions, different model frameworks, and region-specific parameters, including electricity, water, and fuel costs, as well as their carbon intensities, comparisons across studies remain challenging. However, the overall cost trajectories of e-fuels identified in this study, along with key scalability drivers such as policy measures (e.g., carbon tax), DAC learning rates, and declining renewable electricity costs, are aligned with existing literature estimates.

As discussed in section 3.2, e-fuel cost reduction primarily depends on energy prices and DAC technology learning rates and will be in range of 3200 \$/ton to 2000 \$/ton in 2050 considering high learning rate of solid DACs at an electricity cost of 18\$/GJ to 10 \$/GJ, which is in the similar range highlighted by prior research [28-32]. However, unlike prior studies, this assessment incorporates and extends the discussion on additional aspects related to spatially explicit ecological parameters and their availability, required incentives, and transportation infrastructure. These factors play a critical role in identifying the hotspots to set up e-fuel production facilities and DACs. This study indicates China has the potential to generate 121 Mt of e-fuels, and the e-fuels costs could further drop down to 1400 \$/ton, with an electricity cost of 5.2 \$/GJ, a scenario projected to be feasible in China by 2045–2050 [57]. However, this production needs approximately 3457 TWh of renewable electricity and 597 billion liters of water. Further, with IRA incentives and low electricity costs, e-fuels achieve cost-competitiveness in 2050 w.r.t fossil fuels at a cost of 900 – 1000 \$/ton, which is in line with studies [17] and [58]. Further, the abatement cost of e-fuels estimated by Gray et al. [35] is around 750 \$/tonCO_2 at an considering electricity cost of 11 \$/GJ and DAC CAPEX of 900 \$/tonCO_2, and is found to be lower than this study's estimate of approx. 900 \$/tonCO_2 under the similar DAC cost with LR-12.5 % (Fig. 16). This is due to the higher electricity cost of 18 \$/GJ considered in this study. However, it is in the similar range of 400–550 \$/tonCO_2 as estimated in [66] under the higher DAC learning rate scenario.

5. Conclusion

This study explores the opportunities and challenges in producing Direct Air Capture (DAC) and green hydrogen-based e-fuels to ensure the low-emission aviation sector, focusing on the 2020–2050 timeframe. It evaluates e-fuel production costs, energy requirements, and potential, incorporating spatial and temporal variations in renewable electricity, water resources, transportation networks, different types of DAC technologies, and policy measures. Additionally, it compares e-fuel pathways with a Direct Air Capture with Carbon Storage (DACCS) route involving continued fossil fuel use.

The findings indicate that e-fuel production costs and potential are significantly influenced by DAC technology type, learning rates, resource availability, and cost (e.g., renewable electricity, water). E-fuel production via L-DAC technology has a high water requirement, approximately 60 L per gallon of e-fuel, making it highly dependent on desalination plants. However, due to the lower capital costs of L-DAC, e-fuel costs range from \$4944/ton to \$3208/ton in 2050. In comparison, S-DAC requires 71 % less water, but due to higher capital costs, estimated production costs range from \$5875/ton to \$3176/ton. However, e-fuel costs remain 2.5 to 3 times higher than fossil jet fuels (\$700/ton to \$1300/ton) [68]. To achieve the cost-comparability, the study highlights the importance of low electricity prices (~ 5 \$/GJ), along with high learning rate of DAC (80 \$/ton to 50 \$/ton), electrolysers (5 \$/GJ to 3 \$/GJ) and incentive frameworks similar to the U.S. Inflation Reduction Act (IRA), which lowers the cost to \$1300–900/ton. Further, it evaluates the DACCS pathway, highlighting a 70 % lower carbon abatement cost and significantly reduced energy usage compared to e-fuel production. However, over-reliance on DACCS pathways raises long-term concerns, including storage limitations and delayed progress in alternative decarbonization strategies.

China, the world's second-largest aviation market, heavily relies on energy imports to meet its growing fuel demand. This study suggests that by 2050, under an ambitious scenario, China could produce 102 Mt of e-fuels (equivalent to 34 billion gallons), meeting 84 % of the projected aviation fuel demand. Leveraging this e-fuel production potential enables an opportunity to develop the domestic e-fuel industry to enhance energy security and reduce reliance on fossil fuels while supporting the country's low emission targets. However, immediate policy action is critical to support the scale-up of DAC and e-fuels, ensuring that China capitalizes on this significant opportunity to develop a low-emission aviation sector.

This study specifically focuses on evaluating the e-fuel production potential for the aviation sector. However, a comprehensive system-level assessment is needed to account for multi-sectoral competition over shared resources such as renewable electricity, water, and CO_2 infrastructure. The results presented here provides critical estimates of the renewable energy and water requirements needed to scale e-fuel production under the assumption of sector-specific deployment. Expanding this analysis to include cross-sectoral energy demands, particularly from other hard-to-abate sectors such as maritime transport and heavy industries, would enable a more integrated and realistic estimation of resource allocation and infrastructure needs. Such an approach would also help identify opportunities for utilizing otherwise curtailed renewable energy, improving overall system efficiency, and potentially lowering e-fuel production costs. By coupling multi-sectoral demands, the utilization of dedicated CO_2 pipeline infrastructure can be justified and leveraged more effectively. Furthermore, exploring alternate cost-effective CO_2 sources i.e., from point sources, especially from biogenic origins and incorporating revenues from byproducts, such as other hydrocarbons, waste heat, and hydrogen, can enhance the economic viability of e-fuel production.

CRediT authorship contribution statement

Shubham Tiwari: Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Piera Patrizio:** Supervision, Formal analysis, Conceptualization. **Sylvain Leduc:** Software, Data curation. **Anna Stratton:** Supervision. **Florian Kraxner:** Supervision, Conceptualization.

Declaration of competing interest

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Appendix A. Input data and cost parameters

1 Ground Water

The spatial distribution of groundwater is extracted from the study conducted by Greve et al. [69]. The database shows the model estimates of both groundwater supply (the amount of available water) and demand (the amount of water that is withdrawn). These projections are influenced by changes in the climate, society, and the economy. The data used in this study are on a grid of 100 km × 100 km and cover four decadal climates from 2020 to 2050, with a 10-year timestep. The difference between supply and demand at the grid cell level is used to calculate the net water availability. Fig. A1 presents the spatial distribution of groundwater availability from 2020 to 2050. The water availability is highest in Hubei, Anhui, Jiangsu, and Sichuan, while the economic centers of China, i.e., Beijing and Shanghai, have the least water availability. Further, the model considers a price of \$0.724 per cubic meter as the cost of groundwater for industrial use [70].

2 Sea Water

Due to acute water constraints in many of China's industrial centers, saltwater desalination has emerged as a critical option. In 2019, there were around 97 reverse osmosis (RO) and 15 multiple effect distillation (MED) desalination units, for a total desalination capacity of 1573.76 ML/day [71] in China. Further, according to the latest 'five-year plan' from 2021 to 2025, China's desalination capacity will be around 2.9 ML/day (14th Five-Year Plan (2021–2025), 2024). The average cost of seawater in China, including the energy consumption while considering the operation and maintenance cost, is in the range 0.9 to 2.35 $\$/m^3$ [72]. In this study, the levelized cost of 2.2 $\$/m^3$ is considered and assumes that the e-fuel plant can access seawater within a maximum distance of 200 km from the coastline. Based on the assumption, Fig. A2, shows the airports that have access to desalination water.

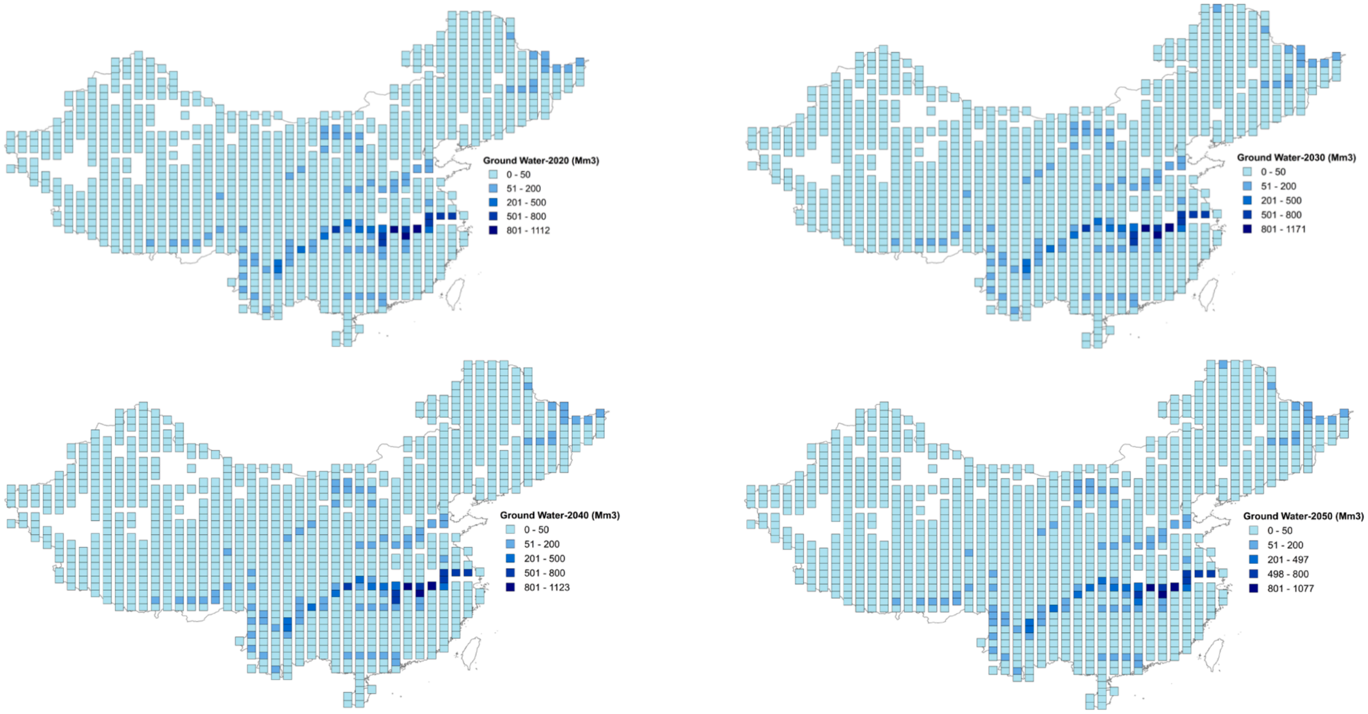


Fig. A1. Ground water availability (Mm3) in China for 2020 to 2050

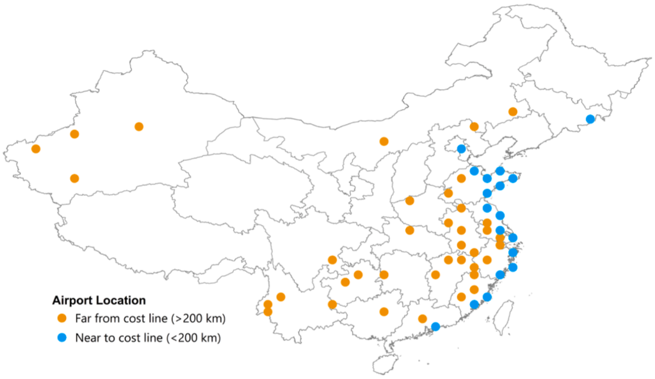


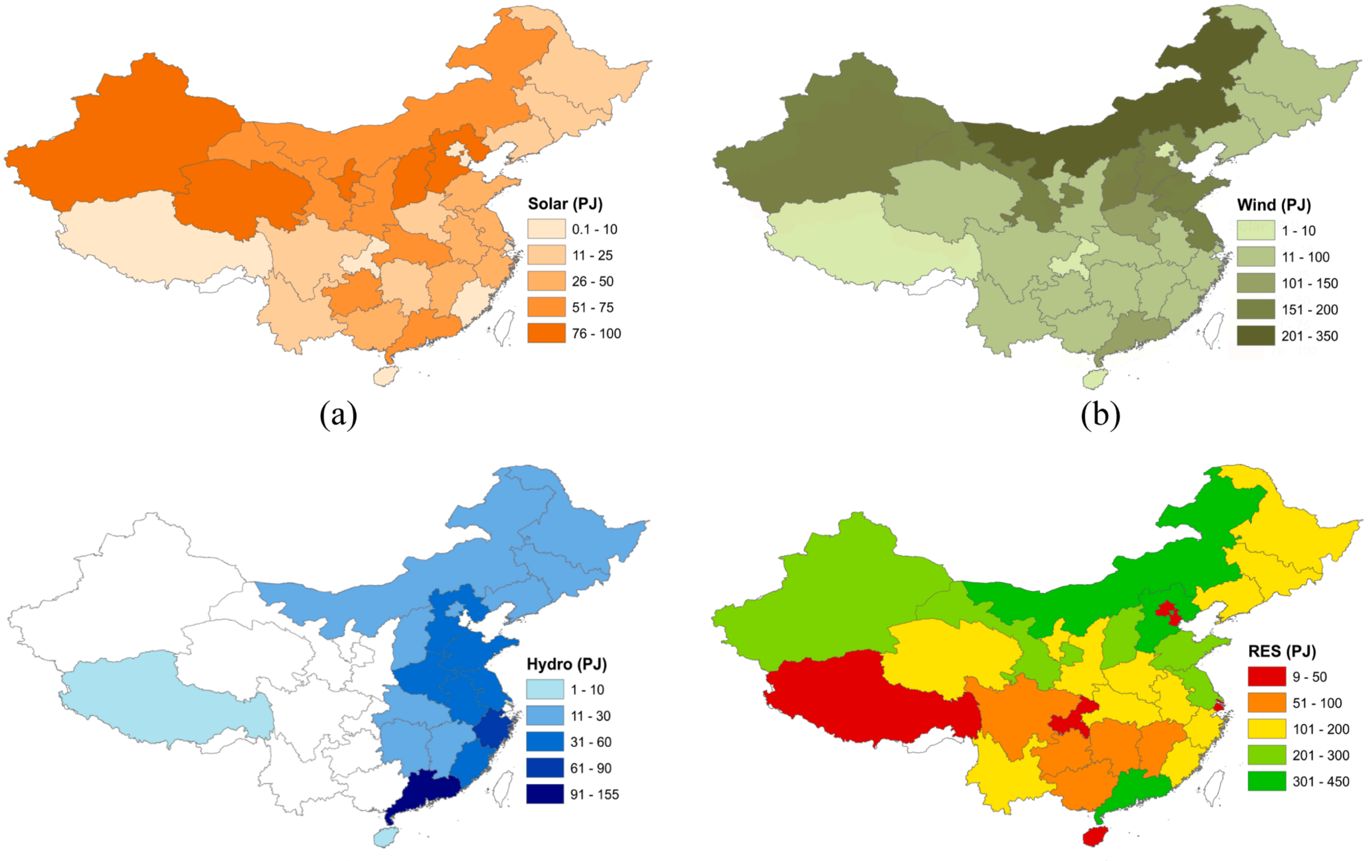
Fig. A2. Airport locations, where the blue circles represent the airports close to coastline and able to use desalinated water.

3 Renewable Energy

Renewable energy has grown rapidly in recent decades and proven to be an effective way of reducing greenhouse gas (GHG) emissions [73]. In 2022, China became the world's largest producer of wind and solar energy [74]. To map the spatial location of current installed RE plants across China, the provincial-level plant capacity data is extracted from the [75] and [76]. In this study, solar PV, onshore wind, offshore wind, and hydro power are considered as the main sources of renewable energy with a capacity factor of 15.9 % [77], 26 % [78], 35 % [79], 40 % [80] respectively. Based on this, the spatial distribution of renewable energy generation (PJ) for the year 2022 is created, as shown in Fig. A3. It can be noticed that provinces such as Inner Mongolia, Guangdong, Hebei, Shandong, and Xinjiang have the highest renewable energy production. Further, the model considers the industrial electricity price of $0.08 per kWh as the cost of electricity for industrial use with an assumption of a 1 % annual decrease over the years [81].

4 Aviation fuel demand

The list of Chinese airports is gathered from web databases provided by the Civil Aviation Administration of China (CAAC) [82]. Based on the data availability, this study considers the main 70 airports of China, and there current (2022) jet fuel demand is marked in Fig. A4. To estimate the jet fuel demand at each airport, all the flights (per year) departing from the individual airports of China are considered, along with their respective numbers of passengers flying (passenger traffic). According to the China Aviation Administration of China (CAAC) website, the total transport turnover was 59.928 billion ton-km in 2022. The fuel consumption of China's aviation sector is 0.302 kg per ton-km [83]. It can be noticed that the majority of the airports are located in the eastern coastal part of China and showcase the peak demand at Beijing, Shanghai, Shandong, Zhejiang, Jiangsu, and Anhui. The net jet fuel demand of China in 2022 is calculated to be 613 PJ or 14.1 Mt, considering the energy density of aviation fuels is 43.5 MJ/kg. To forecast the mid-century aviation demand for China, a base case scenario considering an annual growth of 8 % is assumed, based on historical growth rate [84]. With an 8 % yearly increase, the projected demand of China in 2050 will be 5295 PJ or 121.7 Mt. The fossil jet fuel cost is considered to be constant throughout China and is 995 $/ton [68].



(a) (b) (c) (d)

Fig. A3. Spatial distribution of China's installed (a) solar (b) wind (c) hydro and (d) total renewable energy capacity in 2022.

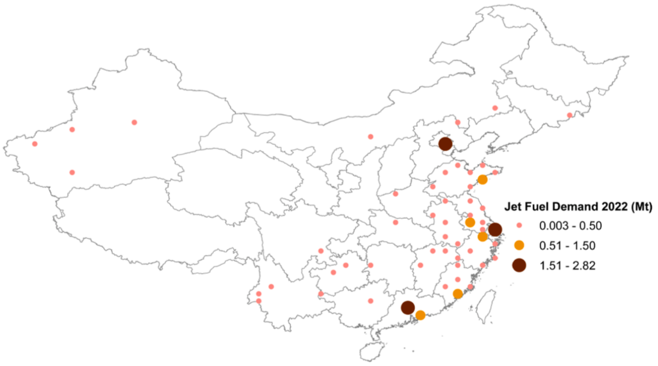


Fig. A4. Distribution of airports in China and their corresponding demand in 2022.

5 Electrolysers

In addition to DACs, electrolyzer is the another key technology in the e-fuel production process. The capital expenditure (CAPEX) for electrolyzer (EL) systems varies significantly across different technologies. For alkaline ELs (AEC), the current capital cost ranges from USD 500 to 1400 per kW, whereas for PEMs, it ranges from USD 1100 to 1800 per kW. SOEC systems have higher CAPEX estimates, ranging from USD 2800 to 5600 per kW [48].

Wang et al. [57] reports that the current hydrogen production cost ranges from 1493 to 2238 \$/kW for PEM plants and 374–597 \$/kW for AEC plants. Because of the high maturity of AEC technology compared to PEMs in China, this study considers the former technology for hydrogen production and assumes a current capital cost of 600 \$/kW [57], projected growth rate of 15 % [47], capacity factor (for a hybrid renewable supply) between 70–80 % [85]. Accordingly, the future projected cost is estimated and is shown in Table A1. The other key operating parameters, conversion efficiencies, and capacity factors are derived from the [86,87] and the 2020 World Economic Forum report [88].

6 CO_2 conversion and Fischer-Tropsch synthesis

As previously discussed, the reduction of CO_2 to produce syngas is achieved through the reverse water–gas shift reaction and is an energy intensive process. The cost of this technology is assessed by incorporating the CO_2 to CO conversion efficiency in conjunction with DAC costs. Following this, in the Fischer-Tropsch (FT) synthesis reactor, the CO and hydrogen react to form hydrocarbons or the desired e-fuels. The capital cost for the FT reactors is presented in Table A1. The operation and maintenance cost is assumed to be 3 % of the investment cost for all electrolyzers and FT synthesis reactions. The mass and energy balances, along with the efficiencies of all involved processes, are detailed in Table A2. Since this study considers the renewable energy for producing the hydrogen and e-fuels, the emissions related to electricity generation and hydrogen production are considered zero. The emissions related to FT synthesis is 0.08 ton CO_2/GJ derived from [89]. Further, to compare the e-fuel combustion emissions with fossil-based A1-Jet fuel emissions, fossil fuel combustion emission is considered as 73.8 g CO_2/MJ [90].

Table A1
Cost projection of other technologies studied.

Technologies	2020	2025	2030	2035	2040	2045	2050	Reference
Electrolysis ($/GJ)	15	8.5	5.2	4.0	3.5	3.2	3.0	
Synthesis toe-kerosene ($/GJ)	1.48	1.3	1.2	1.07	0.97	0.87	0.78	[51]
Electricity price ($/GJ)	24.44	23.25	22.11	21.02	19.99	19.01	18.08	[81]

Table A2
Key technical parameters used in the study.

Technology	Input	Efficiency	Ratios
Electrolysis (AEC)	Water, Electricity	0.65–0.73 JH2/J_{el} [86]	H2O/electricity = 0,28 l/kWh [91]
Electrolysis (PEM)	Water, Electricity	0.72–0.78 JH2/J_{el} [92].	H2O/electricity = 0,28 l/kWh [91]
SDAC + r-WGS	Water, Electricity, CO_2	0.64 tCO/t CO_2 [51]	Elec/CO_2 = 498 kWh/t CO_2 [86]Heat/CO_2 = 1500 kWh (low grade) [86]Elec/CO_2 red. = 3787 kWh/CO_2 [93,51].Water/CO_2 = 6 L/t CO_2 [86,47]
LDAC + r-WGS	Water, Electricity, CO_2	0.64 tCO/t CO_2 [51]	Elec/CO_2 = 1500 kWh/t CO_2 [47]Elec/CO_2 red. = 3787 kWh/CO_2 [93,51].Water/CO_2 = 2,993 l/t CO_2 [47]
Synthesis toe-kerosene	H2, CO	0.69 J ker./J H2 [94]	H2/CO = 0.15 tH2/tCO [51]

7. Emission factors

This study uses only renewable electricity as the source of electrical energy for all the processes. Thus, assumes negligible emissions from the feedstocks. As e-fuels can be transported through existing pipelines and mainly energy is needed for pumping [95]. Further, the study assumes no potential leakages from CO_2 pipelines; thus, zero emissions are considered from end-product and CO_2 transportation. Carbon emissions from other activities are reported in Table A3.

Table A3
Overview of the emissions of CO_2 for various processes involved.

Technology	Value	Reference
Synthesis to e-kerosene	0.92 gCO_2e/MJ fuel	[89]
Groundwater transport through pipeline	$8.4*10^{-7}$ t/l	[96]
Seawater transport through pipeline	$2.9*10^{-6}$ t/l	[96]
Fuel combustion	94 gCO_2e/MJ fuel	[97]

Table A4
Transport cost of the commodities involved in the supply chain.

Mode	Feedstock	Transport fixed cost	Transportvariable cost	References
Pipeline	Water	$9*10^{-4}$ $/l	$5.8*10^{-7}$ $/l.km	[98]
Pipeline	e-fuel	0.05 $/GJ	0.005 $/GJ.km	[99]

Data availability

Data will be made available on request.

References

[1] Lee H et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. Intergovernmental Panel on Climate Change (IPCC); 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[2] Dray L et al. Cost and emissions pathways towards net-zero climate impacts in aviation. Nat Clim Change 2022;12(10):Art. no. 10. doi: 10.1038/s41558-022-01485-4.

[3] Bains P, Kim H, Teter J. Decarbonising aviation in the IEA's net zero emissions by 2050 scenario. Int Civ Aviat Organ 2022, [Online]. Available: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ENVReport2022_Art48.pdf.

[4] Gegg P, Budd L, Ison S. The market development of aviation biofuel: drivers and constraints. *J Air Transp Manag* Jul. 2014;39:34–40. https://doi.org/10.1016/J.JAIRTRAMAN.2014.03.003.

[5] Neuling U, Kaltschmitt M. Techno-economic and environmental analysis of aviation biofuels. *Fuel Process Technol* Mar. 2018;171:54–69. https://doi.org/10.1016/j.fuproc.2017.09.022.

[6] Hileman JI, Stratton RW. Alternative jet fuel feasibility. *Transp Pol* Jul. 2014;34:52–62. https://doi.org/10.1016/J.TRANPOL.2014.02.018.

[7] IRENA. Biofuels for Aviation - Technology Brief. [Online]. Available: https://www.irena.org/publications/2017/Feb/Biofuels-for-aviation-Technology-brief. Accessed 27/10/2021.

[8] Chiaramonti D. Sustainable aviation fuels: the challenge of decarbonization. Energy Procedia Feb. 2019;158:1202–7. https://doi.org/10.1016/j.egypro.2019.01.308.

[9] Yoo E, Lee U, Wang M. Life-cycle greenhouse gas emissions of sustainable aviation fuel through a net-zero carbon biofuel plant design. *ACS Sustain Chem Eng*, Jul. 2022;10(27):8725–32. https://doi.org/10.1021/acssuschemeng.2c00977.

[10] ICAO Environmental Report 2019_Chapter 6.pdf. Accessed: Jan. 30, 2024. [Online]. Available: https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20Environmental%20Report%202019_Chapter%206.pdf.

[11] Pavlenko N, Kharina A. Policy and Environmental Implications of Using HEFA+ for Aviation".

[12] Bann SJ, et al. The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresour Technol*, Mar. 2017;227:179–87. https://doi.org/10.1016/j.biortech.2016.12.032.

[13] Sustainable Aviation Fuels. EASA Eco. Accessed: Jan. 30, 2024. [Online]. Available: https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels.

[14] Tao L, Markham JN, Haq Z, Biddy MJ. Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks. Green Chem Feb. 2017;19(4):1082–101. https://doi.org/10.1039/C6GC02800D.

[15] Fantuzzi A et al. Low-carbon fuels for aviation; 2023. doi: http://doi.org/10.25561/101834.

[16] Rojas-Michaga MF, et al. Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): a combined techno-economic and life cycle assessment. *Energy Convers Manage* Sep. 2023;292:117427. https://doi.org/10.1016/j.enconman.2023.117427.

[17] 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), doi: 10.1038/s41558-021-01032-7.

[18] "clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation.pdf." Accessed: Jan. 30, 2024. [Online]. Available: https://www.mckinsey.com/~/media/mckinsey/industries/travel%20logistics%20and%20infrastructure/our%20insights/scaling%20sustainable%20aviation%20fuel%20today%20for%20clean%20skies%20tomorrow/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation.pdf.

[19] Chong CT, Ng J-H. Limitations to sustainable renewable jet fuels production attributed to cost than energy-water-food resource availability. Nat Commun 2023; 14(1), Art. no. 1. doi: 10.1038/s41467-023-44049-6.

[20] Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal.

[21] European Commission. Proposal for a regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561. Accessed 20/10/2021.

[22] Vardon DR, Sherbacow BJ, Guan K, Heyne JS, Abdullah Z. Realizing 'net-zero-carbon' sustainable aviation fuel. Joule Jan. 2022;6(1):16–21. https://doi.org/10.1016/j.joule.2021.12.013.

[23] Annual Energy Outlook 2023 - U.S. Energy Information Administration (EIA). Accessed: Jan. 30, 2024. [Online]. Available: https://www.eia.gov/outlooks/aeo/index.php.

[24] Bergero C, Gosnell G, Gielen D, Kang S, Bazilian M, Davis SJ. Pathways to net-zero emissions from aviation. *Nat Sustain* Jan. 2023;6(4):404–14. https://doi.org/10.1038/s41893-022-01046-9.

[25] Sacchi R et al. How to make climate-neutral aviation fly. Nat Commun 2023;14(1), Art. no. 1, doi: 10.1038/s41467-023-39749-y.

[26] Gössling S, Humpe A, Fichert F, Creutzig F. COVID-19 and pathways to low-carbon air transport until 2050. *Environ Res Lett* Mar. 2021;16(3):034063. https://doi.org/10.1088/1748-9326/abe90b.

[27] IEA, "Net Zero by 2050," IEA. Accessed: Nov. 27, 2024. [Online]. Available: https://www.iea.org/reports/net-zero-by-2050.

[28] Becattini V, Gabrielli P, Mazzotti M. Role of carbon capture, storage, and utilization to enable a net-zero-CO_2-emissions aviation sector. *Ind Eng Chem Res* May 2021;60(18):6848–62. https://doi.org/10.1021/acs.iecr.0c05392.

[29] Ballal V, Cavalett O, Cherubini F, Watanabe MDB. Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios. *Fuel* Apr. 2023;338:127316. https://doi.org/10.1016/j.fuel.2022.127316.

[30] Peacock J, Cooper R, Waller N, Richardson G. Decarbonising aviation at scale through synthesis of sustainable e-fuel: a techno-economic assessment. *Int J Hydrog Energy* Jan. 2024;50:869–90. https://doi.org/10.1016/j.ijhydene.2023.09.094.

[31] Paulsen MM, Petersen SB, Lozano EM, Pedersen TH. Techno-economic study of integrated high-temperature direct air capture with hydrogen-based calcination and Fischer–Tropsch synthesis for jet fuel production. *Appl Energy* Sep. 2024;369:123524. https://doi.org/10.1016/j.apenergy.2024.123524.

[32] D'Adamo I, Gastaldi M, Giannini M, Nizami A-S. Environmental implications and levelized cost analysis of E-fuel production under photovoltaic energy, direct air capture, and hydrogen. *Environ Res*, Apr. 2024;246:118163. https://doi.org/10.1016/j.envres.2024.118163.

[33] ElSayed M, Aghahosseini A, Caldera U, Breyer C. Analysing the techno-economic impact of e-fuels and e-chemicals production for exports and carbon dioxide removal on the energy system of sunbelt countries – Case of Egypt. *Appl Energy* Aug. 2023;343:121216. https://doi.org/10.1016/j.apenergy.2023.121216.

[34] Sendi M, Bui M, Mac Dowell N, Fennell P. Geospatial techno-economic and environmental assessment of different energy options for solid sorbent direct air capture. Cell Rep Sustain 2024;1(8):100151, doi: 10.1016/j.crsus.2024.100151.

[35] Gray N, O'Shea R, Smyth B, Lens PNL, Murphy JD. The role of direct air carbon capture in decarbonising aviation. *Renew Sustain Energy Rev* Jul. 2024;199:114552. https://doi.org/10.1016/j.rser.2024.114552.

[36] Gonzalez-Garay A, et al. 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.

[37] IIASA. BeWhere. Accessed: Oct. 16, 2017. [Online]. Available: http://www.iiasa.ac.at/bewhere.

[38] Leduc S, Lundgren J, Franklin O, Dotzauer E. Location of a biomass based methanol production plant: a dynamic problem in northern Sweden. *Appl Energy* Jan. 2010; 87(1):68–75. https://doi.org/10.1016/j.apenergy.2009.02.009.

[39] Leduc S, Schwab D, Dotzauer E, Schmid E, Obersteiner M. Optimal location of wood gasification plants for methanol production with heat recovery. *Int J Energy Res*, 2008;32(12):1080–91. https://doi.org/10.1002/er.1446.

[40] Harahap F, Nurdiawati A, Conti D, Leduc S, Urban F. Renewable marine fuel production for decarbonised maritime shipping: pathways, policy measures and transition dynamics. *J Clean Prod*, Aug. 2023;415:137906. https://doi.org/10.1016/j.jclepro.2023.137906.

[41] Mesfun S, et al. Power-to-gas and power-to-liquid for managing renewable electricity intermittency in the Alpine Region. *Renew Energy* Jul. 2017;107:361–72. https://doi.org/10.1016/j.renene.2017.02.020.

[42] Mohd Idris MN, Hashim H, Leduc S, Yowargana P, Kraxner F, Woon KS. Deploying bioenergy for decarbonizing Malaysian energy sectors and alleviating renewable energy poverty. Energy 2021;232:1209672021, doi: 10.1016/j.energy.2021.120967.

[43] García-Velásquez C, Leduc S, van der Meer Y. Design of biobased supply chains on a life cycle basis: a bi-objective optimization model and a case study of biobased polyethylene terephthalate (PET). *Sustain Prod Consum*, Mar. 2022;30:706–19. https://doi.org/10.1016/j.spc.2022.01.003.

[44] Mandova H, et al. Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. *J Clean Prod*, May 2019;218:118–29. https://doi.org/10.1016/j.jclepro.2019.01.247.

[45] Daniel T, Masini A, Milne C, Nourshagh N, Iranpour C, Xuan J. Techno-economic analysis of direct air carbon capture with CO2 utilisation. *Carbon Capture Sci Technol*, Mar. 2022;2:100025. https://doi.org/10.1016/j.ccst.2021.100025.

[46] Keith DW, Holmes G, St. Angelo D, Heidel K. A process for capturing CO2 from the atmosphere. Joule, 2018; 2(8): 1635, doi: 10.1016/j.joule.2018.06.010.

[47] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO2 direct air capture plants. *J Clean Prod*, Jul. 2019;224:957–80. https://doi.org/10.1016/j.jclepro.2019.03.086.

[48] IEA. "Direct Air Capture - Energy System," IEA. Accessed: Jun. 21, 2024. [Online]. Available: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture.

[49] National Academies of Sciences, Engineering, and Medicine. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda | The National Academies Press. Accessed: Jun. 21, 2024. [Online]. Available: https://doi.org/10.17226/25259.

[50] Young J et al. The cost of direct air capture and storage: the impact of technological learning, regional diversity, and policy. *ChemRxiv*. doi: 10.26434/chemrxiv-2022-dp36t-v2.

[51] Becattini V, Gabrielli P, Mazzotti M. Role of carbon capture, storage, and utilization to enable a Net-Zero-CO2-emissions aviation sector. *Ind Eng Chem Res*, May 2021;60(18):6848–62. https://doi.org/10.1021/acs.iecr.0c05392.

[52] An K, Li K, Yang C-M, Brechtl J, Nawaz K. A comprehensive review on regeneration strategies for direct air capture. J CO2 Util 2023;76:102587, doi: 10.1016/j.jcou.2023.102587.

[53] Zero Emissions Platform. The Costs of CO2 Transport, Transport and Storage," 2011. [Online]. Available: https://www.globalccsinstitute.com/archive/hub/publications/17011/costs-co2-capture-transport-and-storage.pdf.

[54] Rubin ES, et al. A proposed methodology for CO2 capture and storage cost estimates. *Int J Greenh Gas Control* Sep. 2013;17:488–503. https://doi.org/10.1016/j.ijggc.2013.06.004.

[55] Cauchois G. Re-Stream - Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe – Executive Summary," 2021. [Online]. Available: https://iogpeurope.org/wp-content/uploads/2021/10/Re-stream-Executive-summary-October-2021.pdf.

[56] Brownsort PA, Scott V, Haszeldine RS. Reducing costs of carbon capture and storage by shared reuse of existing pipeline—Case study of a CO2 capture cluster for industry and power in Scotland. *Int J Greenh Gas Control* Sep. 2016;52:130–8. https://doi.org/10.1016/j.ijggc.2016.06.004.

[57] Wang Y, et al. The multi-scenario projection of cost reduction in hydrogen production by proton exchange membrane (PEM) water electrolysis in the near future (2020–2060) of China. *Fuel* Dec. 2023;354:129409. https://doi.org/10.1016/j.fuel.2023.129409.

[58] Phadke A, Bennett JLD, Popovich N, Paliwal U. Inflation reduction act incentives increase cost-competitiveness of lower-footprint clean hydrogen-based sustainable aviation fuel; 2024. doi: 10.21203/rs.3.rs-4530317/v1.

[59] Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China_News_福建省人民政府门户网站." Accessed: Jul. 29, 2024. [Online]. Available: https://www.fujian.gov.cn/english/news/202108/t20210809_5665713.htm.

[60] IRENA. REmap 2030: A Renewable Energy Roadmap," IRENA, 2014. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Nov/IRENA_REmap_China_summary_2014_EN.pdf?la=en&hash=20CE156A1ADA8CD0EFE142C2437FADBB0FED480C#:~:

text=Under%20current%20policies%20and%20investment,of%20modern%20renewables%20to%2026%25.

[61] China Statistics Press. China Statistical Yearbook, National Bureau of Statistics of China. Accessed: Nov. 27, 2024. [Online]. Available: https://www.stats.gov.cn/sj/ndsj/2023/indexeh.htm.

[62] Gaillot T, Beauchet S, Lorne D, Krim L. The impact of fossil jet fuel emissions at altitude on climate change: a life cycle assessment study of a long-haul flight at different time horizons. *Atmos Environ*, Oct. 2023;311:119983. https://doi.org/10.1016/j.atmosenv.2023.119983.

[63] Bui M, et al. Carbon capture and storage (CCS): the way forward. *Energy Environ Sci* May 2018;11(5):1062–176. https://doi.org/10.1039/C7EE02342A.

[64] Voigt C, et al. Cleaner burning aviation fuels can reduce contrail cloudiness. *Commun Earth Environ*, Jun. 2021;2(1):1–10. https://doi.org/10.1038/s43247-021-00174-y.

[65] Ozkan M et al. Forging a sustainable sky: unveiling the pillars of aviation e-fuel production for carbon emission circularity. iScience 2024;27(3):109154. doi: 10.1016/j.isci.2024.109154.

[66] Martin J, Dimanchev E, Neumann A. Carbon abatement costs for renewable fuels in hard-to-abate transport sectors. *Adv Appl Energy* Dec. 2023;12:100156. https://doi.org/10.1016/j.adapen.2023.100156.

[67] Bonesso F, D'Adamo I, Gastaldi M, Giannini M. Green hydrogen as a sustainable operations strategy: A socio-economic perspective. *Sustain Oper Comput*, Jan. 2025; 6:1–14. https://doi.org/10.1016/j.susoc.2024.11.002.

[68] "Jet Fuel Price Monitor, IATA." Accessed: Feb. 19, 2024. [Online]. Available: https://www.iata.org/en/publications/economics/fuel-monitor/.

[69] Greve P et al. Global assessment of water challenges under uncertainty in water scarcity projections. Nat. Sustain 2018;1(9), Art. no. 9. doi: 10.1038/s41893-018-0134-9.

[70] China Usage Price: 36 City Avg: Tap Water: Industrial Use | Economic Indicators | CEIC. Accessed: Feb. 19, 2024. [Online]. Available: https://www.ceicdata.com/en/china/price-monitoring-center-ndrc-36-city-monthly-avg-transaction-price-production-material/cn-usage-price-36-city-avg-tap-water-industrial-use.

[71] Gong S, Wang H, Zhu Z, Bai Q, Wang C. Comprehensive Utilization of Seawater in China: a Description of the present situation, restrictive factors and potential countermeasures. Water 2019;11(2), Art. no. 2, doi: 10.3390/w11020397.

[72] Xiang X, Liu X. Research on the economic and environmental impacts of China's seawater desalination industry with different technologies in the macroeconomic system. *Desalination* Jul. 2022;533:115734. https://doi.org/10.1016/j.desal.2022.115734.

[73] IEA, Tracking Clean Energy Innovation: Focus on China – Analysis, IEA. Accessed: Jun. 21, 2024. [Online]. Available: https://www.iea.org/reports/tracking-clean-energy-innovation-focus-on-china.

[74] IEA, World Energy Statistics and Balances - Data product, IEA. Accessed: Jun. 21, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances.

[75] Ma L, Wang Q, Shi D, Shao Q. Spatiotemporal patterns and determinants of renewable energy innovation: evidence from a province-level analysis in China. *Humanit Soc Sci Commun*, Jun. 2023;10(1):1–14. https://doi.org/10.1057/s41599-023-01848-y.

[76] Global Energy Monitor, Global Energy Monitor. Accessed: Jun. 21, 2024. [Online]. Available: https://globalenergymonitor.org/projects/.

[77] Ji L, et al. Solar photovoltaics can help China fulfill a net-zero electricity system by 2050 even facing climate change risks. *Resour Conserv Recycl*, Nov. 2022;186: 106596. https://doi.org/10.1016/j.resconrec.2022.106596.

[78] Grid Connected Wind Power in China: Renewable Energy in China, 2004, Accessed: Jun. 21, 2024. [Online]. Available: https://research-hub.nrel.gov/en/publications/grid-connected-wind-power-in-china-renewable-energy-in-china.

[79] Guo X, Chen X, Chen X, Sherman P, Wen J, McElroy M. Grid integration feasibility and investment planning of offshore wind power under carbon-neutral transition in China. *Nat Commun*, Apr. 2023;14(1):2447. https://doi.org/10.1038/s41467-023-37536-3.

[80] IEA. Cumulative renewable electricity capacity in the main and accelerated cases and Net Zero Scenario. IEA. Accessed: Jun. 21, 2024. [Online]. Available: https://www.iea.org/energy-system/renewables/hydroelectricity.

[81] Deng N, Wang B, He L, Liu J, Wang Z. Does electricity price reduction bring a sustainable development of business: evidence from fine-grained industrial electricity consumption data in China. *J Environ Manage*, Jun. 2023;335:117522. https://doi.org/10.1016/j.jenvman.2023.117522.

[82] Civil Aviation Administration of China. Accessed: Feb. 19, 2024. [Online]. Available: https://www.caac.gov.cn/English/.

[83] Statistical Bulletin of Civil Aviation Industry Development. China Civ. Aviat. Annu. Rep. 2022, vol. 2022, 2022, [Online]. Available: http://www.caac.gov.cn/English/Research/Reports/Statistical/202312/P020231225495691527532.pdf.

[84] Statista S. China: number of air passengers 2022. Statista. Accessed: Jul. 24, 2024. [Online]. Available: https://www.statista.com/statistics/275907/number-of-air-passengers-in-china/.

[85] Staab H, Dickinson A. Producing green hydrogen from wind and solar energy: case study. Nat Power 2023, [Online]. Available: https://www.naturalpower.com/uk/knowledge-centre.

[86] IEA. Electrolysers - Energy System. IEA. Accessed: Jun. 21, 2024. [Online]. Available: https://www.iea.org/energy-system/low-emission-fuels/electrolysers.

[87] IRENA. Green hydrogen for sustainable industrial development: A policy toolkit for developing countries. Accessed: Jun. 22, 2024. [Online]. Available: https://www.irena.org/Publications/2024/Feb/Green-hydrogen-for-sustainable-industrial-development-A-policy-toolkit-for-developing-countries.

[88] World Economic Forum & McKinsey & Company. Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation," World Economic Forum. Accessed: Jun. 21, 2024. [Online]. Available: https://www.weforum.org/publications/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation/.

[89] Liu CM, Sandhu NK, McCoy ST, Bergerson JA. A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer–Tropsch fuel production. Sustain Energy Fuels Jun. 2020;4(6):3129–42. https://doi.org/10.1039/C9SE00479C.

[90] Jing L, et al. Understanding variability in petroleum jet fuel life cycle greenhouse gas emissions to inform aviation decarbonization. *Nat Commun*, Dec. 2022;13(1): 7853. https://doi.org/10.1038/s41467-022-35392-1.

[91] Newborough M, Cooley G. Green hydrogen: water use implications and opportunities. *Fuel Cells Bull*, Dec. 2021;2021(12):12–5. https://doi.org/10.1016/S1464-2859(21)00658-1.

[92] ISPT. Gigawatt green hydrogen plant - State-of-the-art design and total installed capital costs. ISPT, 2020, [Online]. Available: https://ispt.eu/media/ISPT-public-report-gigawatt-green-hydrogen-plant.pdf.

[93] Li M, Irtem E, Iglesias van Montfort H-P, Abdinejad M, Burdyny T. Energy comparison of sequential and integrated CO2 capture and electrochemical conversion. *Nat Commun*, Sep. 2022;13(1):5398. https://doi.org/10.1038/s41467-022-33145-8.

[94] Tremel A, Wasserscheid P, Baldauf M, Hammer T. Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis. *Int J Hydrog Energy* Sep. 2015;40(35):11457–64. https://doi.org/10.1016/j.ijhydene.2015.01.097.

[95] van Essen HP, Croezen HJ, Nielsen JB. Emissions of pipeline transport compared with those of competing modes: environment analysis of ethylene and propylene transport within the EU. CE, Delft; 2003.

[96] Meron N, Blass V, Garb Y, Kahane Y, Thoma G. Why going beyond standard LCI databases is important: lessons from a meta-analysis of potable water supply system LCAs. *Int J Life Cycle Assess*, Aug. 2016;21(8):1134–47. https://doi.org/10.1007/s11367-016-1096-7.

[97] Pavlenko N, Searle S. Assessing the sustainability implications of alternative aviation fuels. Int Counc CLEAN Transp., 2021, [Online]. Available: https://theicct.org/sites/default/files/publications/Alt-aviation-fuel-sustainability-mar2021.pdf.

[98] Zhou Y, Tol RSJ. Evaluating the costs of desalination and water transport. Water Resour Res 2005;41(3). doi: 10.1029/2004WR003749.

[99] Green KP, Jackson T. Safety in the Transportation of Oil and Gas: Pipelines or Rail?; 2015.