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Current and future cost of e-kerosene in the United States and Europe

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Introduction

Power-to-liquids (PtL), also known as e-fuels, are getting increased attention, especially in the aviation sector, due to their potential to decarbonize the sector without investments in new fueling infrastructure and engines. PtL are produced by combining carbon dioxide (CO_2) and hydrogen derived from water electrolysis, through chemical reactions, such as Fischer-Tropsch (FT) synthesis. The product of FT synthesis is a mixture of hydrocarbons that can be used in transportation. Outputs include diesel (noted as FT-diesel), jet fuel (noted as e-kerosene), and other hydrocarbons such as propane and naphtha. An overview of the PtL production scheme and product distribution is shown in Figure 1.

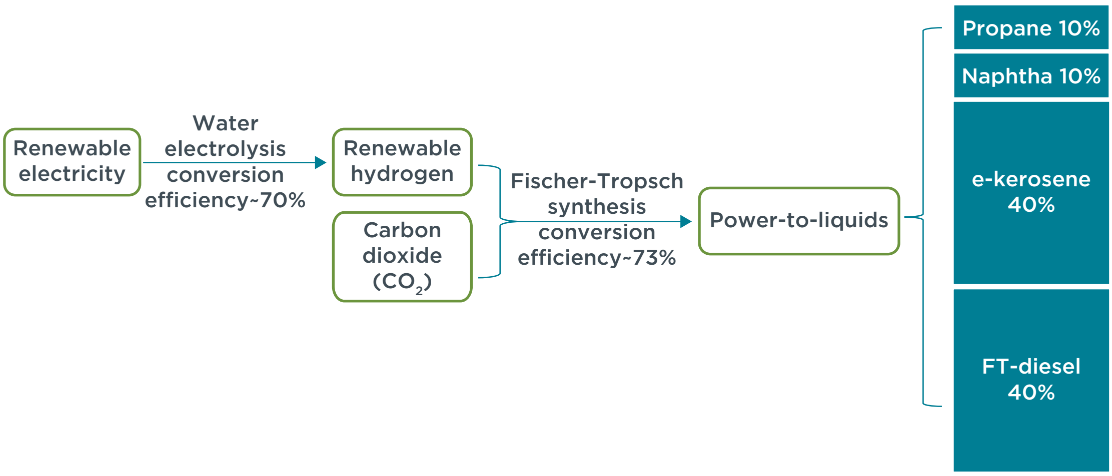

Figure 1. An overview of a power-to-liquids production scheme and product distribution by energy percentage

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As alternative fuels, one main advantage of PtL is that the fuel conversion process generates drop-in fuels compatible with conventional fueling infrastructure and combustion engines. When renewable electricity is used to electrolyze water, PtL could have close-to-zero greenhouse gas (GHG) emissions (Argonne National Laboratory, 2020). However, low GHG emissions can only be reached if the renewable electricity was generated additionally, rather than displacing existing uses. Otherwise, any leakage of fossil electricity for PtL production would not fulfill the decarbonization purpose as intended (Searle & Zhou, 2021). Moreover, given the fact that PtL is a very inefficient process, indicated by the conversion efficiency in Figure 1, displacement of renewable energy in PtL production would lead to significant adverse climate impacts. Previous studies have suggested robust regulations are required to ensure the additionality of renewable electricity; for example, combining renewable electricity certificates and long-term electricity purchase contracts with certificates showing that the renewable electricity used for PtL is not incentivized by other policies (Timpe et al., 2017; Malins, 2019).

CO_2 used in PtL production can be supplied from two types of sources. One is a point source, usually from an industrial plant that emits a large quantity of concentrated CO_2 emissions, such as a steel plant. An alternative source is atmospheric CO_2, which can be sequestered using an emerging technology known as direct air capture (DAC). From either source, the same technique is used to capture the CO_2; the main difference is the starting concentration of the CO_2.

E-kerosene, part of the PtL product slate, is a type of sustainable aviation fuel (SAF). In addition to e-kerosene, biofuels such as hydroprocessed esters and fatty acids (HEFA) produced from waste oils, also count as SAFs. The International Civil Aviation Organization (ICAO) has proposed SAFs as a key measure to achieve GHG emission reduction in aviation (International Civil Aviation Organization, 2021). Echoing this position, several government bodies have provided support for SAFs, especially e-kerosene, in recent years. The European Commission has recently proposed a 5% SAF mandate (as a share of aviation fuels), with a sub-target of 0.7% e-kerosene, for aviation fuel consumed in the EU, by 2030. The proposed SAF target increases to 63%, with a minimum of 28% e-kerosene by 2050 (European Commission, 2021).

Germany took a step in this direction in 2021 when it set an e-kerosene target of 0.5% of fuel used in aviation by 2026, increasing to 2% by 2030 (Appunn, 2021; Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2021). To facilitate meeting the target, the German federal and state government and industry agreed on a roadmap to scale up e-kerosene production (Federal Ministry for Digital and Transport, 2021). Unlike the EU, which mostly supports e-kerosene with volumetric mandates, the United States (U.S.) has provided financial support for its production. In California, e-kerosene producers are eligible to receive credits under the state's Low Carbon Fuel Standard (LCFS) program (California Air Resources Board, 2020).

Not only are policies being developed to support e-kerosene, the aviation industry has also included e-kerosene in its decarbonization roadmaps and has begun to produce e-kerosene. The Waypoint 2050 report, published by the Air Transport Action Group, an industry trade group, asserts that SAFs will account for 65% of aviation carbon reductions by 2050, with e-kerosene providing half of all SAF by volume by mid-century (Air Transport Action Group, 2021). According to the Destination 2050 report put out by five European air industry associations, in Europe SAF will be responsible for approximately one-third of carbon reductions by 2050, with 60% of drop-in alternative fuel supply being e-kerosene (Royal Netherlands Aerospace Centre & SEO Amsterdam Economics, 2021). Moreover, in 2021, Germany opened the world's first e-kerosene production plant powered by wind electricity (Muller & King, 2021). In the same year, the German airline Lufthansa announced that it plans to purchase at least 25 thousand liters of e-kerosene annually in the next five years (Lufthansa Group, 2021). Boom Supersonic, a U.S.-based company that builds supersonic airliners, plans to use e-kerosene produced from renewable electricity combined with DAC (Boom Supersonic, 2019). And Airbus is partnering with a Canadian SAF company aiming for commercial-scale e-kerosene in North America by 2025 (Airbus, 2021).

Nevertheless, unlike other SAFs that are relatively mature, PtL is an emerging market and scaling e-kerosene faces multiple challenges. First, as indicated in Figure 1, turning electricity into hydrogen, then into e-kerosene, is highly inefficient—about half of the energy is lost, which raises the question of whether to use these valuable resources (electricity and hydrogen) directly as fuels rather than wasting the energy in fuel conversion losses (Searle, 2020). Second, cost is a major barrier. Previous studies have shown a huge variation in the estimated cost of e-kerosene production due to different assumptions regarding electricity and CO_2 sources and prices (Agora Verkehrswende et al., 2018; Schmidt et al., 2018; Terwel & Kerkhoven, 2018; Lehmann, 2019; Raab & Dietrich, 2019; Siegemund, 2019; Ash et al., 2020; Becattini et al., 2021; ETH Zurich, 2021; Isaacs et al., 2021). Nevertheless, electrolysis hydrogen itself is expensive (Christensen, 2020); taking the extra step to make PtL will add extra costs. Mukhopadhaya & Rutherford (2022) concluded that, due to the additional costs of converting green hydrogen to e-kerosene, fuel costs for hydrogen-powered aircraft could be lower than for conventional aircraft operated on PtL-fueled conventional aircraft starting in 2035. In addition, Rutherford et al. (2022) concluded that the high cost of e-kerosene makes it unlikely to be viable as a fuel for supersonic aircraft.

The purpose of this study is to understand, from an economic perspective, the potential role of e-kerosene in decarbonizing the aviation sector. We estimate the cost of producing e-kerosene in the United States and the EU from 2020 to 2050. We consider renewable electricity as the energy source for e-kerosene production and assume CO_2 is provided from a point source. We then discuss the cost competitiveness of e-kerosene compared to other aviation fuels as well as the amount of policy support needed.

Methodology

In this study, we estimate the production cost of PtL using a discounted cash flow (DCF) model, following the methodology in previous ICCT studies (Christensen & Petrenko, 2017; Christensen, 2020). This DCF model calculates the levelized cost for an investment to be economically viable and to reach a target rate of return. The main components of a DCF model include the upfront capital investment, the annual operational costs, and revenues from product sales. In addition to these cost components, financial assumptions regarding debt and equity are also crucial in a DCF model as they determine the return required for the process to be economically viable. We estimate the levelized PtL production costs in 356 regions in the United States and the 27 countries of the EU. The lower geographic resolution applied in the case of the EU is due to lack of information. Because of uncertainty regarding where PtL will be produced, we take the arithmetic average of estimated cost across regions or countries to represent the United States or the EU. The timeframe for cost estimates is between 2020 and 2050. As shown in Figure 1, PtL produced through FT synthesis consists of a mixture of fuels and chemicals; we allocate the modeled PtL cost to each product, including e-kerosene. All cost figures in this study are given in 2020 units of the appropriate currency.

Levelized production cost

Estimating the cost of PtL requires analysis of three key processes: renewable electricity generation, water electrolysis, and FT synthesis. In this study, we combine two sets of DCF analyses, one to estimate the levelized cost of renewable electricity (RE_{cost}) and the other for PtL (PtL_{cost}) that covers water electrolysis and FT synthesis. The results from RE_{cost} serve as inputs to the PtL_{cost}. CO_2 price is also an important input to the PtL_{cost}; however, we do not make our own estimate of CO_2 price in this study, but collect it from previous studies.

Renewable electricity cost

The capacity factor—the fraction of a year a power plant can operate—is a key parameter in calculating RE_{cost}. In the case of renewable power plant, the capacity factor is largely dependent on local solar and wind resources, i.e., how often it is windy or sunny enough to generate electricity. Following the methodology in Christensen (2020) and Zhou and Searle (2022), we collect solar and wind capacity factors of 356 U.S. regions from NREL (2021) and 27 European countries from Joint Research Centre (2018), amended by personal communication (2020). Plant capacity is another input that has a significant impact on renewable electricity cost—larger capacity leads to lower levelized costs due to economies of scale. In this study, we assume the installed capacity of renewable electricity plant to be 100 megawatts (MW), which is representative of a utility-scale power plant, in contrast to the 1MW figure assumed in Christensen (2020).

We use the capital and operational costs of solar and wind power plants from NREL (2021) and assume the same costs across all regions and countries. To project future renewable electricity prices, we follow the cost reduction rate and capacity factor improvement rate from NREL (2021). While we model both solar and wind electricity costs, we expect the cheaper technology to be used. Therefore, the renewable electricity cost of each modeled region or country that feeds into PtL_{cost} is the minimum between solar and wind electricity for that region or country.

The PtL facility could connect directly to a renewable electricity generator, or it could utilize renewable electricity delivered over the electricity grid. In this study, we consider both options. In the former case, the levelized cost of renewable electricity (LCOE) calculated from the RE_{cost} serves as the electricity cost for PtL production. However, in the case of grid connection, we need to add the grid and associated taxes and fees to our modeled LCOE to account for electricity transmission and distribution (T&D) cost. We collect U.S. and EU T&D costs from the Energy Information Administration (EIA, 2020) and Searle & Christensen (2018), respectively. We assume that in the case of grid-connection, the PtL facility financially supports a new, additional renewable electricity generator, for example through a Power Purchase Agreement, but does not temporally match its production to that of the renewable electricity generator. While lack of temporal matching will likely cause an indirect increase in use of other electricity generators (i.e., when the contracted renewable electricity generator is not operating), we have previously found this effect to be small (Christensen & Petrenko, 2017). Importantly, the capacity factor of the PtL facility depends on the scenario; if directly connected to a renewable electricity generation, the PtL facility capacity factor matches the renewable electricity generator; however, if using grid electricity, the PtL facility capacity factor could run almost full time. Thus, the benefit of direct connection is lower renewable electricity costs, while the benefit of grid connection is a higher facility capacity factor, which reduces the levelized cost of capital expenses per unit of PtL produced. Which option is cheaper depends on the specific renewable capacity factor and grid fees in each region or country. While we model both direct connection and grid connection, we assume the cheaper option in each region or country would be used.

PtL production cost

In PtL_{cost}, we consider capital and operational costs of both water electrolysis and FT synthesis units. We present key assumptions for PtL_{cost} in Table 1. In this study, we assume use of a big, central PtL production plant with an annual installed capacity of 400 $MW_{input\ power.}$[1] The actual production output is determined by the capacity factor. As mentioned above, in the case of direct connection, the PtL capacity factor would be restricted by the capacity factor of the power generator. In the case of grid connection,

1 In our economic model, the assumed PtL plant capacity in PtL_{cost} is irrelevant to the assumed renewable electricity capacity in RE_{cost}. The RE capacity assumption is simply used to estimate the levelized cost of renewable electricity (LCOE) in each modeled region or country. This estimated LCOE represents the market price of RE that the PtL producers need to pay for.

we assume a capacity factor of 95% to account for potential electricity distribution losses and facility downtime.

Table 1. Assumptions of power-to-liquids production parameters

Input parameter	Data assumption		
Installed capacity	400 $MW_{input\ power}$		
Capacity factor	Grid connection: 95%	Direct connection: same as renewable generator	
Contingency factor	1.2		
	Alkaline electrolyzer	Proton exchange membrane	Solid oxide electrolyzer
Electrolyzer system capital cost in 2020 (2020 USD/$kW_{input\ power}$)	988	1,182	1,346
Electrolyzer system capital cost reduction in the future	2% annually		
Electrolyzer efficiency in 2020	70%	60%	81%
Electrolyzer efficiency in 2050	80%	74%	90%
Electrolyzer lifetime in 2020 (hours)	75,000	60,000	20,000
Electrolyzer lifetime in 2050 (hours)	125,000	125,000	87,500
Fischer-Tropsch capital cost	450 USD per kW_{fuel}		
Fischer-Tropsch efficiency	73%		
Fixed annual operational cost	4% of system capital cost		
Renewable electricity price	Own model—see Appendix		
Water price	Country-specific		
Carbon dioxide price	40 USD per tonne CO_2		
Oxygen wholesale price	0.15 USD per m^3 oxygen		

The capital cost of a PtL plant includes upfront investment in equipment for both electrolysis and FT synthesis. In addition, we apply a contingency factor of 1.2 to the total capital cost to account for other unforeseeable upfront expenses, such as project design (Christensen, 2020). For water electrolysis, we use the same assumptions of capital costs and cost reduction projection, electrolyzer efficiency and efficiency improvement projection, and electrolyzer lifetime and lifetime improvement projection in Christensen (2020). Electrolyzer lifetime determines the frequency, and thus the cost, of electrolyzer replacement. While that study provides three scenarios regarding how electrolysis cost changes in the future—pessimistic, mid-level, or optimistic—we use only the mid-level scenario in this study. We model three types of electrolyzers, but we expect the cheapest technology to be used.

FT synthesis capital cost is subject to economies of scale and thus impacted by plant capacity (Brynolf et al., 2018). We collect the FT capital costs of similarly sized plants of 400 $MW_{input\ power}$ as well as fuel conversion efficiencies from Brynolf et al. (2018). Unlike water electrolysis, we assume that future FT cost and efficiency remain at current levels since this technology is relatively mature. We assume the same electrolysis and FT synthesis costs across U.S. regions and EU countries.

Annual operational cost (OPEX) is usually divided into two subcategories: fixed OPEX and variable OPEX. Fixed OPEX includes plant maintenance costs and labor costs. We assume the annual fixed OPEX to be 4% of the total capital cost, including both water electrolysis and FT synthesis. Variable OPEX is a function of the actual PtL production amount each year. The costs of input feedstock and materials of electricity, water, and

CO_2 all contribute to variable OPEX. Oxygen is a by-product of the water electrolysis used to produce hydrogen for PtL production and can be sold for revenue. Therefore, we assume the PtL plants sell oxygen along with PtL hydrocarbons to bring in additional revenue. We use the same country-specific water price and oxygen wholesale price from (Christensen, 2020 and Zhou and Searle, 2022).

As mentioned in the Introduction, CO_2 could be supplied from a point source or using DAC. DAC is more expensive than point-source capture, and has large uncertainties regarding costs. DAC also requires more energy than capturing CO_2 from a point source because the latter provides a much more concentrated source of CO_2. Therefore, in this study, we estimate PtL costs using only point source CO_2 at a price of $40 per tonne (Christensen & Petrenko, 2017; Terwel & Kerkhoven, 2018), compared to estimates of $100 to $700 per tonne CO_2 using DAC (Keith et al., 2018; Becattini et al., 2021). This approach may underestimate the cost of PtL under deep decarbonization scenarios where point sources of CO_2 become scarce in 2050; on the other hand, it is very unclear what level of cost reductions we may expect for DAC within that timeframe.

In sum, the modeled PtL cost is an optimistic one, taking into account the cheapest renewable electricity source between solar and wind in region and year, the cheapest water electrolysis among three electrolyzer types, and the cheaper electricity connection mode. The regional variation of PtL cost is a combined result of the modeled region/country-specific renewable electricity price, the capacity factor if directly connected, and country-specific water price. The projected reductions in future PtL costs are a combined result of mid-level forecasts in renewable electricity price reduction, capacity factor improvement in the case of direct connection, and ongoing cost reductions, efficiency improvements, and increases in the lifespan (i.e., reduced cost of electrolyzer replacement) of water electrolysis equipment.

PtL cost allocation

The modeled cost of PtL production reflects the sum of four products: FT-diesel, e-kerosene, naphtha, and propane, as shown in Figure 1. To estimate e-kerosene cost, we allocate the result from PtL_{cost} to each of the four products on an energy basis. The calculated e-kerosene production cost in this study can be treated as the wholesale price that excludes delivery and fueling costs, and taxes. We also do not consider any external financial incentives or policies in this estimated production cost.

During FT synthesis, the PtL plant can adjust the chemical reaction conditions, such as temperature, to optimize the production of certain products. For this analysis, we assume that the bio-refinery will attempt to maximize the quantity of jet fuel in the product slate. To develop a realistic assumption regarding product distribution, we take the average of product slates that maximize e-kerosene production from previous studies (Swanson et al., 2010; (S&T) 2 Consultants Inc., 2018; Argonne National Laboratory, 2020; Prussi et al., 2020). The production distribution assumed in this study is thus 40% each of e-kerosene and FT-diesel, and 10% each of naphtha and propane, on an energy basis, shown in Figure 1.

We collect the wholesale prices of naphtha and propane in 2020 from (Trading Economics, 2021; U.S. Energy Information Administration, 2021a), which could represent the production cost of naphtha and propane. We expect the prices of naphtha and propane to increase and assume both prices in 2050 to be 1.5 times their 2020 values; we assume a linear increase for the years in between. We convert the collected and projected naphtha and propane prices into 2020 USD per megajoule (MJ), based on their lower heating values. We then subtract naphtha and propane wholesale prices from the modeled PtL production cost, weighted by the corresponding production distribution, to estimate the production cost of e-kerosene and FT-diesel. Since we assume the same share of e-kerosene and FT-diesel, they would have the same production cost on an energy basis. However, given that FT-diesel is more energy dense, it has a higher value than e-kerosene on a weight or volume basis.

Results and Discussion

In this section, we present our modeled average e-kerosene production cost (i.e., the wholesale price) in the United States and the EU and discuss the implications of these results. Specifically, we compare our cost estimates with previous studies to understand the consistency and variations among studies. We also compare the cost of e-kerosene with other aviation fuels to understand the cost competitiveness of e-kerosene. While in this section we only present the average cost estimates in the United States or EU, we present the minimum and maximum costs among all modeled regions in the Appendix. Intermediate modeling results include renewable electricity, hydrogen, and FT-diesel costs, but we show these estimated costs in the Appendix. We also present the cost implications from grid connection and direct connection modes in the Appendix.

In Figure 2, we present the estimated e-kerosene production cost from our DCF model and how these results compare to other studies. We estimate the average e-kerosene production cost in the United States to be $8.80 per gallon (€2 per liter) in 2020 and we project it to decrease by half to $4 per gallon (€0.9 per liter) in 2050.[2] The average e-kerosene price in the EU is higher than in the United States by about 45%, as a result of a higher renewable electricity price in the EU, indicated by Table A1 in the Appendix.

We collect e-kerosene production cost estimates for the years of 2020, 2030, and 2050 from 10 U.S.- or EU-based studies and summarize the maximum and minimum costs for each corresponding year from those studies in Figure 2. As shown, there is a huge variation in e-kerosene cost among studies; the highest cost estimate can be triple the lowest one.

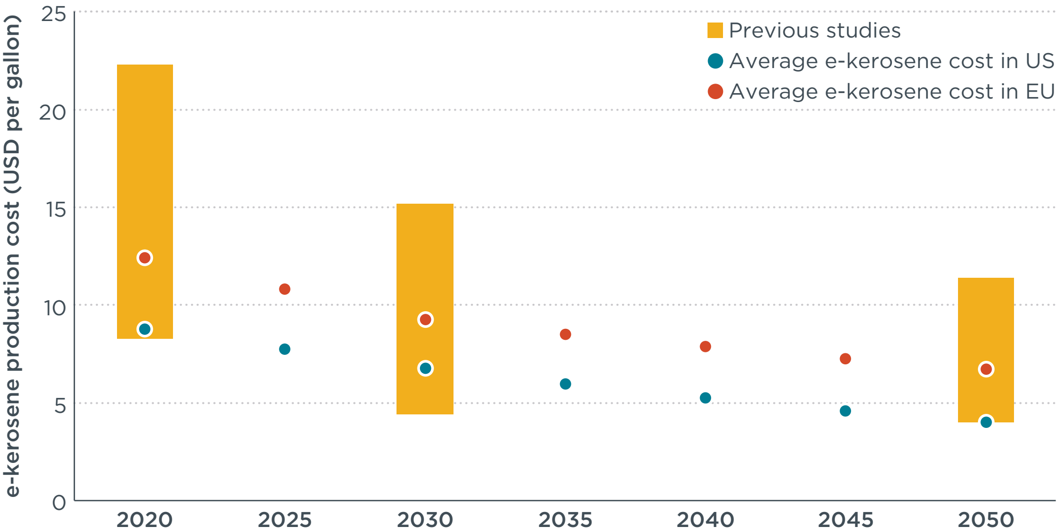

Figure 2. Estimated average e-kerosene production cost in the United States and the EU, compared to previous studies

Sources: (Agora Verkehrswende et al., 2018; Schmidt et al., 2018; Terwel & Kerkhoven, 2018; Lehmann, 2019; Raab & Dietrich, 2019; Siegemund, 2019; Ash et al., 2020; Becattini et al., 2021; ETH Zurich, 2021; Isaacs et al., 2021)

Any differences in underlying model assumptions would contribute to the varying results. Here, we highlight two main contributing parameters, electricity price and CO_2 price. In terms of electricity, some studies considered the use of grid electricity, while others considered just LCOE of renewable electricity–the former being more expensive

2 We assume an exchange rate of 0.85 Euro to 1 USD in this study.

due to T&D costs. As mentioned in the Methodology section, CO_2 captured from a point source is significantly cheaper than DAC. However, even among the studies that fully assume DAC, there is a huge variation in CO_2 price.

Taking the year 2020 as an example (Figure 2), the lowest e-kerosene production cost of $8.30 per gallon from previous studies is taken from an analysis that assumed a relatively low renewable electricity price of $46 per MWh (Ash et al., 2020), compared to the high electricity price of $72 per MWh for the highest e-kerosene price of $22.30 per gallon (Becattini et al., 2021). Moreover, while both studies considered DAC as the source of CO_2, the former assumed $260 per tonne CO_2, whereas the latter assumed $690 per tonne CO_2. The combined impact of high electricity and CO_2 prices resulted in the significantly higher e-kerosene production cost. While it is hard to make apple-to-apple comparisons due to the different model assumptions across studies, our e-kerosene cost estimates are within the study range. Particularly, the U.S. costs are toward the lower end of the ranges because of relatively low renewable electricity prices in the United States and point source CO_2. Our estimated EU costs are in the middle of the ranges.

Comparing the cost of e-kerosene with conventional jet fuel and other SAFs can help policymakers and the industry better understand the potential role of e-kerosene. In Figure 3, we show our estimated average e-kerosene production cost on an energy basis in the United States and EU as blue bars and orange bars respectively (detailed numbers can be found in Table A5 in the Appendix). For comparison, we show the wholesale prices of HEFA as green bars and Jet A fuel, i.e., fossil kerosene, as grey bars. We collect the Jet A price of all years from U.S. Energy Information Administration (2021b). A previous ICCT study estimated the production cost of HEFA produced from four different feedstocks of vegetable oil or waste oil (Pavlenko et al., 2019). We choose used cooking oil as the feedstock to represent HEFA price in Figure 3, because of its better climate performance and lower feedstock cost compared to vegetable oils. The 2050 HEFA price reflects an assumption of lower capital costs based on Pavlenko et al. (2019) and we assume a linear decrease of HEFA price for the years between 2020 and 2050. Neither Jet A nor HEFA price differentiates between the United States and EU.

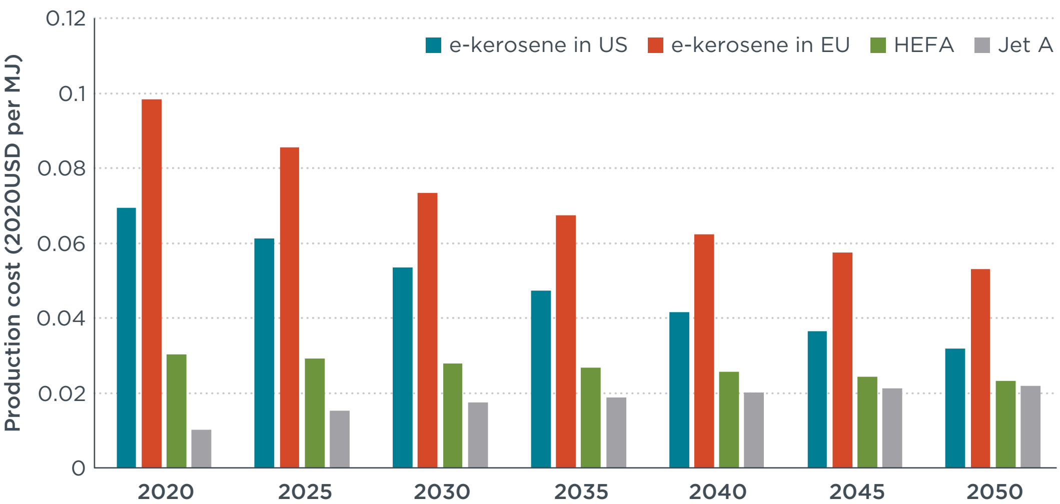

Figure 3. Estimated e-kerosene production cost in the United States and the EU, compared to hydroprocessed esters and fatty acids (HEFA) and fossil Jet A fuel

We find that e-kerosene is currently 7–10 times more expensive than Jet A fuel and 2–3 times more expensive than HEFA due to the great amount of investment needed to produce e-kerosene. While U.S. Energy Information Administration (2021b) projects Jet A price in 2050 to double, SAF prices, including both e-kerosene and HEFA, are likely to decrease as the market gets mature and technology improves. In particular, e-kerosene production costs are projected to drop substantially as the cost of renewable electricity continues to decline. However, even with this opposite price trend, e-kerosene still will not be cost competitive with Jet A or HEFA by 2050. Specifically, the U.S. average e-kerosene production cost will be 45% or 37% higher than Jet A or HEFA respectively, in 2050. The price discrepancy is even larger for e-kerosene produced in the EU. Moreover, if CO_2 from DAC were used, the price gap between e-kerosene and Jet A could grow, as the CO_2 price from DAC can be almost 20x the CO_2 price from a point source. On the other hand, while HEFA has the potential to be cost competitive in the future, its production is limited due to low levels of feedstock availability (Pavlenko et al., 2019).

Results from this study indicate that without policy support, especially financial incentives, it is unlikely that airlines will use e-kerosene now or in the future, from an economic perspective. Our results show that policy support of about $4.60 per gallon (€1 per liter) in the United States or $7 per gallon (€1.6 per liter) in the EU would be necessary in 2030 for airlines to use e-kerosene. This is equivalent to a carbon price of $400 per tonne of carbon dioxide equivalent (CO_2e) (United States) or $630 per tonne CO_2e (EU), using carbon intensities of 89 g CO_2e per MJ for Jet A and 0.44 CO_2e per MJ for renewable e-kerosene (Mukhopadhaya & Rutherford, 2022). Currently, the maximum credit of California's LCFS program is $218 per per tonne CO_2e (in 2020 dollars) (California Air Resources Board, 2022). If we assume e-kerosene producers in the United States will receive this maximum LCFS credit now and in the future, e-kerosene will be cost-competitive with Jet A fuel by around 2042, as indicated by Figure 4. Over time, the size of the needed incentive can shrink substantively. By 2050, the estimated cost differential between e-kerosene and Jet A narrows considerably, requiring a much lower subsidy of $110 per tonne CO_2e (United States) or $350 per tonne CO_2e (EU). In addition, high incentives provided in the early years can help establish an e-kerosene market and narrow the price gap even further in the long term.

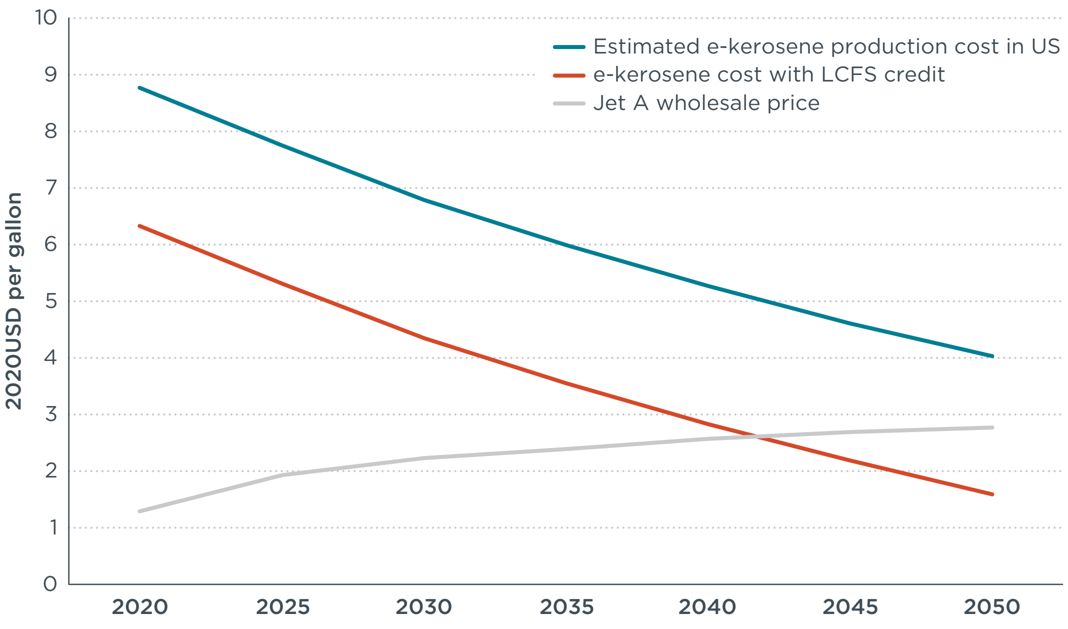

Figure 4. The impact of California's LCFS credit on the cost of e-kerosene production in the United States

Conclusions

Interest in e-kerosene as a mitigation measure to decarbonize the aviation sector is on the rise. If produced from additional renewable electricity, e-kerosene has close to zero well-to-wake greenhouse gas emissions. Another advantage of e-kerosene is that it is a drop-in fuel that is compatible with existing fuel systems and combustion engines. This means that using e-kerosene does not require investing in new fueling infrastructure or aircraft, in contrast to electricity or hydrogen.

This study evaluates the potential of e-kerosene from an economic perspective. We estimate the average e-kerosene production cost in the United States to be $8.80 per gallon (€2 per liter) in 2020, decreasing to $4 per gallon (€0.9 per liter) in 2050. We estimate the average e-kerosene production cost in the EU to be $12.40 per gallon (€2.8 per liter) in 2020, decreasing to $6.70 per gallon (€1.5 per liter) in 2050. The EU has higher e-kerosene costs due to more expensive renewable electricity.

Another parameter with a significant impact on e-kerosene cost is the source of CO_2. In general, CO_2 could be sourced in either of two ways: from a concentrated point source such as an industrial plant, or captured from the atmosphere directly (i.e., DAC). In this study, we assume CO_2 is captured from a point source, which is currently much cheaper than DAC.

Even though we are considering low CO_2 costs and the combination of technologies that gives the lowest e-kerosene cost (i.e., renewable source, electrolyzer type, and grid or direct connection mode), and despite assuming mid-level cost reductions in the future, e-kerosene cannot be cost-competitive with fossil kerosene as far out as 2050. Based on our estimates, the 2020 production cost of e-kerosene is 7x (U.S.) or 10x (EU) fossil kerosene. This price gap decreases substantively to 1.5x (U.S.) or 2.5x (EU) in 2050. Results from this study indicate that financial incentives are necessary for e-kerosene to be adopted on a large scale if it is to play a role in aviation decarbonization, especially in the near term. We estimate that a carbon price of $400 per tonne CO_2e in the United States or $630 per tonne CO_2e in the EU can make e-kerosene cost competitive in 2030, decreasing to $110 per tonne CO_2e (United States) or $350 per tonne CO_2e (EU) in 2050. High incentives in the early years can help pave the way for more and cheaper e-kerosene in the long term.

Appendix

Table A1 shows the estimated renewable electricity price in the United States and the EU. We model solar and wind price in 356 regions in the United States and 27 countries in the EU. For each region or country, we choose the lower price between solar and wind. We then take the arithmetic average across regions or countries to represent the United States or the EU, shown as the numbers in Table A1. In this study, we model both grid connection and direct connection to a renewable generator as the two possible electricity connection modes for a PtL plant. LCOE is the estimated levelized production cost of renewable electricity, which is the electricity price used in the direct connection scenario. LCOE+T&D is the electricity price used in the gird connection scenario where grid and associated electricity taxes are included.

Table A1. Estimated average renewable electricity price in the United States and the EU. LCOE is the levelized cost of electricity, used in the direct connection mode. LCOE+T&D considers electricity grid and tax fee and is used in the grid connection mode. Unit: 2020 USD per MWh.

Year	United States		European Union	
	LCOE	LCOE+T&D	LCOE	LCOE+T&D
2020	36	80	72	117
2030	28	77	51	97
2040	24	76	46	92
2050	21	72	41	88

While we model two electricity connection modes in this study, we assume that whichever enables a lower PtL cost will be used. The cost result is a trade-off between electricity price and plant capacity factor. As shown in Table A1, if the PtL is connected to the grid, it would have to pay a higher electricity price that includes a grid fee and tax. On the other hand, a grid-connected plant can benefit from running the plant for longer periods, which reduces the levelized PtL production cost. Which mode enables the lower cost is dependent on the abundance of local renewable sources and T&D cost.

Table A2 shows the percentage of 356 modeled U.S. regions and 27 EU countries that enables lower PtL production cost if grid connected. Direct connection would be more promising in the United States due to better renewable sources. In both regions, direct connection would become more and more favorable due to increasing renewable capacity factors and increasing T&D fees. Nonetheless, grid connection seems to be the only way to enable lower PtL price in most locations in the EU, especially in the near-term.

Table A2. Number and percentage of regions or countries that have lower PtL cost if grid-connected, among 356 regions in the United States and 27 EU countries

	United States	European Union
2020	158 (44%)	27 (100%)
2025	123 (35%)	26 (96%)
2030	94 (26%)	26 (96%)
2035	59 (17%)	26 (96%)
2040	47 (13%)	26 (96%)
2045	37 (10%)	25 (93%)
2050	32 (9%)	24 (89%)

Table A3 shows the estimated hydrogen production cost in the United States and Europe with a mid-level cost reduction projection. For each of the 356 regions in the United States and 27 countries in Europe, we choose the lowest hydrogen production cost from the combination of renewable source, electrolyzer type, and electricity connection type. We then take the average across the regions and countries. This cost is for hydrogen production only and does not include costs for liquefaction or compression needed for hydrogen fuels to be used in aircraft or road vehicles, respectively. Among the three types of electrolyzers, alkaline electrolyzer results in the cheapest hydrogen production cost in the short term due to its low capital cost. However, in the long term, the solid oxide electrolyzer technology will provide lower hydrogen and PtL costs due to its significantly improved conversion efficiency and lifetime.

Table A3. Estimated average hydrogen production cost in the United States and the EU. Unit: 2020 USD per kg hydrogen

Year	United States	European Union
2020	4.3	6.4
2030	3.1	4.7
2035	2.7	4.3
2040	2.3	3.9
2050	1.6	3.2

FT-diesel, as one of the PtL products, is also drop-in and can be used in internal combustion engines. Table A4 shows the FT-diesel production cost in the United States and the EU. As with e-kerosene, this cost is allocated from the modeled PtL cost based on product distribution. We show the estimated e-kerosene production cost in Table A5. Since we assume the same percentage distribution for FT-diesel and e-kerosene in the PtL product slate, they have the same production cost on an energy basis, indicated in Table A4 and Table A5. However, the two fuels would have different costs on a volumetric basis due to differences in their lower heating values.

Table A4. Estimated average FT-diesel production cost in United States and the EU

	United States		European Union	
Year	2020 USD per MJ	2020 USD per gallon	2020 USD per MJ	2020 USD per gallon
2020	0.069	9.061	0.098	12.840
2025	0.061	8.006	0.086	11.168
2030	0.054	6.999	0.073	9.585
2035	0.047	6.187	0.067	8.802
2040	0.042	5.438	0.062	8.133
2045	0.037	4.763	0.057	7.499
2050	0.032	4.155	0.053	6.939

Table A5. Estimated minimum, average, and maximum e-kerosene production costs across 356 modeled regions in the United States and 27 countries in the EU. All numbers are in 2020 dollars.

Year	United States				European Union			
	U.S. average (USD per MJ)	U.S. average (USD per gallon)	U.S. min (USD per gallon)	U.S. max (USD per gallon)	EU average (USD per MJ)	EU average (USD per gallon)	EU min (USD per gallon)	EU max (USD per gallon)
2020	0.069	8.776	6.53	11.91	0.098	12.437	8.73	16.98
2025	0.061	7.754	5.52	10.67	0.086	10.817	7.71	14.47
2030	0.054	6.779	4.70	9.39	0.073	9.284	6.23	12.87
2035	0.047	5.993	4.04	8.70	0.067	8.525	5.56	12.06
2040	0.042	5.267	3.46	8.04	0.062	7.878	4.96	11.37
2045	0.037	4.614	2.95	7.41	0.057	7.264	4.37	10.34
2050	0.032	4.025	2.50	6.78	0.053	6.721	3.85	9.33

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