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Final Report to ClimateWorks

Results from the IIASA-EDF study on

Direct Air Capture to Fuel

ADEPT - Assessing DAC Fuel Potentials

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Abstract

The aviation industry is considered one of the hardest sectors to decarbonize and will most likely continue to rely on high-energy liquid fuels in the upcoming decades due to missing viable alternatives and long use cycles of existing airplanes. Nevertheless, various concepts for the production of advanced liquid fuels for the aviation sector with very low or even zero emissions, i.e., sustainable aviation fuels (SAF), have been developed in recent years and some of these alternatives, such as biofuels, have already been implemented on a semi-industrial scale.

In addition, e-fuels produced from the synthesis of carbon dioxide (CO2) and hydrogen derived from electrolytic processes, are being increasingly discussed globally as a carbon neutral alternative for the aviation industry. Whilst benefitting from a small land footprint compared to biofuels, their production relies on capital intensive technologies, such as Direct Air capture (DAC) and electrolysis processes, and on the availability of cheap, abundant, and carbon neutral electricity. Hence, the costs and emission savings associated with their deployment need to be evaluated against the background of existing resource constraints.

In this final report of ADEPT – a 12-month collaboration between the International Institute for Applied Science Analysis (IIASA) and the Environmental Defense Fund (EDF) to estimate the potentials of aviation fuel (i.e., e-fuel) production in Europe and the U.S. via direct-air capture (DAC) – we summarize the results of our assessment of the role of e-fuels for decarbonizing the aviation sector in Europe and the US. The report puts special emphasis on the latest technologies suitable to produce e-fuels and it presents analysis on the different cost options and key drivers for the development of the DAC technologies until 2050. EDF modeled the electricity potential in North America to produce Hydrogen with renewable energies, which results have been used for the techno-economic analysis carried out by IIASA. With the input from EDF on the production cost of technologies and the renewable electricity availability in the U.S., IIASA modeled and estimated the potential of e-fuel production in Europe and the U.S. under sustainable and economic conditions.

The project findings indicate inter alia that the potentials of e-fuels for Europe and the U.S. very much depend on the availability and price of both water and electricity. Europe indicates a higher dependency on the use of desalination plants whereas for the U.S. freshwater availability – and hence cost – is less critical. Finally, the cost of e-fuel can fluctuate between 20 to 45 US$/GJ in 2050 depending on the rate of development assumed for the respective technology, which in turn is dependent on policy measures applied, such as the cost of CO2.

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1 Literature Review One: "Identify the main variables in determining DAC-fuel costs against past literature”

Direct air capture (DAC) electrofuels (e-fuels), also known as power-to-liquids or e-kerosene, are produced by synthesizing carbon dioxide (CO_2), which has been captured from the air, with hydrogen. The hydrogen is generated through the electrolysis of water, whereby water is split into hydrogen and oxygen through the use of electricity.

Electrofuels are anticipated to be a key enabling technology for the eventual decarbonization of aviation. However, predicting the costs of DAC e-fuels is difficult because the market for both DAC itself and DAC e-fuel production is still nascent. While each stage of the DAC e-fuel production has been demonstrated, no facilities are producing sustainable aviation fuel (SAF) (Malins, 2017). Therefore, to estimate DAC e-fuel costs, the key steps on the production pathway must evaluated, namely, direct air capture, electrolysis and fuel synthesis. Key cost variables include CAPEX (capital expenditures) for acquiring and building facilities and plants, as well as OPEX (operational expenditures) such as the cost for the energy needed for DAC and electrolysis.

1.1 Variables in Determining Costs for Direct Air Capture

A number of factors contribute to the cost of DAC, including the specific design of the DAC-fuel plant as well as operational and maintenance costs. In particular, the cost is influenced by the equipment and the energy used, as well as costs associated with enabling the end-use of the CO_2 captured, e.g., costs for compression and transport (E4tech, 2021). According to a study commissioned by Transport and Environment, costs for DAC currently range between EUR 100-500/tCO_2 captured, as reported by DAC development companies (E4tech, 2021).

DAC as the name implies, requires the use of materials that can recover carbon dioxide from the air via either absorption or adsorption. Designing a DAC-fuel plant requires engineers to choose a capture media of either solid sorbents or aqueous basic solutions (Keith et al., 2018). 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 (Keith et al., 2018). Solid sorbents do, however, require more maintenance to ensure optimal performance (Socolow et al., 2011). 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 (Brethomé et al., 2018; McQueen et al., 2021).

The true cost of sorbent selection is not readily apparent; a study by Sinha et al. (2017) estimated sorbent selection to account for up to 32% of the cost of direct air capture, while another study by the National Academies of Science and Medicine (2019) found the cost made up somewhere between 20% to 90% of total costs depending on the sorbent selected. Both solid and aqueous sorbents have a wide variety of capture media to select from that differ in capture capacity, heat of adsorption, lifetime of the material, and cost of material (Sinha and Realff, 2019; Azarabadi, 2019).

Within the aqueous sorbent category, typically chemical sorbents with strong CO2-binding affinities such as Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) are selected as capture media (Sanz-Pérez et al., 2016). While KOH is more expensive than NaOH, a study by Mahmoudkhani et al. (2009) found that KOH captured more CO_2 using less energy. Solid sorbents have a wider range of media to select from including solid alkali carbonates like CaO, $Ca(OH)_2$, or MgO or even organic-inorganic hybrid sorbents (Sanz-Pérez et al., 2016). As with the solvents, these sorbents differ in a variety of ways that can impact cost either directly through purchase price or indirectly through efficiency impacts.

The different temperature requirements of liquid solvent DAC systems and solid sorbent DAC systems further impact cost due to differences in the amount of energy required for operation of these systems. To release captured CO_2, solid sorbent systems require temperatures between 80 and 120 degrees Celsius (176 to 248 degrees Fahrenheit), while liquid solvent systems require temperatures of 900 degrees Celsius (1652 degrees Fahrenheit) (Liebig et al, 2021). One study concluded that solid sorbent DAC systems that operate with low temperatures are favorable because of lower costs for heat supply and the option of using waste heat from other systems (Fasihi et al., 2019).

Regardless of sorbent choice, there will always be a necessary capital investment in the DAC plant and ongoing energy and maintenance costs. In terms of capital investment, for each process type, there are a few units that will substantially impact costs: the contactor, the calciner, and the slaker as well as the pellet reactor for solid sorbent process types or the precipitator for solvent-based processes (Keith et al., 2018). Broadly, for a solid sorbent process, DAC proceeds by passing air through the contactor, where a large surface area of capture media binds to carbon dioxide, effectively trapping the CO_2 (Carbon Engineering, 2021). Next, the trapped CO_2 undergoes a series of reactions to isolate the CO_2 gas. A pellet reactor then separates salt from the solution (Mazzotti et al., 2013). The product is then dried in a slaker before being passed to the calciner where calcination occurs (Sabatino et al., 2020). In an aqueous solution process, a solvent pump distributes the solution across the packing material in the contactor, and as air passes through, the CO_2 chemically binds the capture media. The captured CO_2 solution is then passed through a slaker to dry and a causticizer to precipitate the carbonate before being passed to the calciner where calcination occurs (National Academies of Sciences, Engineering and Medicine, 2019.

Presently, these types of units are not manufactured commercially for DAC so there is room for novel developments that could significantly lower costs of production. For example, Keith et al. (2018) suggest modifying contactor design from a typical vertical flow (VF) model to a horizontal flow (HF) model; the gross capture costs for VF and HF have been estimated to be USD 390 and 220, respectively, per ton of CO_2. Moreover, a study by Zeman (2014) suggests that careful selection of packing material for the absorption surface could significantly reduce costs.

Going forward, as more DAC projects will be developed, learnings from these projects are expected to reduce costs, although estimates differ as to how much (Liebig, 2021). A study by Frontier Economics (2018) projected DAC costs to be EUR 145/tCO_2 through 2030 and EUR 100/tCO_2 thereafter. However, the study concluded that DAC would not reach scale fast enough for rapid cost reductions due to the availability of low-cost CO_2 from the steel and cement industry (Frontier Economics, 2018). Conversely, the study commissioned by Transport and Environment projected that DAC costs would range between EUR 40-70/tCO_2 or even as low as EUR 25/tCO_2 in the future; although, the timeline for these developments was unclear (E4tech, 2021).

Finally, a DAC plant must account for the source of its energy in a cost breakdown. This is difficult to estimate as energy costs vary by region. However, what is clear is the cost of electricity has a high impact on the cost for the final fuel production as DAC is an energy intensive process (E4tech, 2021; Liebig, 2021). Theoretically, a DAC plant could choose between any number of energy sources but to provide a climate benefit the energy source must be renewable. Untapped potential of renewable resources around the world provide the opportunity to build synthetic fuel plants where renewable energy is cheap and abundant. Besides scale, availability, and cost of renewable energy, decisions about plant deployment would also have to take into consideration power requirements and fuel production volumes as well as capital requirements (Liu et al., 2020).

The optimal location and the total area needed to situate such a plant would also have associated costs for consideration. The land area needed for DAC deployment depends on the type of DAC system used as well as the source of energy powering the plant; while liquid solvent system plants are larger than solid sorbent plants due to integrating multiple process units that benefit from economies at scale, solid sorbent plants are smaller because they benefit from using a single contactor geometry (Liebig, 2021).

1.2 Variables in Determining the Cost of Electrolysis

Although the cost of electrolysis equipment continues to fall, it still represents a significant cost factor in the production of DAC-fuels (Liu et al., 2020). A study by Liu et al. (2020) investigating the techno-economics of e-fuel production concluded that the highest share of total production cost of these fuels are the costs of electricity and water electrolysis for H_2 production. Therefore, in the near term, the cost of DAC e-fuels will hinge on sourcing low-cost renewable electricity and markets that incentivize the production of such fuels, e.g. through tax benefits (Liu et al., 2020).

Three electrolysis technologies show the most promise: alkaline electrolysis, proton exchange membrane (PEM) electrolysis and solid-oxide electrolyser cell (SOEC) electrolysis (Baldino et al., 2019). Alkaline and PEM electrolysis are categorized as low temperature technologies and are market ready (Cames et al., 2021). SOEC electrolysis is categorized as a high-temperature technology, it operates between 600°C– 800°C (1112°F – 1472°F), and is not yet commercialized (Baldino et al., 2019; Malins, 2017).

Alkaline electrolysis is already used at an industrial scale, produces hydrogen that is very pure and is slightly more efficient than PEM electrolysis (Baldino et al., 2019). By some estimates, PEM electrolysers are 50%-60% more expensive than alkaline but PEM is also thought to be more flexible, have a higher energy density and the ability to change its operating load in seconds (IRENA, 2020; Baldino et al., 2019; Cames et al., 2021). Regardless of the precise differences, both are well positioned to reduce costs as they scale (IRENA, 2020).

Compared to alkaline and PEM electrolysis, SOEC electrolysis has more favorable thermodynamics and faster kinetics that should mean it has lower OPEX and CAPEX if scaled successfully (Baldino et al., 2019; Hauch et al., 2020). The high temperature of SOEC electrolysis improves its efficiency by 20-30% and allows for lower cell voltage and higher current densities than PEM electrolysis. The efficiency and lower cell voltage of SOEC electrolysis should reduce OPEX costs, as there will be lower electricity demand, and the higher current densities should reduce CAPEX costs because fewer electrolysers will be needed to achieve the required capacity of gas production (Hauch et al, 2020). Another important advantage of the SOEC pathway is that it can be thermically integrated with the FT process to tap of the highly exothermic FT reaction to fulfil the system thermal needs, bringing down the operational costs of the electrolyser(Dieterich et al., 2020; Malins, 2017).

Overall, it is difficult to find precise cost estimates for electrolysers as data is often kept confidential (IRENA, 2020). It is also too soon to make definitive cost estimates for SOEC electrolysis as the technology is still in the proof-of-concept phase, meaning many of the components are at the lab-scale (IRENA, 2020). However, it is widely accepted that the capital cost of electrolysers and the electricity price for their operation are two of the most important factors affecting overall production costs for e-fuels (Brynolf et al., 2018).

Generally, the capital costs for electrolysis are expected to be more significant than the operational costs. A study by Brynolf et al. (2018) estimated that costs for alkaline and PEM electrolysis range between EUR 600-3700/kWe in the short term but would decline to EUR 300-1300/kWe in the longer term. In other words, a plant with 100 MWe input capacity would require EUR 100 million of investment (Brynolf et al., 2018). More specifically, a study by Liu et al. (2020) estimated that PEM electrolysis has higher investment cost, estimating USD 1000-1800/kW compared to alkaline electrolysis USD 500-1400/kW. Although SOEC electrolysis is unlikely to be commercialized before 2030, it is estimated to be the lowest cost option, with investment needs estimated to range between EUR 400 – 1000/kWe (Brynolf et al., 2018).

Operational costs are anticipated to be mainly from stack maintenance for alkaline and PEM electrolysers and electricity costs. The electrolyser stacks will likely need to be replaced multiple times during an electrolyser plant lifetime. For a plant operating year-round, stack replacement may need to occur every ten years of less, which could be equivalent to up to 16% of overall costs (Brynolf et al., 2018).

The cost of electricity is more difficult to predict, as it depends on a range of variables, including location and renewables deployment. However, an element that will be critical to minimizing electricity costs is the fact that electrolysers, unlike fuel the fuel synthesis pathway, have the flexibility to react to intermittent renewable electricity generation by changing their operating state (Cames et al., 2021). This will allow electrolysers to increase production when renewable electricity is cheap and abundant and scale-down production when renewable electricity is in short supply and more expensive. PEM electrolysis which can most easily adapt to variable supply of power and make use of intermittent renewables (Liu et al., 2020). The flexibility of electrolysers is key not only to reduce costs but also as a way to balance grids with a large share of renewables, something explored later in this report. (See "North American hydrogen production potential from solar and wind power excessive electricity supply").

1.3 Variables in Determining the Cost of Fuel Synthesis

Once hydrogen is produced and CO_2 captured, there are two fuel synthesis pathways that can be used to produce jet fuel: the methanol and the Fischer-Tropsh pathway. The methanol synthesis pathway produces methanol which can then be converted into hydrocarbon end-products (Cames et al., 2021). There are two pathways by which methanol can be produced. The first uses syngas to synthesize methanol (Marlin et al., 2018). This pathway operates at the industrial scale using fossil fuel inputs to produce the syngas, but for applicability to DAC e-fuels syngas production using renewable inputs will need to scale (Cames et al., 2021). The second pathway is still in the development phase but would allow for direct methanol synthesis, without first creating a syngas, the key advantage being impurities in the crude methanol are minimized (Marlin et al., 2018).

An important caveat that applies to both methanol pathways is the processing step to convert methanol into jet fuel has not been demonstrated, so the methanol pathway has not achieved ASTM certification which would allow it to be used for commercial aviation (Schmidt et al., 2016; Van Dyk & Saddler, 2021). While there are no anticipated issues achieving this final step, producing jet fuel will require modifications to existing refineries (Cames et al., 2021).

The Fischer-Tropsch (FT) pathway is already established to produce liquid fuels using syngas either from coal, natural gas or biomass (see Literature Review Two for more). Completing the power-to-liquids pathway using FT synthesis requires a syngas input, which can be produced via a reverse water gas shift (RWGS) reaction that converts carbon dioxide to carbon monoxide (Malins, 2017). Although the rest of the FT pathway is well established, work remains to scale the RWGS reaction (Schmidt et al., 2016).

As neither the methanol nor the FT pathway is at scale, it is difficult to make precise cost estimates for the final fuel synthesis step. However, the consensus is that overtime the FT synthesis pathway has the potential to operate at a lower price point the methanol pathway (Malins, 2017). Cost estimates for FT synthesis range between EUR 400-1300 per kW of fuel, whereas estimates for methanol are EUR 550 – 860 per kW of fuel (Malins, 2017).

1.4 Cost Estimates for the Complete DAC e-fuel pathway

Overall, the cost of renewable electricity production is a key driver for the overall cost of the DAC e-fuel pathway, as both DAC and electrolysis are energy intensive (Baldino et al., 2019; Malins, 2017). Cost estimates for the pathway in 2020 range between three to six times the price of fossil jet fuel, or roughly EUR 3,000 to 4,000 per tonne of fuel (Cames et al., 2021; Malins, 2017; World Economic Forum and McKinsey & Company, 2020). However, prices are expected to rapidly decline as renewable electricity costs fall and electrolyser and DAC technologies scale. By 2030, costs for DAC e-fuels are expected to be between EUR 1,700 and EUR 2,300 per tonne of fuel and as low as EUR 1,000-1,500 per tonne by 2050 (Cames et al., 2021; World Economic Forum and McKinsey & Company, 2020).

1.5 Summary Table of Cost Estimates

Table 1: Overview of costs for DAC, electrolysis, fuel synthesis and the full DAC e-fuel SAF pathway in USD ($) and EUR (€). (Note 1 USD is approximately 0.80 EUR).

Pathway Step	**Cost Estimates**			**Source**
	Present	**2030**	**2050**	
DAC	€100-500/tCO_2	€ 40-70/tCO_2	€ 25/tCO_2	E4tech (UK) Ltd. (2021). Role of DAC in e-fuels for aviation. https://www.transportenvironment.org/wp-content/uploads/2021/08/Role-of-DAC-in-e-fuels-for-aviation-report-v7.0.docx-1.pdf
	$390/t$CO_2$ (vertical flow model) $220/t$CO_2$ (horizontal flow model)			Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A process for capturing co2 from the atmosphere. Joule, 2(8), 1635. doi:10.1016/j.joule.2018.06.010
	€145/tCO_2	€145/tCO_2	€100/tCO_2	Frontier Economics. (2018). The Future Cost of Electricity-Based Synthetic Fuels. Commissioned by Agora Verkehrswende, Agora Energiewende.
Electrolysis	€ 600-3700/kWe (Alkaline and PEM)	€600-3700/kWe (Alkaline and PEM)	€ 300-1300/kWe (Alkaline and PEM)	Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2018). Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews, 81, 1887-1905.
	$1000-1800/kW (PEM) $500-1400/kW (Alkaline)			Liu, C., Sandhu, N., McCoy, S., Bergerson, J. (2020). A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. Sustainable Energy Fuels 4, 3140.
		€400 – 1000/kWe (SOEC)		Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2018). Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews, 81, 1887-1905.
Fuel Synthesis	€550 – 860/kW fuel			Malins, C. (2017). What role is there for electrofuel

	(Methanol) €400-1300 per kW (FT)			technologies in European transport's low carbon future. Cerulogy Report
DAC e-fuel SAF pathway	$3,800/MT	$2,000/MT	$1,300/MT	World Economic Forum (WEF) and McKinsey & Company. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Insight Report. https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/scaling-sustainable-aviation-fuel-today-for-clean-skies-tomorrow
	€4,000/MT	€2,300/MT	€1,575/MT	Cames, M., Chaudry, S., Göckeler, K., Kasten, P., and Kurth, S. (2021) E-fuels versus DACCS, Study on behalf of Transport and Environment. Oko-Institut e.V.
	$4974/MT			Van Dyk, S. and Saddler, J. (2021). Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, potential and challenges. IEA Bioenergy: Task 39.
	€3,000/MT		€2,000/MT	Malins, C. (2017). What role is there for electrofuel technologies in European transport's low carbon future. Cerulogy Report.

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2 Literature Review Two: "Comparison of DAC-fuel cost to alternatives"

Sustainable aviation fuel (SAF) production pathways must be approved by ASTM International, a standard setting organization, in order for SAF to be used on commercial flights. Currently, ASTM requires SAF be blended with fossil jet fuel, to a maximum of 50% (ICAO, 2021a). As of October 2021, seven conversion processes and two co-processing pathways have been approved for SAF production (see Appendix 1 for full list) (ICAO, 2021a). This analysis will focus on three SAF production pathways: hydro-processed esters and fatty acids (HEFA), gasification Fischer-Tropsch and alcohol-to-jet. These pathways are the most developed and therefore have the most robust techno-economic analyses to allow for comparison to the power-to-liquids pathway.
Overall, the three pathways face the same barrier: cost compared to fossil jet fuel. The magnitude varies but ranges between two and eight times the cost of fossil jet fuel (Pavlenko et al., 2019). By some estimates, crude oil prices would need to be between USD 90 and 310 per barrel in order for SAF to be cost competitive (IEA, 2020). Feedstock costs as well as capital costs to deploy early-stage technology are widely accepted as key factors in the price differential (Van Dyk & Saddler, 2021). Overtime, the cost of SAF is expected to decline but is unlikely to reach price parity with fossil jet fuel (World Economic Forum and McKinsey & Company, 2020). This highlights the need for policy interventions that reward fuels based on emissions reductions and level the playing field between SAF and fossil jet fuel.

2.1 Hydro-processed esters and fatty acids (HEFA) Pathway

2.1.1 Overview of the production pathway

The Hydrotreated Esters and Fatty Acids (HEFA) pathway converts a fatty acid feedstock (e.g., vegetable oils, waste oils, or fats) into SAF via hydro-processing (ICAO, 2021b). In general terms, the first part of the process involves treatment of the feedstock to remove the oxygen molecule, and the second step requires cracking and isomerization so that molecules are jet fuel length (ICAO, 2021b).
Under the normal HEFA process, 15% of the final product slate is suitable for jet fuel, and the remaining is Renewable Diesel with a small portion of light ends (Pavlenko et al., 2019). However, the HEFA process can be modified to maximize the jet fuel end-product, to as high as 50% of the final product slate (EASA, 2021; Van Dyk & Saddler, 2021). Doing so requires additional cracking to create the smaller hydrocarbon chains suitable for SAF (Pearlson, 2011). A final distillation step is required to separate the jet range molecules and renewable diesel molecules. However, distillation does not always happen as demand for renewable diesel is greater than for jet fuel, and molecules suitable for jet fuel can also be burnt in a diesel engine (Van Dyk & Saddler, 2021).

2.1.2 Key Cost Drivers

Due to demand for renewable diesel for road transportation, the HEFA pathway is technologically mature and operates at a commercial scale. It is estimated that globally, between 5 and 6 billion litres of renewable diesel are produced using HEFA production processes, with that number expected to grow (Pavlenko and Kharina, 2018; Van Dyk & Saddler, 2021).
Given the pathway's commercial and technical maturity, it is widely accepted that the key factor that will determine the future cost of HEFA fuels is feedstock price (Bann et al., 2017; de Jong, 2018; Van Dyk & Saddler, 2021; World Economic Forum and McKinsey & Company, 2020). A study by Bann et al. (2017) found the minimum selling prices for HEFA ranges between USD 825 to 1550 per tonne where the feedstock is yellow grease; USD 988 to $1775 per tonne where the feedstock is tallow, and USD 1086 to 2000 USD per tonne

where the feedstock is soybean oil. This analysis concluded that feedstock cost can amount to as much as much as 80% of the total production costs for HEFA (Bann et al., 2017).

Another factor to consider is that if the HEFA pathway is modified to increase SAF output, costs will increase because of additional processing required and higher hydrogen demand (Pearlson, 2011). The cost is further exacerbated by the fact that the final product slate has less renewable diesel which is the product with the highest market value (Pearlson et al., 2013).

2.1.3 Cost Forecasts to 2050

Looking ahead, HEFA is anticipated to remain the dominant SAF pathway to 2035, because of its technical and commercial maturity (E4tech, 2020). However, HEFA is unlikely to see major production cost reductions, unless feedstock prices decline dramatically. Analysis by McKinsey & Company (2020) commissioned by the World Economic Forum, Clean Skies for Tomorrow Coalition, predicted that HEFA production costs will decline 22% by 2050, assuming CAPEX and OPEX see modest declines. In other words, the cost could decline from approximately USD 1,400 per metric ton of SAF today, to USD 1,100 per metric ton of SAF in 2050 (World Economic Forum and McKinsey & Company, 2020).

2.2 Gasification Fischer-Tropsch Pathway

2.2.1 Overview of the production pathway

ASTM has certified two Fischer-Tropsch (FT) pathways: Fischer-Tropsch-SPK which only produces paraffinic jet fuel and Fischer-Tropsch-SAK which also produces other aromatic compounds (SkyNRG, 2019). The first step in the FT SAF pathway is to create a synthesis gas "syngas" (Basu, P, 2018). Gasification gives the pathway flexibility in terms of the feedstock that can be used, meaning lignocellulosic materials, biogenic residues and wastes are all eligible (ICAO, 2021b). Once the syngas is produced, it is cleaned and then undergoes the Fischer-Tropsch synthesis reaction that produces a range of hydrocarbon products, including for use in jet fuel (Basu, P, 2018). Overall, the entire product slate produced by Fischer-Tropsch is thought to include a jet fraction between 25% and 40% (Van Dyk et al., 2019).

2.2.2 Key Cost Drivers

Capital expenditure (CAPEX) is the main cost driver for the Fischer-Tropsch production pathway (Pavlenko et al., 2019). The higher CAPEX costs are primarily associated with the syngas production, and result from the need to install boilers, gas-cleaning devices, ash disposal systems and storage facilities for syngas (IRENA, 2021). CAPEX estimates vary, particularly for the gasification step. For example, de Jong (2018) estimated that a project with capacity to produce 220 million liters of fuel per year is estimated to have an associated CAPEX of anywhere between EUR 339 million and 1,230 million for gasification. However, as the technology matures, and improvements are made to the process design and operational conditions, CAPEX for gasification is expected to fall, by as much as 30% (IRENA, 2021; Peters et al., 2015). Once a Fischer-Tropsch production system is established, operating expenses (OPEX) are low compared to CAPEX but remain higher than the OPEX for HEFA (IRENA, 2021). Costs vary by gasifier type, with the key factors being the cost of the catalyst and the cost of hydrogen (IRENA, 2021).

As stated in the overview of the FT pathway, a key benefit is that it is flexible in terms of the feedstock it uses. However, that also contributes to a wide variance in estimated production costs (World Economic Forum and McKinsey & Company, 2020). For example, Bann et al. (2017) estimated that minimum fuel selling price estimates for SAF with a Municipal Solid Waste (MSW) feedstock range between USD 1188 and 1738 per tonne, compared to estimates by de Jong et al. (2017) of between USD 2124 and 3127 per tonne for SAF with forest residue or wheat straw feedstocks.

2.2.3 Cost Forecasts to 2050

Looking ahead, production costs for the Fischer-Tropsch pathway are expected decline by a similar magnitude as the HEFA pathway. For example, Fischer-Tropsch SAF production with a MSW feedstock, should decline by approximately 24%, from around USD 1,900 per metric ton today to USD 1,600 in 2030 and USD 1,400 in 2050 (World Economic Forum and McKinsey & Company, 2020). For a production pathway using forestry residues and other cellulosics, production costs per metric ton are anticipated to fall from approximately USD 2,100 today to USD 1,800 in 2030 and USD 1,550 in 2050 (World Economic Forum and McKinsey & Company, 2020).

2.3 Alcohol-to-Jet Pathway

2.3.1 Overview of the production pathway

Compared to the HEFA and Fischer-Tropsh pathways, the alcohol-to-jet pathway is less developed, meaning there is comparatively less literature that covers the pathway. It has two core components: alcohol production followed by jet fuel production. Three alcohol feedstocks can be used to produce SAF: ethanol, iso-butanol and n-butanol, however only the alcohol-to-jet pathways that use ethanol or iso-butanol have achieved ASTM certification (Holladay & Hyne, 2020; Van Dyk & Saddler, 2021). Once the alcohol is sourced, the production of SAF requires three steps: dehydration of the alcohol; oligomerization and then hydrogenation (ICAO, 2021b). The alcohol-to-jet product slate is roughly 70% jet fuel and the remainder renewable diesel and lights end, a significantly higher proportion of jet fuel than other SAF pathways (Pavlenko et al., 2019).

2.3.2 Key Cost Drivers

Costs for the alcohol-to-jet pathway are similar to HEFA, in that they are heavily influenced by feedstock cost (World Economic Forum and McKinsey & Company, 2020; Van Dyk & Saddler, 2021). However, unlike for HEFA, alcohol-to-jet has more potential to reduce costs through improvements to technological pathways (Van Dyk and Saddler, 2021). To understand the factors that contribute to the cost, it helps to differentiate between the costs to produce alcohol and the costs to produce jet fuel.

There is very little effect on the total production cost if ethanol or iso-butanol is used. However, there is a wide range (USD 33-220 per metric ton) in feedstock cost for the alcohol production, with grain or sugar feedstocks generally cheaper than lignocellulosic (Van Dyk and Saddler, 2021). As well, while alcohol production using first-generation feedstocks (e.g., corn) is well established from a technological and commercial standpoint, alcohol production using second generation crops and residues requires further development, and so has higher costs associated (World Economic Forum and McKinsey & Company, 2020). Finally, even where ethanol or iso-butanol can be produced for a reasonable cost, a remaining challenge is the alcohol has a higher value in the road transport fuels and the biochemicals market than for use in the jet fuel market (Karatzos et al., 2014).

Most facilities require upgrades in order to produce jet fuel, the cost of which also varies by feedstock. For example, a study by Tao et al. (2017) estimated that a corn ethanol facility with a 230-million-liter annual capacity would cost EUR 78 million to upgrade to add a hydrocracking system to produce jet fuel. However, the CAPEX for a cellulosic alcohol-to-jet facility is estimated to be an additional 60% higher because upgrades would also have to be done to allow for additional pre-treatment of the feedstocks (Tao et al., 2017).

2.3.3 Cost Forecasts to 2050

Looking ahead, production costs for the alcohol-to-jet pathway are expected to decline as alcohol production and CAPEX costs for facility upgrades decline. By some estimates, SAF production costs should fall from USD 2,400 per metric ton today, to USD 1,800 in 2030 and USD 1,600 by 2050 (World Economic Forum and McKinsey & Company, 2020). To put this in context, it will mean the production of SAF using the alcohol-to-jet pathway is expected to remain more expensive than the HEFA or Fischer-Tropsch, although it will be close to price competitive.

2.4 Comparison of HEFA, Gasification FT and Alcohol-to-Jet to DAC e-fuel costs

Overall, it is difficult to find estimates for SAF costs as the consensus in the literature is there are too many variables which could influence future costs to produce meaningful long-term estimates. However, generally speaking, DAC e-fuels are estimated to have the potential for more significant cost declines than the HEFA, FT and alcohol-to-jet pathways. This will primarily be driven by lower renewable electricity prices and further scale-up of electrolysis. For the HEFA and alcohol-to-jet pathways, cost declines will be contingent on declining feedstock prices, and for the Fischer-Tropsch on declining CAPEX costs as the technology scales.

Table 2: Summary of SAF cost estimates, prices in USD ($) or EUR (€) (Note 1 USD is approximately 0.80 EUR).

SAF Pathway	**Cost Estimates**			**Source**
	Present	**2030**	**2050**	
DAC e-fuel	$3,800/MT	$2,000/MT	$1,300/MT	World Economic Forum (WEF) and McKinsey & Company. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Insight Report. https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/scaling-sustainable-aviation-fuel-today-for-clean-skies-tomorrow
	€4,000/MT	€2,300/MT	€1,575/MT	Cames, M., Chaudry, S., Göckeler, K., Kasten, P., and Kurth, S. (2021) E-fuels versus DACCS, Study on behalf of Transport and Environment. Oko-Institut e.V.
	$4974/MT			Van Dyk, S. and Saddler, J. (2021). Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, potential and challenges. IEA Bioenergy: Task 39.

	€3,000/MT		€2,000/MT	Malins, C. (2017). What role is there for electrofuel technologies in European transport's low carbon future. Cerulogy Report.
HEFA	€950-1,015/MT (used cooking oil feedstock)			EASA. (2021). Bio-based aviation fuels. https://www.easa.europa.eu/eaer/topics/sustainable-aviation-fuels/bio-based-aviation-fuels
	$825-1,150/MT (yellow grease) $988-1,775/MT (tallow feedstock) $1,086-2,000/MT (soybean oil feedstock)			Bann, S. J., Malina, R., Staples, M. D., Suresh, P., Pearlson, M., Tyner, W. E., ... Barrett, S. (2017). The costs of production of alternative jet fuel: A harmonized stochastic assessment. Bioresource Technology, 227, 179–187.
	$1,400/MT		$1,100/MT	World Economic Forum (WEF) and McKinsey & Company. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Insight Report. https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/scaling-sustainable-aviation-fuel-today-for-clean-skies-tomorrow
Gasification FT	$1,188-1,738/MT (MSW feedstock) per tonne			Bann, S. J., Malina, R., Staples, M. D., Suresh, P., Pearlson, M., Tyner, W. E., ... Barrett, S. (2017). The costs of production of alternative jet fuel: A harmonized stochastic assessment. Bioresource Technology, 227, 179–187.
	$2,124-3,127/MT forest residue or wheat straw feedstock			de Jong, S. (2018). Green Horizons: On the Production Costs, Climate Impact and Future Supply of Renewable Jet Fuels (master's thesis, Utrecht University); http://skynrg.com/ wp-content/uploads/2018/06/dJong.pdf.
	$1,900/MT	$1,600/MT MSW	$1,400/MT (MSW feedstock)	World Economic Forum (WEF) and McKinsey &

	(MSW feedstock) $2,100/MT (Forestry residues/cellulosics)	$1,800/MT (Forestry residues/cellulosics)	$1,550/MT (Forestry residues/cellulosics)	Company. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Insight Report. https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/scaling-sustainable-aviation-fuel-today-for-clean-skies-tomorrow
Alcohol-to-jet	$1,387/MT (ethanol to jet corn grain) $1,773/MT (ethanol to jet corn stover)			Tao, L., Markham, J. N., Haq, Z., & Biddy, M. J. (2017). Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks. Green Chemistry, 19(4), 1082–1101. doi:10.1039/c6gc02800d
	$2,400/MT	$1,800/MT	$1,600/MT	World Economic Forum (WEF) and McKinsey & Company. (2020). Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Insight Report. https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/scaling-sustainable-aviation-fuel-today-for-clean-skies-tomorrow

2.5 Appendix 1: ASTM Certified SAF Production Pathways

Table 3: ASTM approved production pathways. Source: https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

ASTM reference	Conversion process	Possible Feedstocks	Blending ratio by volume
ASTM D7566 Annex 1	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	Coal, natural gas, biomass	50%
ASTM D7566 Annex 2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	Bio-oils, animal fat, recycled oils	50%
ASTM D7566 Annex 3	Synthesized iso-paraffins from hydroprocessed fermented sugars	Biomass used for sugar production	10%
ASTM D7566 Annex 4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	Coal, natural gas, biomass	50%
ASTM D7566 Annex 5	Alcohol to jet synthetic paraffinic kerosene	Biomass from ethanol or isobutanol production	50%
ASTM D7566 Annex 6	Catalytic hydrothermolysis jet fuel	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%
ASTM D7566 Annex 7	Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids	Algae	10%
ASTM D1655 Annex A1	FOG Co-processing	Fats, oils, and greases (FOG) from petroleum refining	5%
ASTM D1655 Annex A1	FT Co-processing	Fischer-Tropsch (FT) biocrude as an allowable feedstock for petroleum co-processing	5%

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3 North American hydrogen production potential from excessive renewable electricity supply

The production of e-fuels is energy intensive. One unit of e-fuel energy could require an input of around two units of energy (Malins, 2017) and in some cases more (Adelung, 2021). It is therefore necessary to ensure that the origin of the electricity is renewable and that it does not result in displacements that could generate large indirect emissions. Otherwise, e-fuels could end up with higher life-cycle emissions – total emissions from production to combustion – than conventional jet fuel. Securing sufficient renewable energy supply for e-fuels is a challenge because electricity grids are at varying stages of decarbonization. Therefore, to support e-fuel scale-up, barriers to sufficient renewable electricity supply must be addressed and displacement effects minimized.

A promising solution is for e-fuel production to rely exclusively on surplus renewable electricity. This minimizes the risk of displacement effects and means that e-fuel production would help balance the electricity grid, which is essential for decarbonization. The concept of using surplus renewable electricity to balance the electricity grid goes beyond curtailment – whereby electricity output is deliberately reduced to balance supply and demand – in demand-driven electric power systems. Unlike demand-driven systems, renewables-based power generation systems are supply driven and can operate without significant energy storage while still providing a high level of reliability (Lugovoy et al., 2021). However, once wind or solar capacity is in place, power production becomes intermittent, and the ability to manage the load becomes a critical feature for balancing the grid. In this context, a significant fraction of demand would need to be flexible, making interruptible technologies like electrolysers essential to, rather than in competition with, a comprehensive energy transition.

Hydrogen production from electrolysis is flexible due to its literally instant ramping speed, and ability to store hydrogen as a back-up energy supply (IRENA, 2018; IRENA 2019; IRENA 2020). This makes e-fuel production facilities particularly well suited to balance grids with a high share of renewable electricity, both instantly and across seasons.

To test the impact that operating e-fuel production on an interruptible basis could have on its cost competitiveness, we estimated present and future SAF costs for the gasification Fischer Tropsch, alcohol-to-jet, HEFA and e-fuel pathways, with varying feedstocks and technology choices The estimates are based on data from: (1) the Hydrogen Production Analysis model, version 3.2018 (a discounted cash flow model providing transparent reporting of process design assumptions and a consistent cost analysis methodology for H2 production) (Peterson et al., 2020a; Peterson et al., 2020b); (2) The joint World Economic Forum, McKinsey & Company, Clean Skies for Tomorrow report: "Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation" for Fischer-Tropsch and Reverse Water-Gas Shift processes (2020); and (3) the International Civil Aviation Organization's (ICAO) "SAF Rules of Thumb" (n.d.) and default lifecycle emissions values (2021) for biogenic SAF estimates.

Our results illustrate the significant cost savings that e-fuel pathways may unlock if they are designed to operate flexibly, reducing the cost of renewable electricity (see Figure 1). Critically, this could allow e-fuel pathways to become cost competitive with SAF pathways such as HEFA-SPK sooner than anticipated, provided countries seriously embark on the transformation of their power generation systems.

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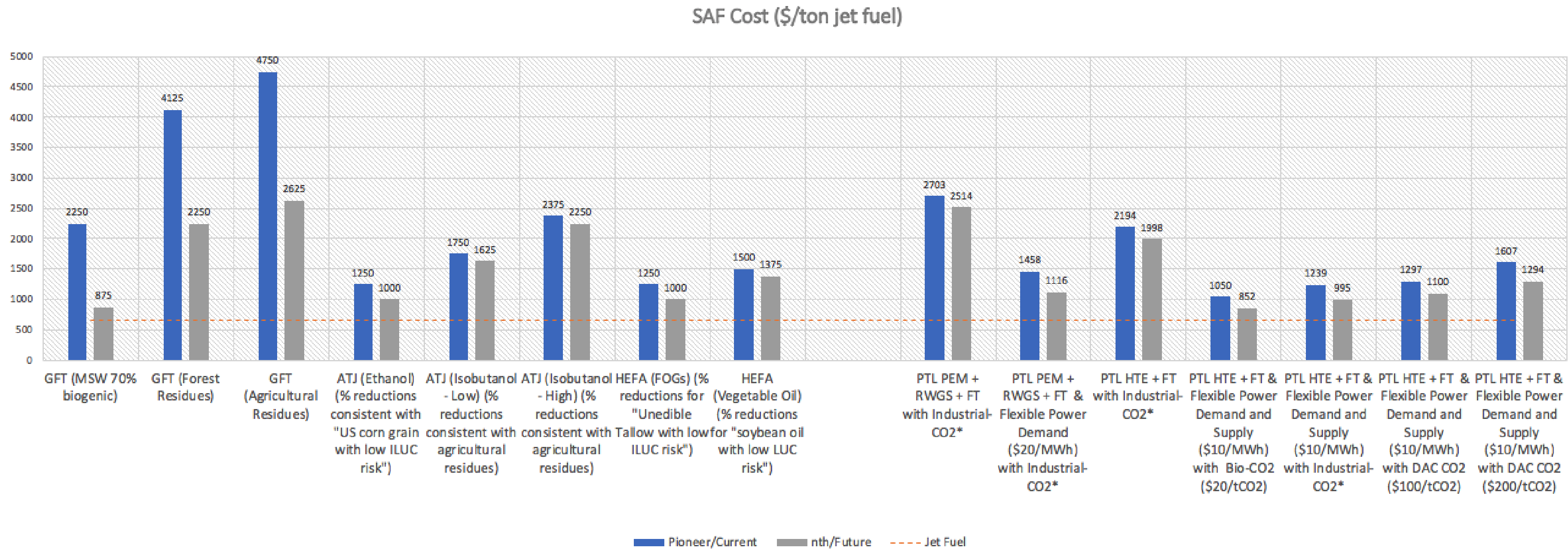

Figure 1: SAF cost ($/ton jet fuel) estimated for the present and in the future, as compared to a constant jet fuel price.

Furthermore, our results show that when SAF pathways are assessed based on abatement costs, e-fuels have a far more cost-efficient price per ton of CO_2 abated than other pathways (see Figure 2). This is particularly noteworthy for a jurisdiction like Europe, where an EU ETS allowance price of €100/tCO_2 is a real possibility and would provide a sufficient incentive to cover the future abatement costs for e-fuels.

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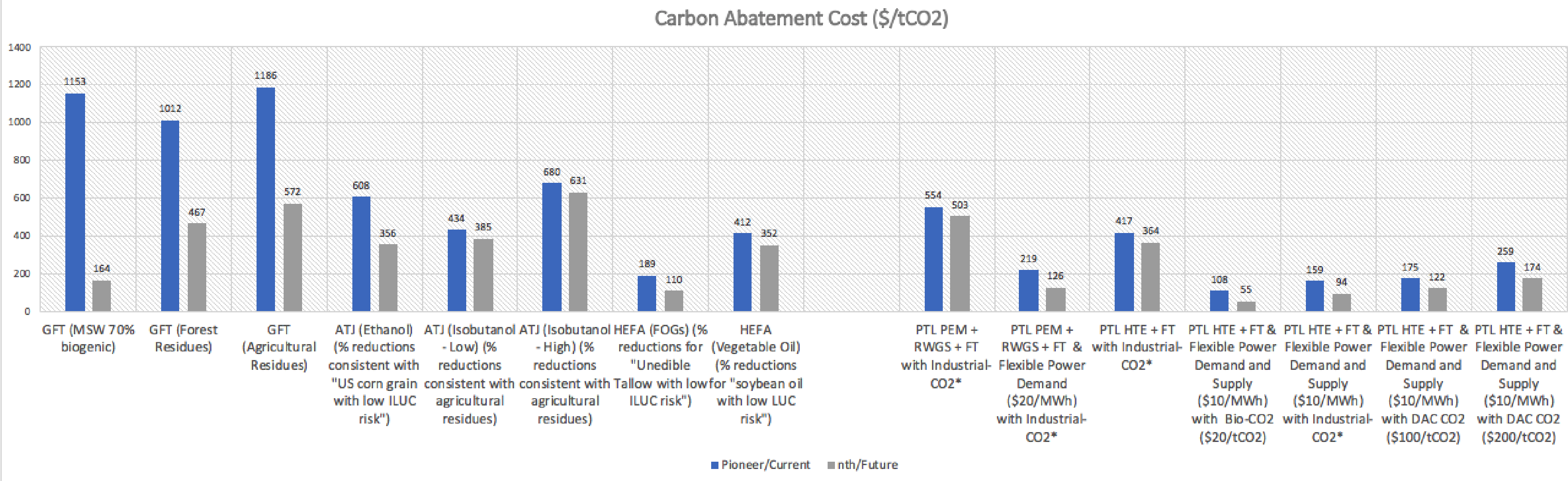

Figure 2: SAF cost ($/tonCO2) estimated for the present and in the future.

Finally, to further highlight the impact of flexible power demand on the e-fuel production pathway, we provide a breakdown of estimated costs now and in the future for a PEM pathway (see Figure 3). As the graphs clearly show, reducing the electricity costs by operating e-fuels production on an interruptible basis provides significant cost savings.

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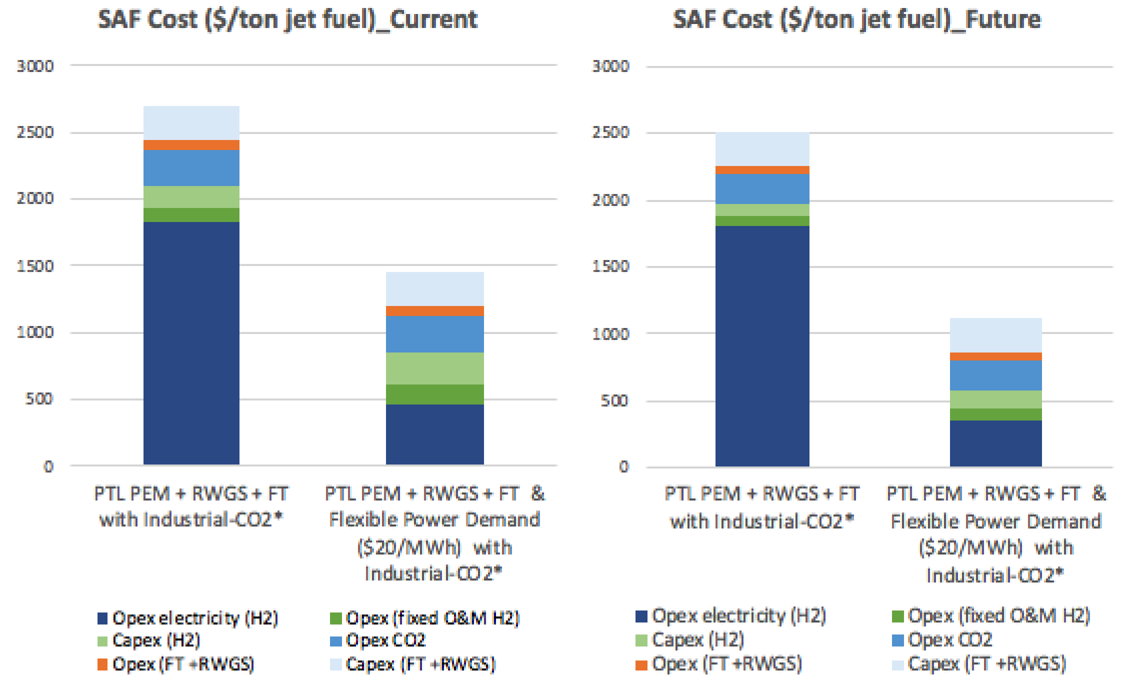

Figure 3: A breakdown of e-fuel costs ($/tonCO2) with and without flexible power demand, estimated for the present and in the future.

To summarize, considering e-fuel integration with renewable-based power systems is relevant as the synergies could: (a) minimize the risk of displacement effects, safeguarding the environmental integrity of the e-fuels production pathway; (b) support the power sector energy transition by providing essential grid balancing services; (c) provide significant cost savings to make the e-fuels pathway cost competitive. Of course, integration with the renewable-based power system only works in a scenario where the country is transitioning away from fossil-based energy and has attained a critical level of renewable electricity deployment. Where that is the case, the potential synergies look promising. For example, a feasibility study of China's power sector transformation into a renewable-based system found the amount of surplus electricity available for interruptible demand could in theory be sufficient to cover around 10% of global aviation jet fuel demand with e-fuels in 2030 and 100% by 2050 (Lugovoy et al., 2021).

In this section we estimate the potential annual electricity surplus that can be used for hydrogen production assuming a close to 100% renewable-based electric power system in the US, Canada, and Mexico, in 2050. We also evaluate the impact of electrolysis on energy storage requirements to understand how the scale-up of DAC e-fuels could help balance an increasingly decarbonized power grid.

3.1 Methodology

To simulate expansion and operation of carbon-free North American electric power system we apply an extended 88-region version of USENSYS (United States ENergy SYStem) optimization model (see Figure 4). The USENSYS model is an open-source capacity expansion model designed for renewables and the energy transition.

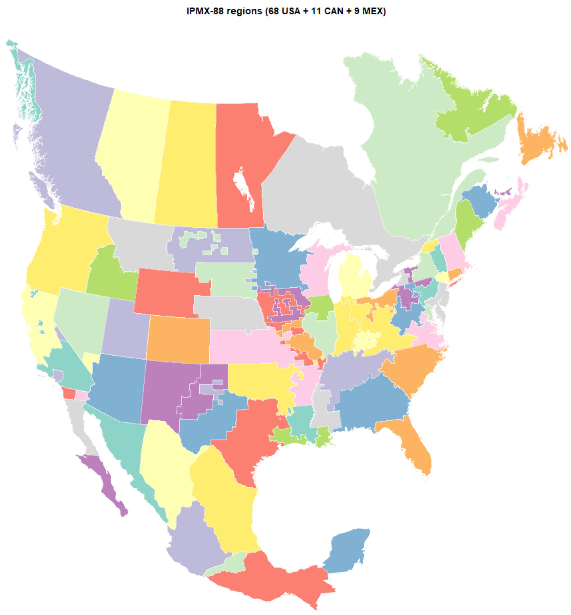

Figure 4: Regional division of 88-region version of USENSYS model.

The base-year generation capacity of USENSYS model is calibrated to the United States Environmental Protection Agency (EPA) Integrated Planning Model (IPM) NEEDS database. The production of renewables is predetermined by capacity factors in different locations, estimated based on historical reanalysis weather data (MERRA-2). Each model region has up to 10 spatial clusters with similar patterns of wind or solar energy (see Figure 5 and Figure 6).

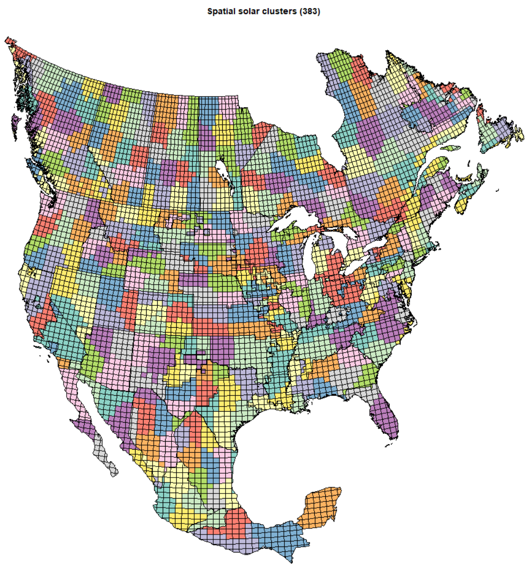

Figure 5: Spatial clusters of solar energy (clustering is based on similarity of photovoltaics output and the number of clusters in each region is defined to retain at least of 97% of the hourly capacity factors' standard deviation).

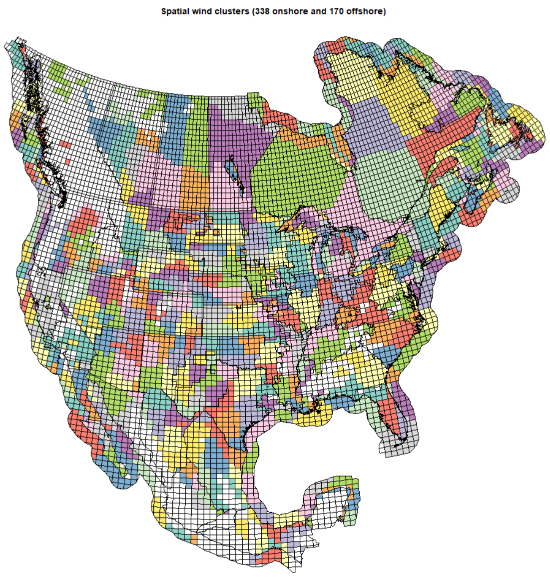

Figure 6: Spatial clusters of wind energy (clustering are based on similarity of estimated output of wind turbines, number of clusters in each region is defined to retain at least of 90% of the hourly capacity factors' standard deviation).

Electricity demand in the base year is taken from the IPM/NEEDS datasets (Figure 7). Costs of wind and solar generation technologies are taken from NREL Annual Technology Baseline (ATB).

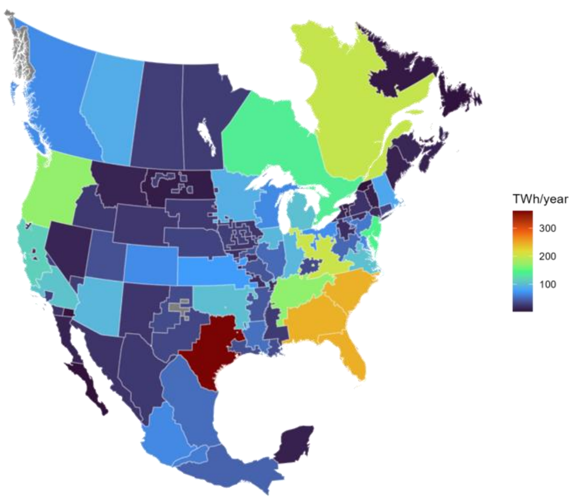

Figure 7: Annual electricity load by region (from NEEDS database, September2021 with the addition of Mexico).

The interregional transmission network is adopted from IPM framework, and extended with a simplified Mexico grid and additional potential grid upgrades of East-West interconnect (Figure 8). The model also includes a full grid optimization scenario (Figure 9).

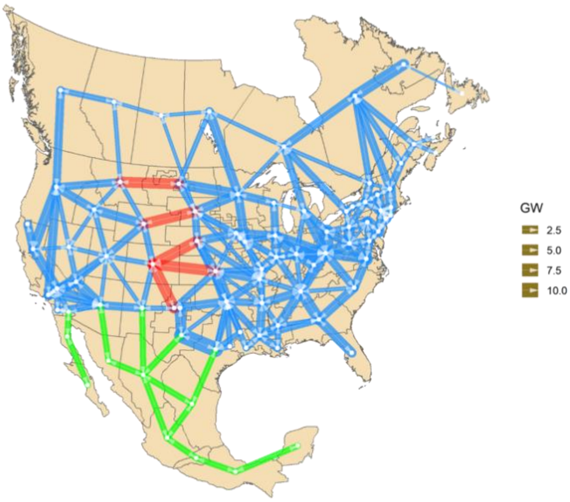

Figure 8: Transmission system, data from IPM/NEEDS (blue) with added simplified Mexico grid (green), and the potential expansion (red).

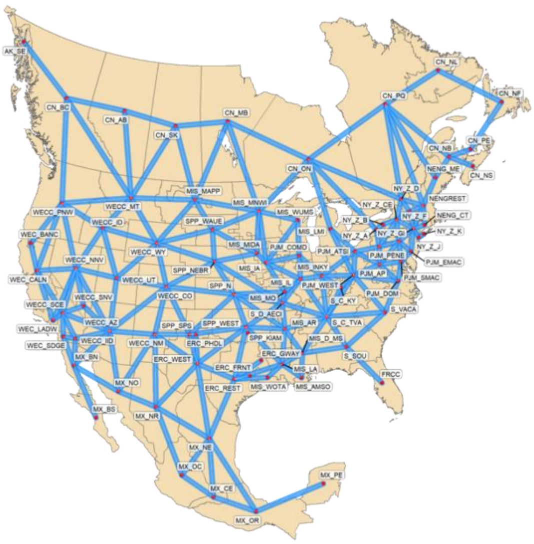

Figure 9: Transmission lines available for investment ("Grid from scratch" and "Grid upgrade" scenarios).

3.2 Scenarios

To prove the concept of the applied methodology we start the analysis with two simplified scenarios which simulate 100% renewable electric power system in 2050, optimizing the required wind and solar generation capacity and storage from scratch (assuming that all existing renewables in the base year capacity has been retired by 2050). The first scenario (HR_BAS) simulates the electric power system, assuming demand is equivalent to 2019 levels, for each model region. The goal of the scenario is to evaluate the storage, grid expansion, back-up capacity for black-out hours, and curtailed electricity supply required for a 100% renewable electricity power system.

Curtailed electricity supply is an unavoidable feature of weather-driven high-renewables systems with rigid demand. When both supply and demand are predefined by third factors, the only balancing options are energy storage or back-up generation, which is intentionally limited in the scenarios. Therefore, to meet the total demand, the model has to scale up either generation that leads to overproduction, or energy storage, with the two options competing based on costs.

The second scenario (HR_P2L) is identical to the base scenario (HR_BAS) with an added option to invest in hydrogen production. Since the hydrogen is used for the e-fuel production pathway, we abbreviate the whole technological chain as power-to-liquid (P2L). The cost of electricity for hydrogen production is fixed at 10 USD/MWh (1 US cent per kWh). The low price of electricity is required to ensure competitiveness of the technology and because it is lower than levelized electricity costs, also limits an increase to generation capacity just for hydrogen production. From the whole system perspective, electricity sold to hydrogen producers is considered as a credit which allows the production of electricity to meet the base load requirements and may reduce requirements for storage and improve grid stability.

3.3 Results and discussion

Table 4 below compares results of solved scenarios with and without optional production of hydrogen (P2L). The model optimized the location of solar and wind power capacity, storage, and P2L technology under given hourly demand by regions and weather-driven production of renewable technologies. Figure 10 through Figure 13 provides an overview of the location of installed technologies by the model regions and clusters.

Table 4: Comparison of high renewables scenarios with and without P2L technology.

	HR_BAS	*HR_P2L*
Solar, GW	2,394.7	2,231.9
Wind offshore, GW	146.9	68.0
Wind onshore, GW	1,050.7	951.7
4h Storage, GWh	2394.3	1557.8
P2L, GW	-	238.8
Demand, TWh	5,064.1	5,064.1
P2L input, TWh	-	2,092.1

Overall, the results show that solar generation will take a dominant role in a 100% renewable electricity grid, both for the scenario without hydrogen production (HR_BAS) and the scenario with hydrogen production (HR_P2L). Solar capacity is twice as high as wind capacity (see Figure 10 and Figure 11), a result which is largely driven by the fact that solar is cheaper, particularly compared to offshore wind farms. As well, the assumed height of wind power plants is from 50 to 100 meters but modern wind turbines in the US tend to be more than 100 meters, capturing stronger and steadier winds.

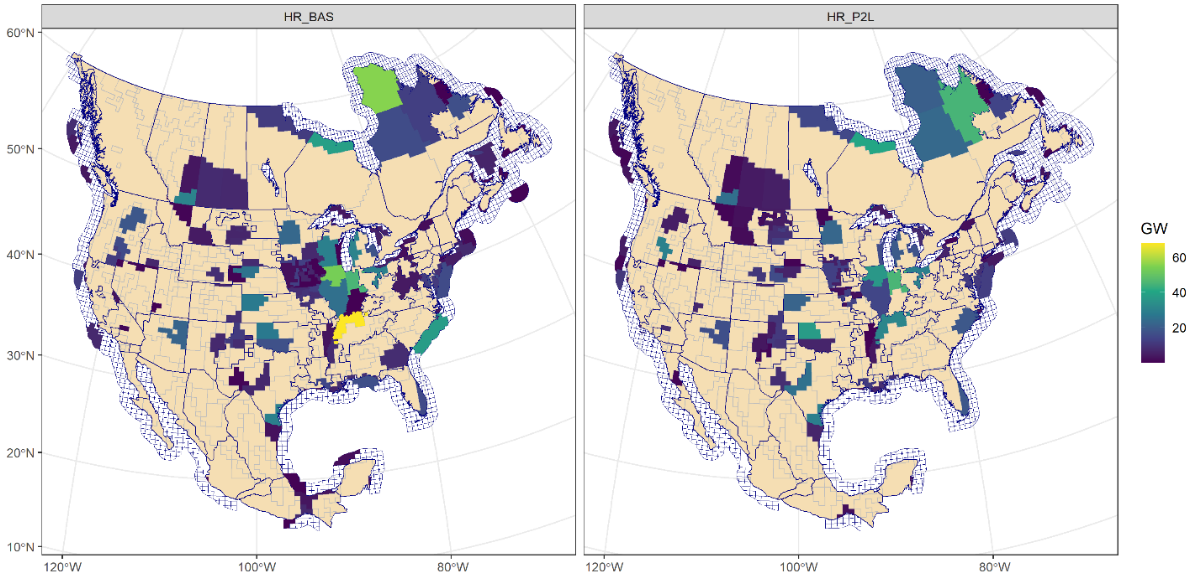

Figure 10: Installed wind power capacity in scenarios with (HR_P2L) and without (HR_BAS) power-to-liquid technology.

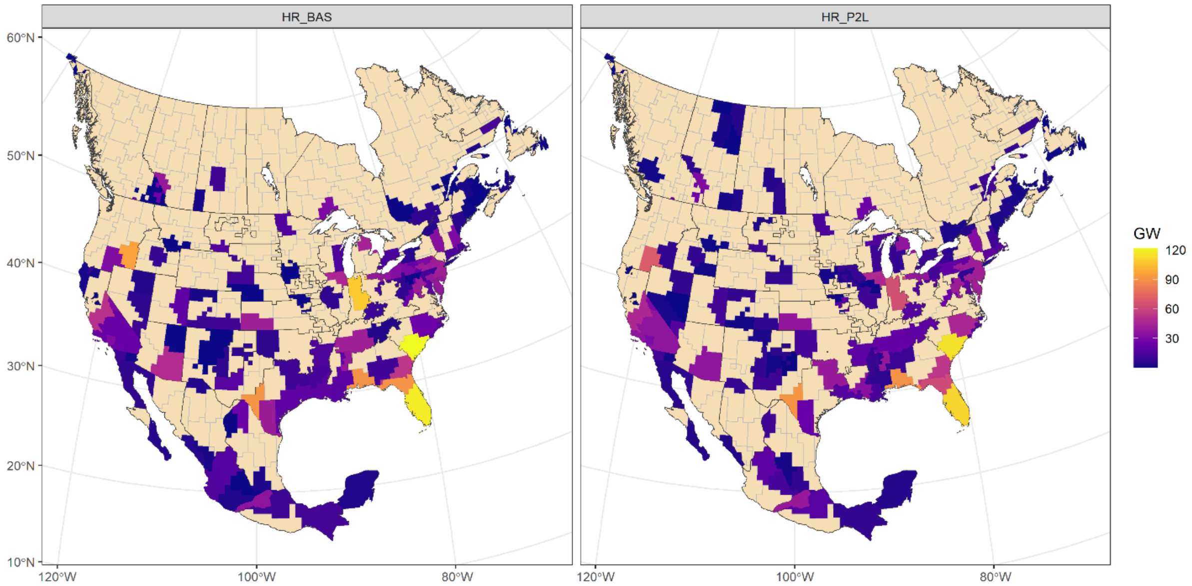

Figure 11: Installed solar power capacity in scenarios with (HR_P2L) and without (HR_BAS) power-to-liquid technology.

The results for the scenarios with hydrogen production technologies (HR_P2L) show lower overall capacity than the base scenario (HR_BAS) and significantly lower energy storage requirements; 1,558 GWh of storage every 4 hours when hydrogen production occurs compared to 2,395 GWh every 4 hours without hydrogen production (see Table 4). The reduction in energy storage requirements is expected given the capacity reduction and reflects the substitution where surplus electricity is used for hydrogen production, rather than stored (see Figure 12).

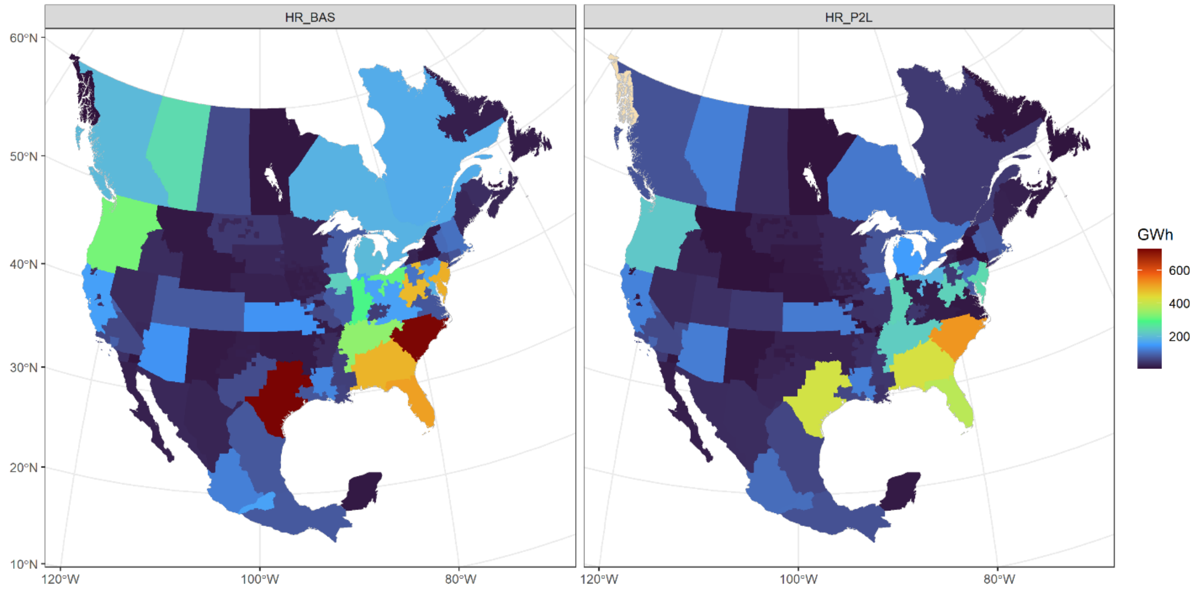

Figure 12: Energy storage by regions.

The siting of P2L technologies varies by region and is dependent on the scale of regional demand, and installed wind or solar capacities. In the United States, Texas and Florida, have the highest electricity consumption and also some of the highest P2L capacity (see Figure 13). In Canada, the province with highest wind potential, Quebec, has the highest P2L capacity (see Figure 13).

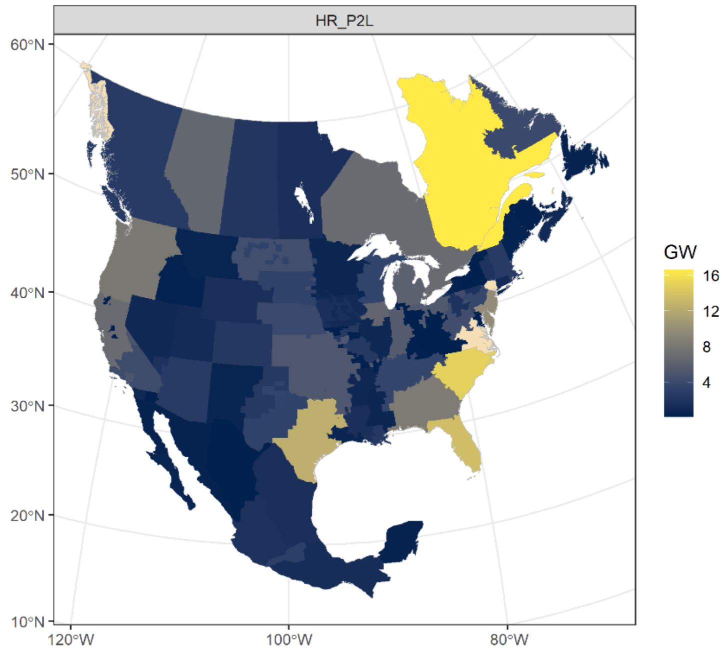

Figure 13: Installed capacity of P2L technology (measured in GW of peak electricity consumption).

The results of this modelling prove the study concept that hydrogen production can provide a critical demand-side flexibility option that helps to balance the grid. As demonstrated in scenario HR_P2L, when hydrogen production is introduced, there is a significant decrease in energy storage, as surplus electricity is used for electrolysis.

The results also prove the overall concept that there will be sufficient surplus renewable electricity to support e-fuel production for aviation. Jet fuel demand in the U.S. in 2050 is expected to be 35 billion gallons (The White House, 2021) which is equivalent to approximately 1,385 Terawatt hours (TWh) of energy. The evaluated surplus energy allocated to hydrogen production in the U.S. in 2050 is 2,092 TWh. This is sufficient supply for electrolysis, which has an energy efficiency of approximately 70%, meaning it is equivalent to 1,464 TWh of hydrogen output; greater than the expected 1,385 TWh of demand from aviation.

A key limitation of this finding is that it only pertains to the energy requirements for hydrogen production and does not include the full e-fuel production pathway. The model focuses on hydrogen production in order to assess its potential to use only surplus electricity and provide grid balancing services. It is also one of the most energy intensive steps on the e-fuels pathway, meaning it provides a good indication of future energy demand. Of course, more renewable electricity will be needed to power the full e-fuel production pathway, but we do not anticipate that this will be an issue as while this model assumes electricity demand is equivalent to 2019 levels, estimates are that demand will be 40% to 50% higher than today (Chakroun et al., 2021 &. IEA, 2021). Greater demand will require additional generation capacity to accommodate demand across sectors, which will result in additional surplus electricity availability.

3.4 Next steps

The demonstrated scenarios prove the overall concept of the study. However further steps are necessary to refine data and assumptions, simulate the transition of the power sector overtime and simulate demand for the entire e-fuels pathway. Future iterations of this model would include more generating technologies such as hydro and nuclear energy, sources that are especially important in Canada. We also envision modelling an expansion of the grid and higher expected levels of total demand.

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4 Techno-Economic Modeling: European Case Study

4.1 BeWhere modeling

IIASA's BeWhere model (Leduc et al., 2009, 2010; Patrizio et al., 2017; Wetterlund et al., 2012) is used to project optimal distribution options of jet fuel facility production plants in Europe and USA. Focus is put on e-kerosene as a substitution for conventional jet fuel, as it requires fewer changes to aircraft propulsion technology and the distribution infrastructure.

The model will identify where to source the CO_2, and water to supply the necessary electrolysis and DAC plants, assuming that costs and GHG emissions must be minimized across the full supply chain of e-kerosene production. Further down the supply chain, the model will also identify optimal CO and H_2 shipping to the synthesis plants and the final product (i.e., e-kerosene) further to the demand points (i.e., airports) (see schematic chart in Figure 14).

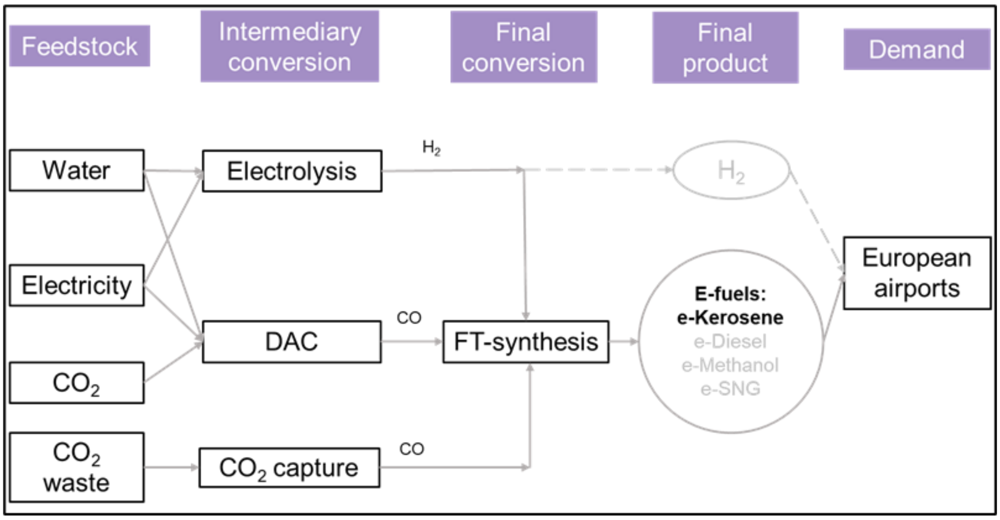


Figure 14: structure of the BeWhere model. In ADEPT, focus is put on the pathway for e-kerosene.

The input data needed for the model is presented below.

4.2 Input data for the European case study

4.2.1 Groundwater

4.2.1.1 Availability

Groundwater availability has been derived from the groundwater supply and demand of the global database provided by (Greve et al., 2018). The data is available for various SSP1/RCP4.5, SPP2/RCP6.0 and SSP3/RCP6.0 from 2010 to 2050 with a 10-year time step at a 50 km^2 resolution (Figure 15). For the runs applied in this report we limited the use of SSP1/RCP4.5.

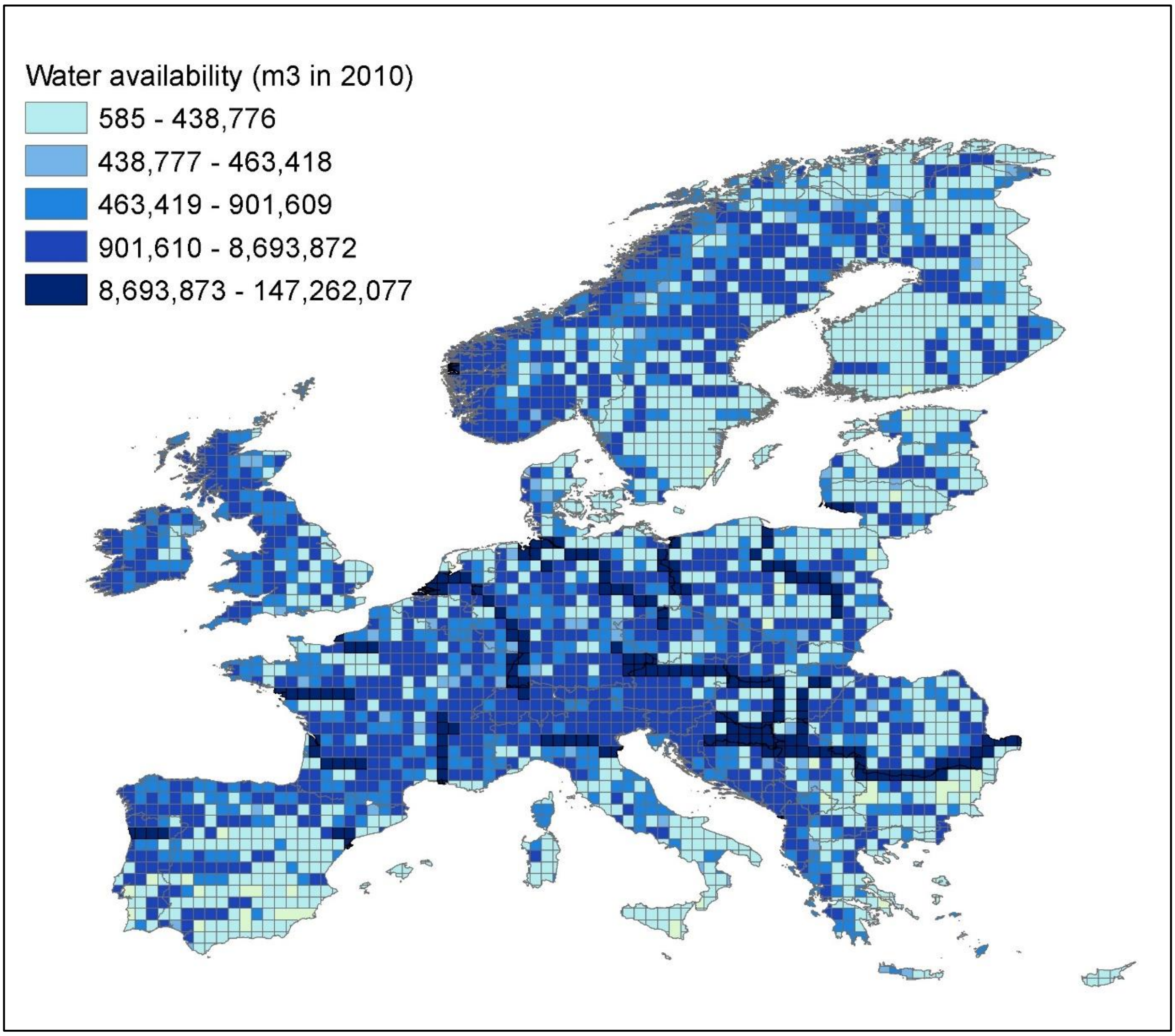


Figure 15: example of the data on freshwater availability in 2010 for the SSP1/RCP4.5 scenario (Greve et al., 2018).

The cost of groundwater is represented per country (Figure 16). The future cost is assumed to increase at an annual rate of 1%.

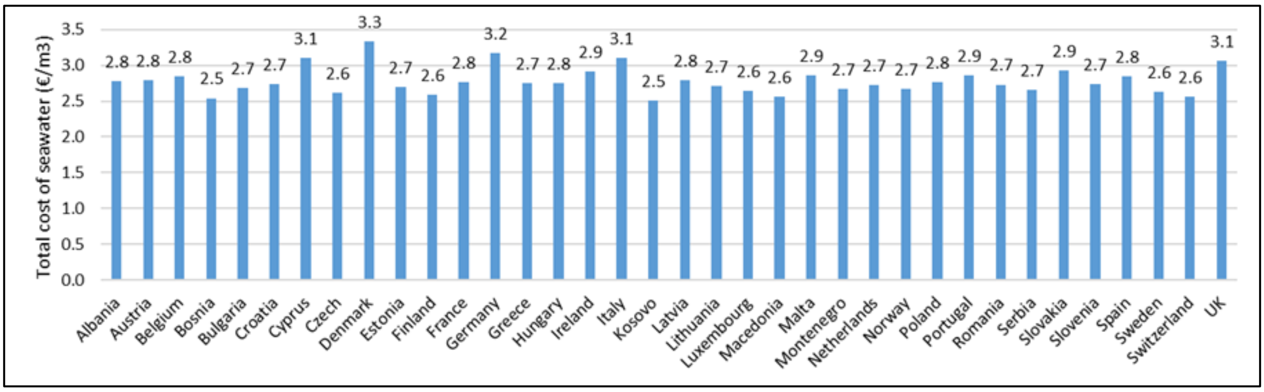


Figure 16: Groundwater cost by country.

** Countries for which data is missing. Water cost for Bosnia and Serbia are assumed to be similar as of Croatia's; for Albania, Kosovo, Macedonia, and Serbia are assumed to be similar to Greece's, for Bulgaria is assumed to be similar to Romania's; for Latvia is assumed to be similar to Estonia's. Source: (Peñalver et al., 2018),*
*** (Reynaud, 2015b)*

Water (groundwater or seawater) can be supplied locally, within an area of no greater than 100 km away the electrolysis or DAC facilities. Shipping water long distances via pipeline would require costly infrastructure and introduce additional geographical constraints/parameters which are not covered in this study. A reasonable share of groundwater is available for e-fuel production, leaving sufficient supply of water to be used for other purposes (e.g., industry, agriculture, direct human consumption). Water availability is studied in the sensitivity analysis, and it shows that a low share (1%) would be sufficient (see the section results).

4.2.2 Seawater

Seawater desalination is a promising technology to achieve an alternative supply of high purity water for the electrolysis process in coastal arid areas with plentiful renewable energy. The most commonly used desalination technologies are reverse osmosis (RO), multi-stage flash distillation (MSF), electrodialysis (ED).
A large water desalination plant has a capacity between 10,000 – 50,000 m^3/d (Eke et al., 2020). In this study, the output capacity of the desalination plant is limited to 15,000 million liter/year (or 41,000 m^3/d). Such capacity limit represents the seawater availability of each grid cell.
The cost of seawater was obtained from (Caldera & Breyer, 2020) for global average levelized cost of desalinated water, which was forecasted from about 2.4 €/m3 in 2015 (Figure 17) to approximately 1.05 €/m^3 by 2050. Values of other years are interpolated. Desalination is the answer to long-term water security, but it's also expensive and energy intensive. To account for electrical energy consumption of the desalination plant, the cost of electricity used in the desalination process is included in the cost of seawater. The electricity consumption is based on the median value of the energy requirements of industrial desalination process with MSF technology, 5 kWh/m3 (Desware, 2021). The MSF technology is the second most dominant water desalination technology with typical unit size of 50,000 – 70,000 m3/d (Desware, 2021; IRENA-IEA-ETSAP, 2012).

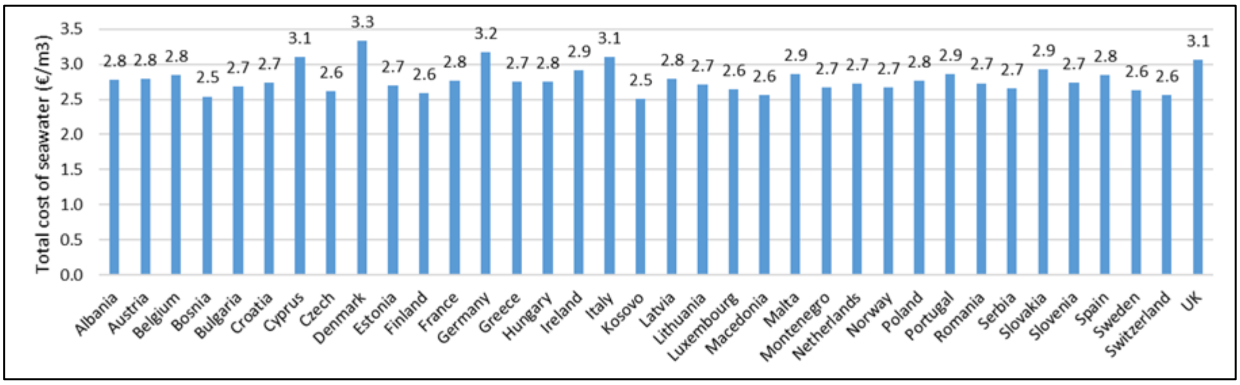


Figure 17: Total seawater cost by country in 2020.
Note: Total seawater cost includes levelized cost of desalinated water and cost of electricity consumption.

A maximum distance of 100 km from the coastline was assumed for seawater accessibility to the plant.

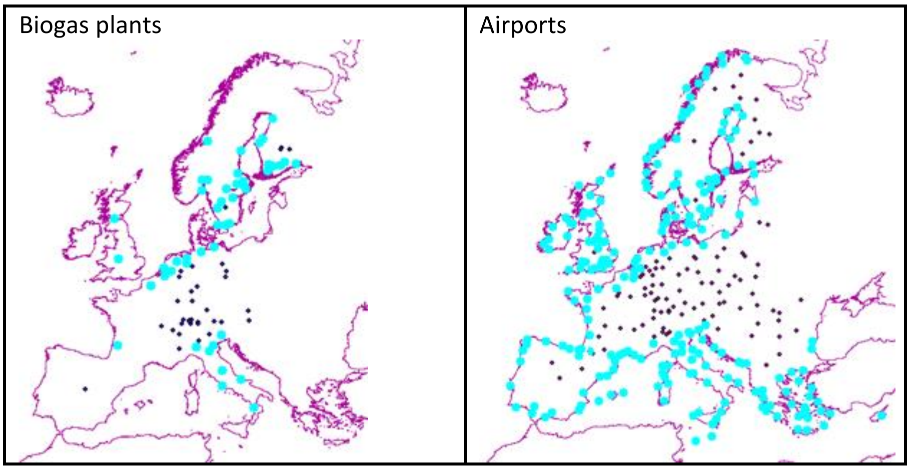


Figure 18: biogas plants (left) and airports (right) with access to seawater within 100 km from the EU coastline. Note: EU coastline map is obtained from (European Environment Agency, 2021).

4.2.3 Electricity

One of the key factors determining the sustainability of e-fuels is the access to electricity. Electricity supply data has been informed by the literature (Mesfun et al., 2017, 2018). The data is spatially explicit for Europe obtained from (Mesfun et al., 2018). Mesfun et al. (2018) focused on the expansion of onshore wind power and solar PV, estimating 400 TW of maximum capacity in EU and Balkan countries. The maximum capacity is derived based on the highest wind or irradiance under the sample year. The study integrated biodiversity conservation and the sustainable use of the ecosystem services, through avoiding potential environmental impacts and land degradation. The total area of the protected regions and their share within each grid cell are excluded from the available area for installing intermittent renewable technologies. This approach reduces potential environmental impacts of e-fuels production. The data from Mesfun et al., (2018) is complemented by Ringkjøb et al., (2020) for the potential in Norway, Switzerland and Czech Republic, and by IRENA (2017) for the potential in Albania, Bosnia and Herzegovina, Republic of Serbia, Kosovo, and Macedonia.

The EU final energy demand is predicted to remain stable until 2050 with significant changes in fuel mix due to further electrification of the EU energy system through renewable power generation technologies. The role of renewable energy in meeting electricity requirements becomes predominant by 2050. The EU energy outlook to 2050 developed by Mantzos et al., (2019) estimated the share of renewables of 76%. To meet the growing electricity demand, 698 GW of wind onshore and PV need to be installed between 2015 and 2050. Such net installed capacity (698 GW) from Mantzos et al., (2019) is used in this study to scale down the potential expansion capacity at grid level provided by Mesfun et al., (2018), equivalent to a factor of 0.17% of available electricity. A spatial constraint for grid connectivity is set to be 500 km as typical transmission radius suggested by Searle & Christensen (2018).

For comparison, Ash estimated the renewable electricity requirements for EU28 zero emission transport for road, shipping and aviation (Ash, 2020). His analysis concluded that a complete switch from fossil-based kerosene to e-fuel to fulfil the aviation demand in 2050 will require about 745 TWh of electricity (2,686 PJ), or equal to 25% of total EU electricity generation in 2019 (Eurostat, 2021c).

The cost of electricity is an annual average value from 2015 to 2020 (Eurostat, 2020). It is the electricity cost for non-household costumers which includes all taxes and levies. The electricity cost until 2050 has been estimated by assuming an annual reduction rate of 1%, due to technology maturity (Figure 19).

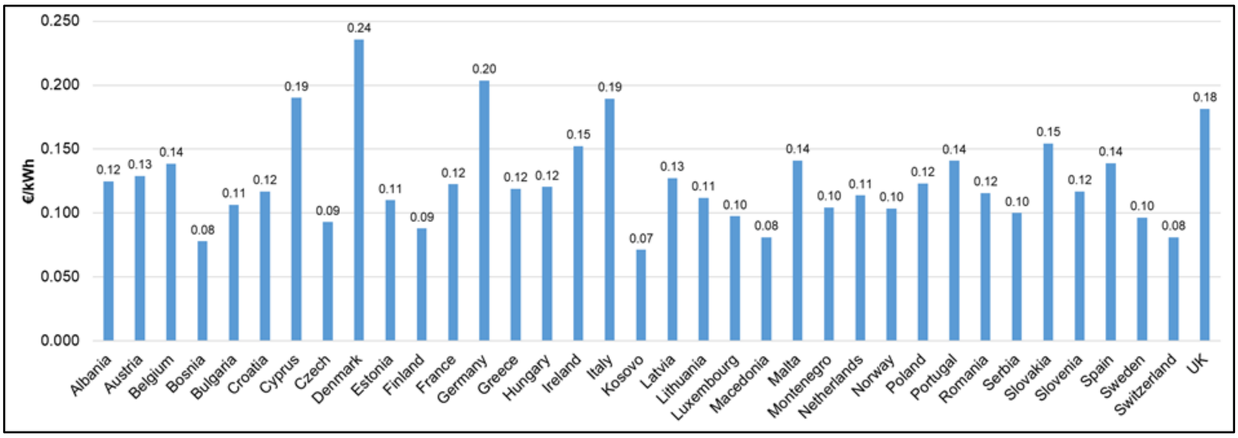


Figure 19: Distribution of the cost of electricity per country (Eurostat, 2021b).

Finally, the desalination process is based on an average of electrity consumption of 5 kWh/m^3.

4.2.4 CO_2 availability

The carbon used in e-fuels should ideally come from two main sources: (1) pre-combustion waste CO_2 from, e.g., MSW based biogas production, and (2) direct air capture. The latter is expected to take a growing role over time as its production cost decreases and waste CO_2 becomes scarce in a carbon constrained world (Table 5). To produce e-fuel, the CO_2 is converted into CO through a reverse water-gas-shift reaction (RWGS) (van Dyk & Saddler, 2021).

Table 5: Cost of capturing CO2

Technology	Unit***	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	2050	References
DAC*	€/t_{CO2}	730	562	378	399	265	235	222	(Fasihi et al., 2019)
Industrial CO_2 **	€/t_{CO2}	252	237	221	206	191	176	161	(Jouny et al., 2018)

* The cost for 2025, 2035 and 2045 are interpolated
** The cost from 2025-2050 follows the cost reduction of electrolysis
*** Conversion/efficiency t_{CO}/t_{CO2} = 0.64 (Becattini et al., 2021)

- Industrial CO_2 from MSW based biogas plant

The plants included in the analysis are biomethane plants which upgrade the raw biogas production to a virtually pure stream of methane, which can then be injected into the local gas grid or used locally for heating and fuelling purposes. At the end of 2018, there were 610 active biomethane-producing plants in Europe using energy crops, agricultural residues, manure, plant residues, sewage sludge, MSW, industrial waste and landfill (EBA-GiE, 2020). In this study, only plants using MSW are included to ensure a biogenic source and avoid direct and indirect land use impacts, giving a total of 81 plants. EBA-GiE map (EBA-GiE, 2020) provides the plant capacity while the plant's coordinates were obtained from Google Maps (Figure 20).
The CO_2 output per plant is estimated based on CO_2 per GWh upgraded biogas, 145.7 tCO_2/GWh (Hansson et al., 2017), using energy content in biogas 9.67 kWh/m^3 (Carlsson & Uldal, 2009) and plant operation hours of 5,500 h/y (Montoro et al., 2015).

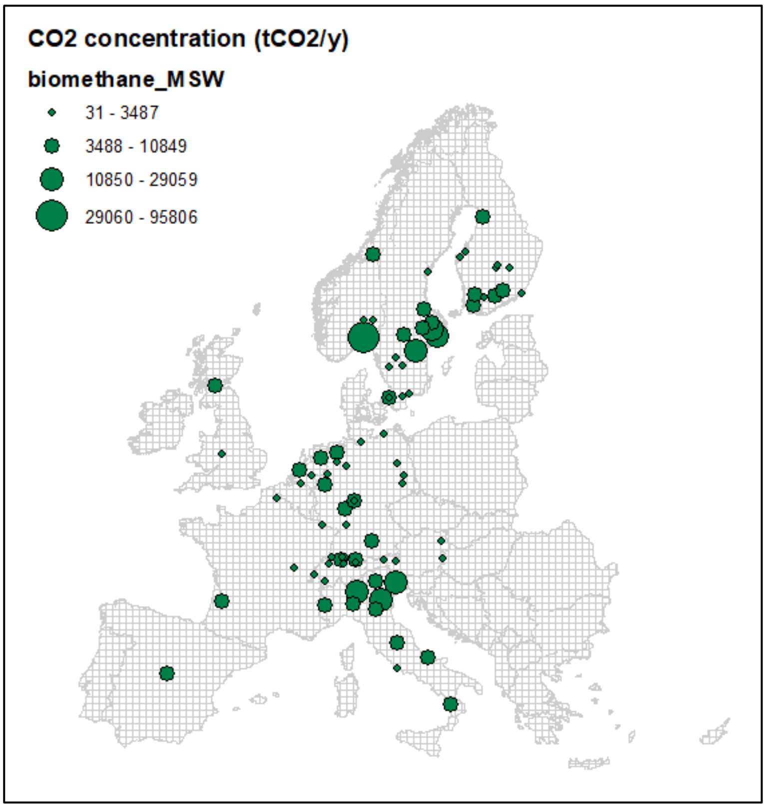


Figure 20: Location and capacities of municipal solid waste

- CO_2 direct air capture (DAC)

Another approach for CO_2 emissions removal is capturing CO_2 directly from the atmosphere. From the energy system perspective, DAC technologies can be categorised as high temperature aqueous solutions (HT DAC) and low temperature solid sorbent (LT DAC) systems (Fasihi et al., 2019). They are also distinguished by high or low-grade heat demand. After binding the CO_2, the sorbent is regenerated releasing high purity CO_2 that can be safely stored (EASAC, 2018). Several companies active in the field of DAC apply HT DAC, including Carbon Engineering, and LT DAC is applied by Climeworks, Global Thermostat, Antecy, Hydrocell, Infinitree, Skytree (Fasihi et al., 2019).

DAC can play an important role for sector coupling, linking high integrity renewable fuel production with a renewable electricity-based energy system of the future, which will be mainly based on solar PV and wind energy. It also avoids major conflicts with land use. Ultimately, it provides additional key advantages over pre-combustion waste CO_2 capture, such as very low-cost energy supply, good energy system integration, access to areas of excellent energy resources and the potential to decouple the locations of DAC and electricity generation (Breyer et al., 2018).

In this analysis, the atmospheric CO_2 concentration is assumed to be 1 Mt_{CO2} per grid. DAC plants are adjacent to the airport location.

4.2.5 Jet fuel demand

Based on the input data, a first estimation of European jet fuel demand has been calculated considering airport location, flight distance of origin and destination, respective flight frequency, based on ICAO's fuel consumption formula (ICAO, 2018). The flight frequencies of point-to-point sources of domestic, intra-EU and extra-EU have been derived from Eurostat database, using the annual average jet fuel consumption between 2015-2019 (Eurostat, 2021a). The jet fuel demand at the European level only accounts for flights departing from European airports. The jet fuel demand until 2050 has been estimated by assuming an annual growth rate of 5%, considering 345 large- and medium-scale airports. The jet fuel demand in Europe represents about 1,230 PJ in the year 2019, including both passenger and freight fuel (Figure 21). Assuming 5% annual demand growth results to 1,597 PJ of aviation fuel in 2050. The estimation is close to estimation from (Ash, 2020). For comparison: (Ash, 2020) estimates that 100% aviation fuel demand from e-kerosene in Europe in 2050 would require 745 TWh of electricity (2,686 PJ) or a total jet fuel demand of about 1,282 PJ (using a conversion of 2.1 $PJ_{electricity}/PJ_{kerosene}$).

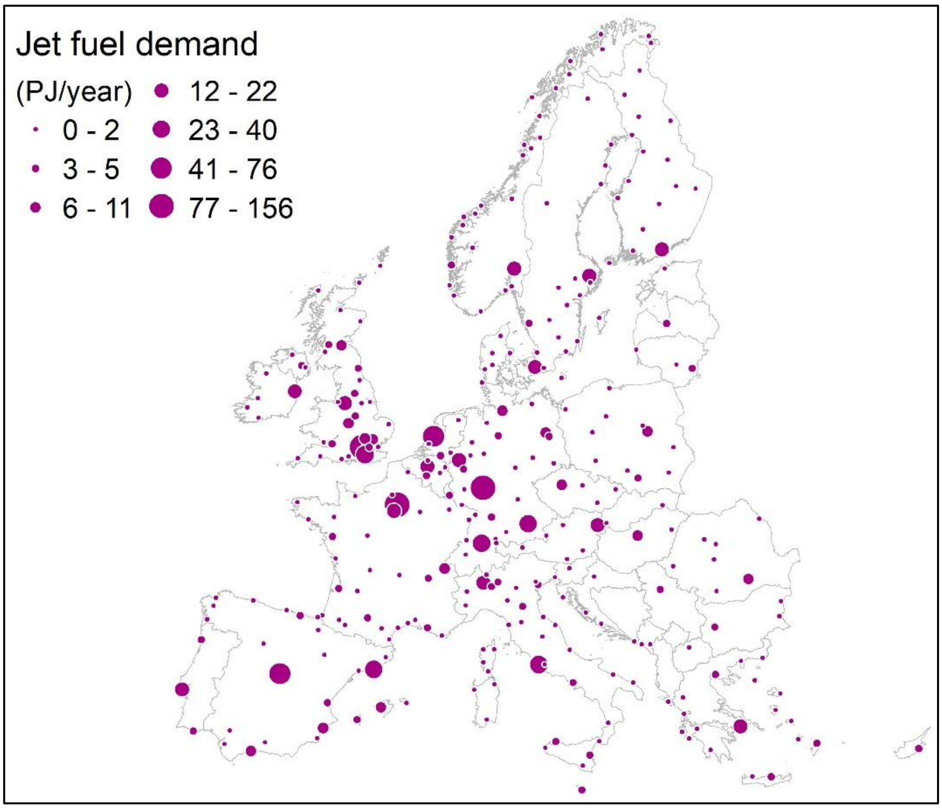


Figure 21: Location and jet fuel demand of the major European airports.

4.2.6 Transport

The model accounts for the transport of all feedstock and energy carriers from the access point to the process facility to the consumption point. The figures assumed for the transport of commodities are presented in Table 6.

Table 6: Transport cost of the commodities involved in the supply chain.

Mode	Feedstock	Unit	Transport fix cost	References	Unit	Transport variable cost	References
Pipeline	Water	€/l	$8.3 \cdot 10^{-4}$	(Zhou & Tol, 2005)	€/l.km	$5.1 \cdot 10^{-7}$	(Zhou & Tol, 2005)
Pipeline	CO	€/GJ	0		€/GJ.km	0	
Grid	Electricity	€/GJ	0		€/GJ.km	0	
Truck	e-kerosene	€/GJ	0.03	(de Jong et al., 2017)	€/GJ.km	0.005	(de Jong et al., 2017)

Train	e-kerosene	€/GJ	0.1	(de Jong et al., 2017)	€/GJ.km	$2 \cdot 10^{-4}$	(de Jong et al., 2017)
Ship	e-kerosene	€/GJ	0.35	(de Jong et al., 2017)	€/GJ.km	$2 \cdot 10^{-4}$	(de Jong et al., 2017)

4.2.7 Emissions

In addition to the costs, the model accounts for the emissions associated with the main activities characterising e-fuel supply chains. CO_2-based synthetic fuels are produced using only surplus renewable electricity generation that would otherwise be unused or curtailed. Therefore, no new electricity installations are built or operated as a result of CO2-based synthetic fuel demand. Thus there are no upstream or indirect emissions from electricity production. CO_2 emissions associated with logistic activities, i.e., groundwater and seawater transport to the plant, as well e-fuel transport to the airports, are also considered, based on the emission factors presented in Table 7. Finally, potential CO_2 leakages from CO_2 pipelines have not been considered in the analysis.

Table 7: Overview of the emissions of CO2 per mode of transport.

Mode	Feedstock	Unit	Transport emissions
Pipeline	Groundwater	t/l	$8.4 \cdot 10^{-7}$
Pipeline	Seawater	t/l	$2.9 \cdot 10^{-6}$
Pipeline	CO_2		0
Truck	e-kerosene	t/GJ.km	1.1
Train	e-kerosene	t/GJ.km	0.717
Ship	e-kerosene	t/GJ.km	0.363
Source: Emission factors for water supply and distribution are obtained from (Meron et al., 2016). Other emission factors are obtained from (Mesfun et al., 2018). LHV of e-fuels (Yugo & Soler, 2019)			

4.2.8 Techno-economic data

There are a range of options for the production of electrolytic hydrogen, including alkaline electrolysis cells (AEC), polymer electrolyte membrane (PEM) and solid oxide electrolysis cell (SOEC). These technologies are at varying levels of commercial maturity; alkaline electrolysis has been in commercial operation since 1902 whereas SOECs are still at the demonstration stage. PEM electrolysis is arguably at an intermediate level of commercial maturity and is regarded as a promising technology towards the deployment of a hydrogen economy given its capabilities to work at low-capacity factors, high system efficiency, and its ability to produce highly pure hydrogen. For these reasons, this works assumes the use of PEM electrolysis as the archetypal technology for hydrogen production. Main operating parameters, such as capital and operational cost as well conversion efficiencies and capacity factor are taken from the 2020 World Economic Forum report (World Economic Forum & McKinsey & Company, 2020).

The hydrogen produced from these reactions is then processed in the fuel synthesis process unit, with CO_2, to create short or long chain hydrocarbons. As discussed in section 2.1, our analysis considers the use of CO_2 captured from the atmosphere with DAC, as a potential feedstock for the fuel synthesis. Two archetypal DAC plants are currently being developed at the demonstration-scale, i.e., high temperature aqueous solutions and low temperature solid sorbent systems. Low temperature DAC systems are generally assumed to have lower heat supply costs, owing to the possibility of using waste heat from other systems, and have been considered here.

Important parameters and economic assumptions for all these subsystems are detailed in Table 8 to Table 10. The cost of DAC is here presented as a high cost. Alternative medium and low costs are taken from Table 1.

Table 8: Summary of the investment cost inputs for the technologies studied.

Technologies	Unit	Investment cost *							**References**
		2020	2025	2030	2035	2040	2045	2050	
Electrolysis	€/GJ_{H2}	7.06	6.64	6.21	5.79	5.36	4.94	4.51	(World Economic Forum & McKinsey & Company, 2020)
DAC	€/t_{CO2}	730	562	378	399	265	235	222	(Fasihi et al., 2019)
Industrial CO2**	€/t_{CO2}	252	237	221	206	191	176	161	(Jouny et al., 2018)
Synthesis to e-kerosene	€/$GJ_{kerosene}$	4.2	4.2	4.2	3.74	3.63	3.46	3.38	(World Economic Forum & McKinsey & Company, 2020)
* Annualized cost is calculated based on 5% discount rate and 20 years plant lifetime. ** calculated using efficiency t_{CO}/t_{CO2} of 88% (Adelung et al., 2021)									

Table 9: Summary of the operation and maintenance cost inputs for the technologies studied.

Technologies	Unit	Operation and Maintenance (O&M) cost							**References**
		2020	2025	2030	2035	2040	2045	2050	
Electrolysis*	€/GJ_{H2}	0.2	0.2	0.2	0.2	0.2	0.1	0.1	
DAC *	€/t_{CO2}	22	17	11	12	8	7	7	
Industrial CO2*	€/t_{CO2}	7.6	7.1	6.6	6.2	5.7	5.3	4.8	
Synthesis to e-kerosene	€/$GJ_{kerosene}$	0.36	0.3	0.25	0.23	0.21	0.19	0.19	(World Economic Forum & McKinsey & Company, 2020)
* O&M cost is fix cost, 3% of annual investment cost. For electrolysis, DAC and industrial CO2, variable cost is included in the form of market prices of electricity (Eurostat, 2021b) and water per country (LópezPeñalver et al., 2018; Reynaud, 2015a)									

Table 10: Summary of the key technical inputs for the technologies studied.

Technology	Input	Efficiency	Ratios
Electrolysis	Water, Electricity	0.65 - 0.76 $J_{H2}/J_{electricty}$ (IRENA, 2020)	H2O/electricity = 0.19 l/kWh (van der Giesen et al., 2014)
DAC	Water, Electricity, CO_2	0.64 t_{CO}/t_{CO2} (Becattini et al., 2021)	Elec/CO_2 = 3.8 MWh/t_{CO2} (Becattini et al., 2021) Water/CO_2 = 1,890 l/t_{CO2} (Fasihi et al., 2019)
Industrial CO2	Water, Electricity, CO_2	0.88 t_{CO}/t_{CO2} (Adelung et al., 2021)	Elec/CO_2 = 6.64 MWh/t_{CO2} (Fasihi et al., 2016) Water/CO_2 = 1,009 l/t_{CO2} (Fasihi et al., 2016)
Synthesis to e-kerosene	H_2, CO	0.69 $J_{kerosene}/J_{H2}$ (Tremel et al., 2015)	H_2/CO = 0.15 t_{H2}/t_{CO} (Becattini et al., 2021)

Once a production plant is setup in a selected year, it stays up for the following years. Plant capacity expansion is feasible at maximum 20% increase in the following year.

5 Scenarios

1.1 Demand projection

Two e-fuel demand projections have been used so far for our analyzes. The first one represents the sustainable share for the aviation until 2050 called the "base case scenario" (Table 11), and the second represents a 100% share met by all countries as an upper limit called the "Extreme scenario" to find the optimal share among the countries at the lowest cost.

Table 11: Base case scenario of the share of the e-fuel target per country.

Country	2020	2025	2030	2035	2040	2045	2050
Finland			30%	30%	30%	30%	30%
France	1%	2%	5%	7%	9%	12%	14%
Germany	1%	1%	2%	3%	4%	5%	5%
Netherlands			14%	35%	57%	78%	100%
Norway	1%	16%	30%	45%	59%	73%	88%
Sweden	1%	5%	30%	65%	100%	100%	100%
UK		1%	2%	4%	5%	7%	8%

5.1 Carbon cost projection

The carbon cost is defined following four scenarios:
(1) A zero-cost scenario as a reference
(2) A Base case scenario following the business as usual
(3-4) An aggressive scenario for which the carbon cost already starts at 100 EUR/tCO_2.

The values for each scenario are presented in Table 12.

Table 12: Overview of the four carbon cost scenarios in EUR/tCO2.

Years	Zero	Base case	Aggressive	Extreme
2020	0	30	100	100
2025	0	33	150	150
2030	0	46	200	200
2035	0	50	250	300
2040	0	58	300	400
2045	0	65	400	500
2050	0	72	500	700

6 European Results

6.1 Impact of the resources

6.1.1 Groundwater access

The impact of the groundwater access on the production of e-fuel is presented in Figure 22. To meet the full European e-fuel demand a significant amount of the share of water (above 32%) would need to be dedicated to the production of jet fuel, which limit the expansion of other activities should they be water intensive.

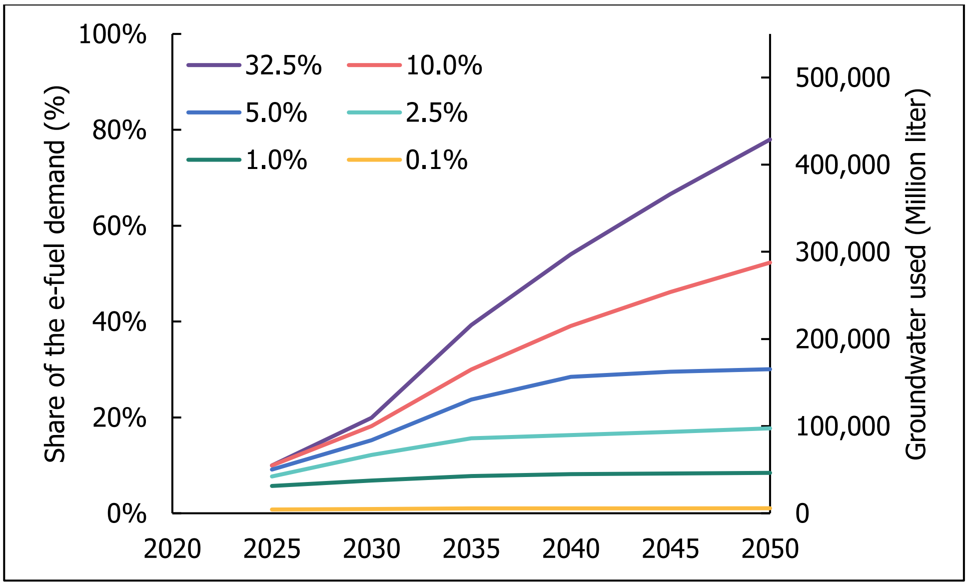


Figure 22: e-fuel production, in share of the European demand and water used in respect of the water availability.

6.1.2 Electricity availability

The impact of electricity availability is presented in Figure 23. Electricity availability is the limiting factor that sets the threshold for e-fuel production. The full demand of e-fuels can be met when at least 2,000 TWh of electricity is available in 2050 and decreases linearly with the electricity available. Note, the electricity available does not correspond to the electricity used, which is represented in the second axis on the right-hand side. To meet the European e-fuel demand in 2050, 1,200 TWh of electricity would be needed.

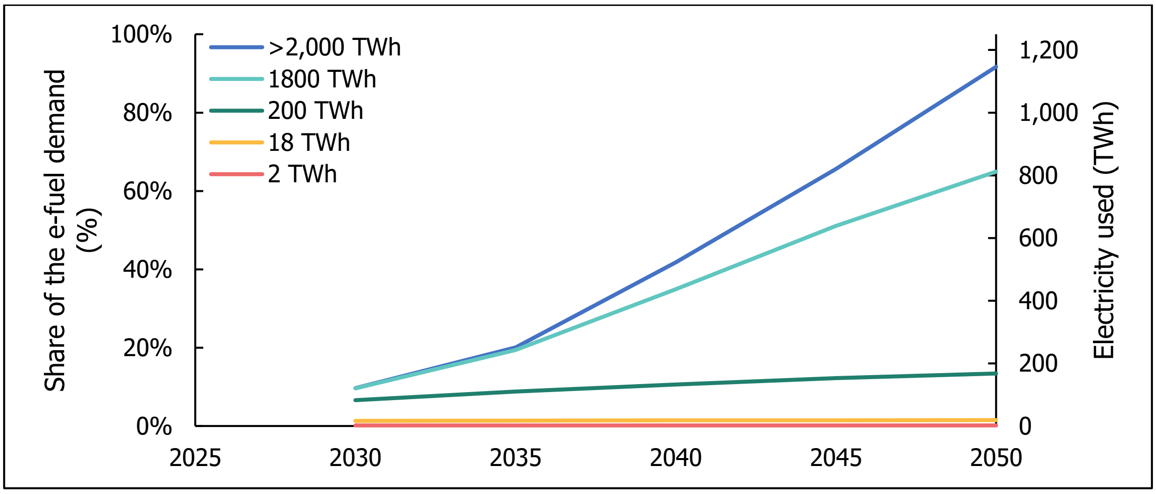


Figure 23: E-fuel production, in share of the European demand in respect with the electricity available.

6.2 Impact of the fossil fuel price

The impact of the fossil fuel price is analyzed and presented in Figure 24. The production of e-fuels only takes off in 2045 with a business-as-usual fossil fuel price (here assigned with the Factor 1). As the price of the fossil fuel increases, e-fuels will be produced earlier and more rapidly. For example, e-fuel production would enter the market 5 years earlier if the fossil fuel price increases by a factor 1.6. Increasing the availability of electricity by 60% would increase the production of e-fuel by at least 50% by 2050.

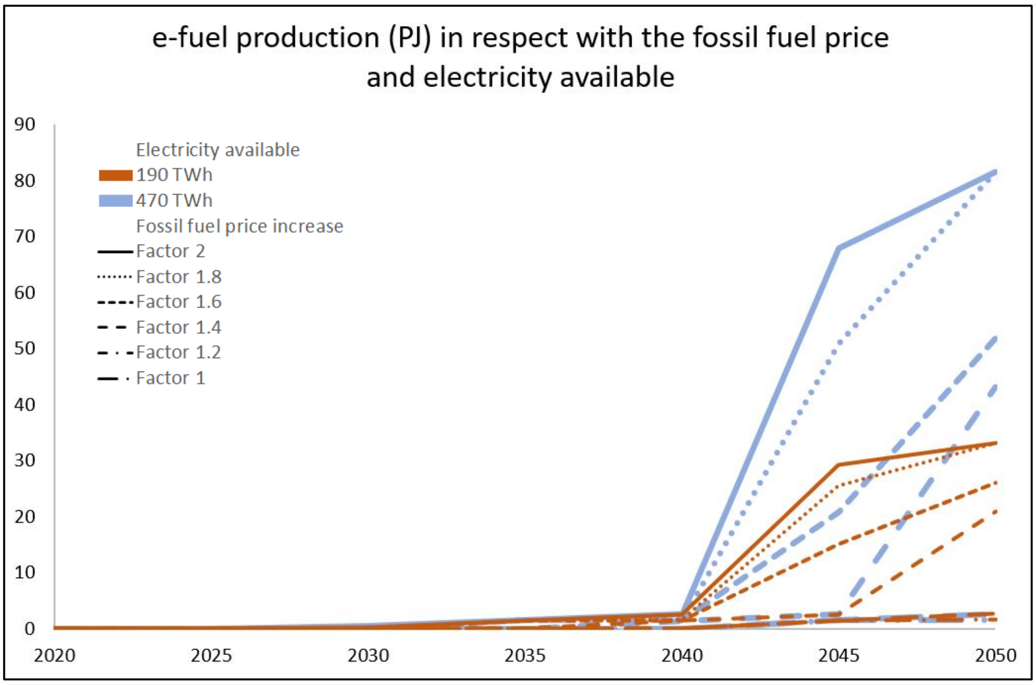
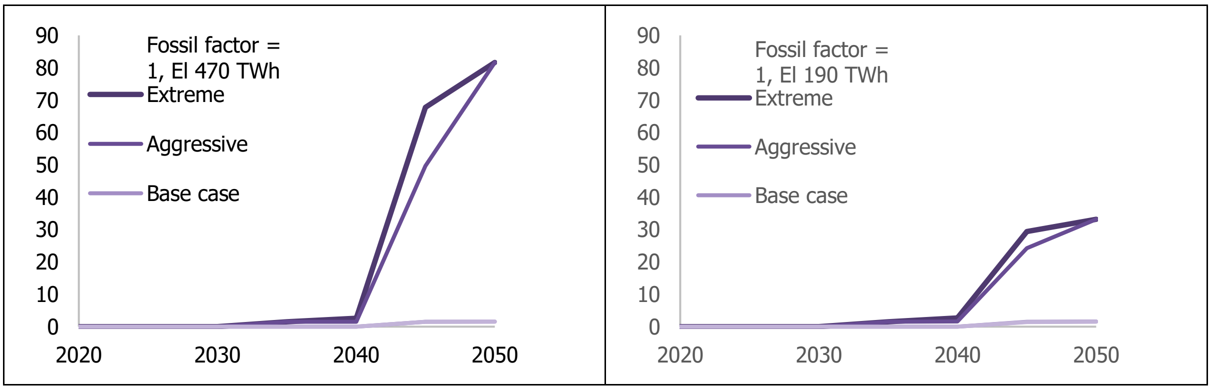


Figure 24: Production of e-fuel depending on the fossil fuel price with a no carbon policy.

6.3 Impact of the carbon cost

The impact of the carbon price on the production of e-fuel is analyzed and presented (see Figure 25). E-fuel production is analyzed with respect to the four carbon cost scenarios, the electricity availability, and the fossil fuel price.

In a *no carbon cost policy scenario,* e-fuel production would be introduced in the market only in 2045 once the fossil fuel price has increased by a factor 1.4 and in 2040 once it has increased by a factor of 1.8. As the carbon cost increases, the e-fuel production will be introduced by as much as 10 years earlier for the two electricity availability scenarios.



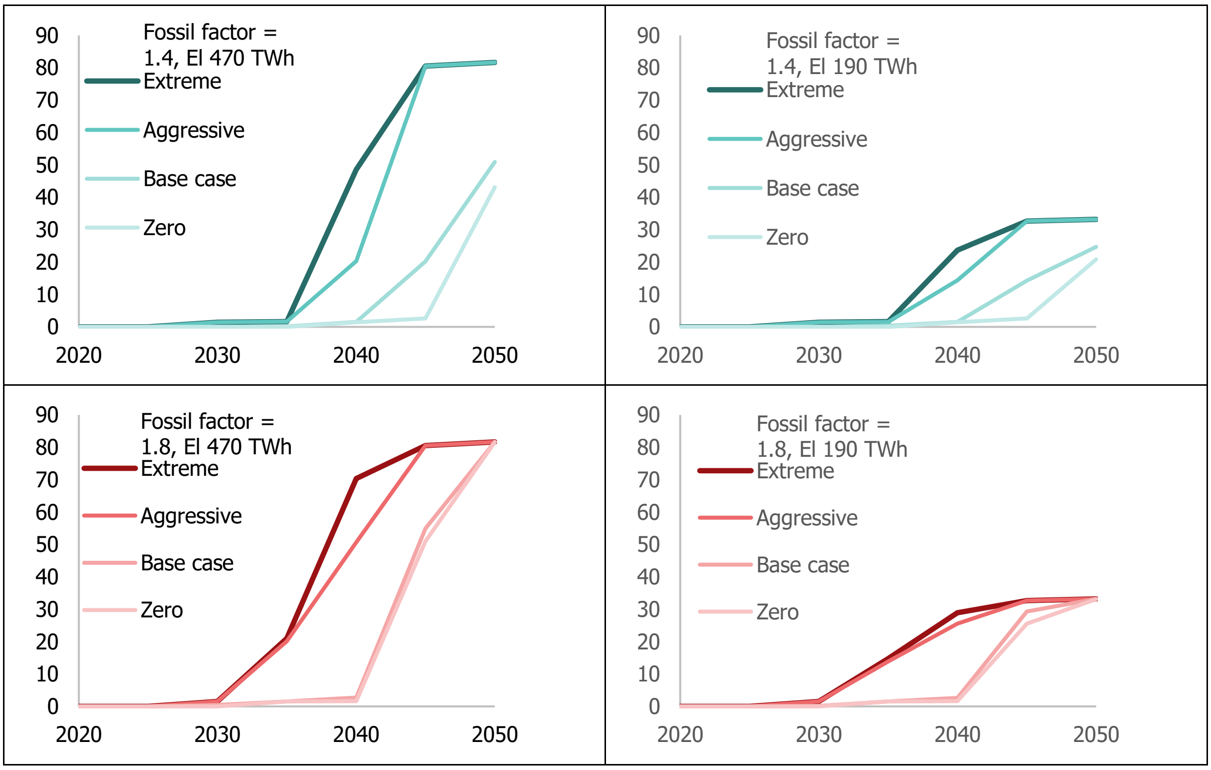


Figure 25: Production of e-fuel (PJ) depending on the four carbon cost scenarios for three fossil fuel price (increase by a factor 1, 1.4 and 1.8 from top to bottom) and two electricity availabilities (470 TWh and 190 TWh from left to right).

6.4 Distribution per countries

The model identifies the optimal location of the production plants as well as the optimal spread of e-fuel for the airports. Figure 26 to Figure 30 present the development of e-fuel in different European airports for different scenarios as detailed in their respective captions. The Nordic countries are well represented due to their lower cost of electricity compared to the other countries and can quickly meet their e-fuel demand based on the mandate. At the same time inland countries such as Switzerland and some eastern European countries have e-fuel production come online first due to the lower price of electricity and water. In the following years, more eastern European countries and countries with a coastline (e.g., France, Spain) begin e-fuel production using desalination plants. Countries like Germany, Italy or Denmark are less conducive to e-fuel production as they have the highest cost of electricity and water. UK has the fourth highest cost of both electricity and water and would be attractive for e-fuel production only when both a high cost of CO_2 and high fossil fuel cost is applied as presented in Figure 26 and Figure 27.

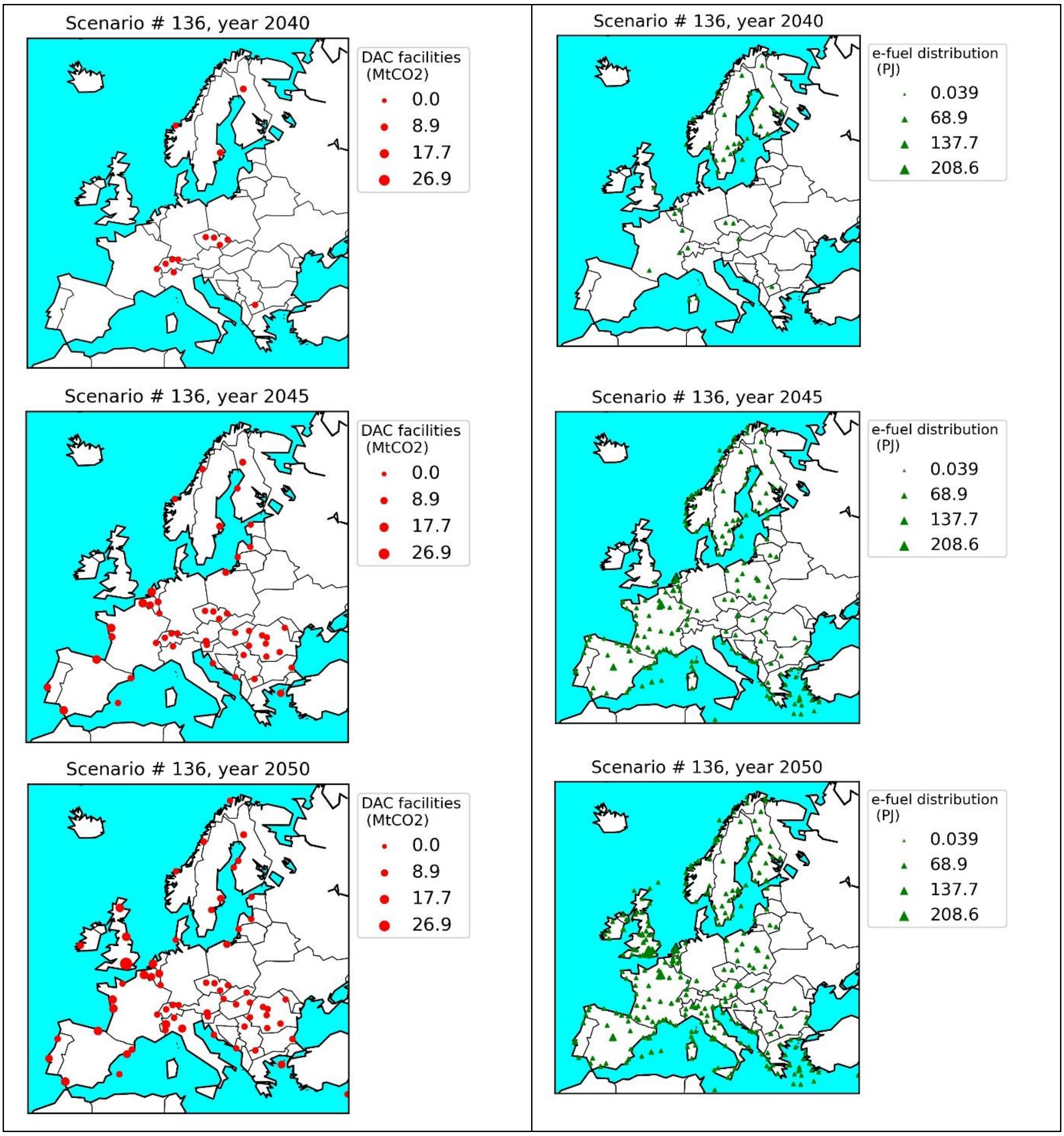


Figure 26: Development of DAC facilities (red dots) and the e-fuel distribution to the airports (green triangles) from 2040 to 2050. Assumptions: High fossil fuel cost, Medium cost of DAC, extreme CO2 price, Blending mandate extreme, desalination plants allowed.

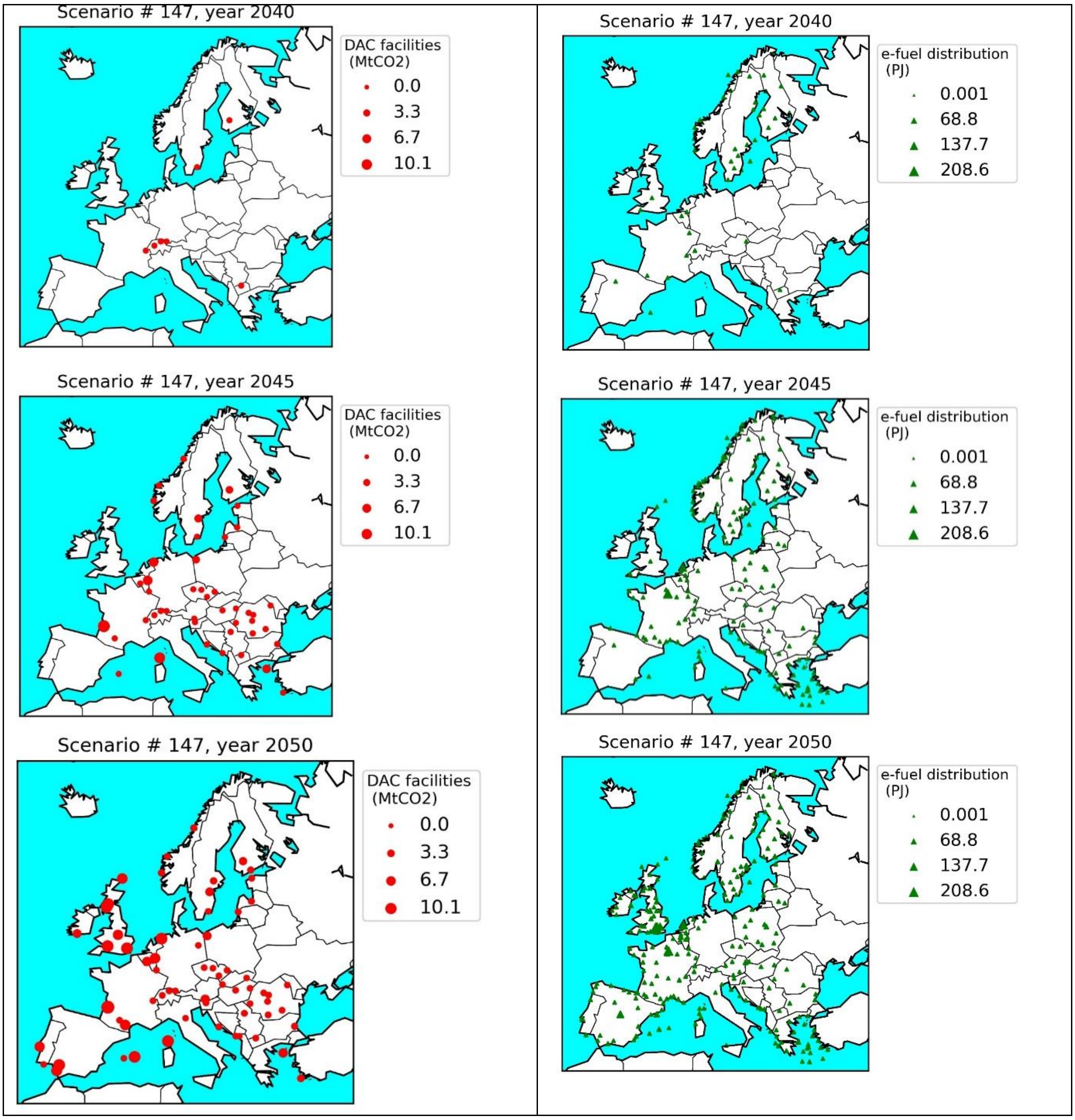


Figure 27: Development of DAC facilities (red dots) and the e-fuel distribution to the airports (green triangles) from 2040 to 2050. Assumptions: High fossil fuel cost, High cost of DAC, Extreme CO2 price, Blending mandate extreme, desalination plants allowed.

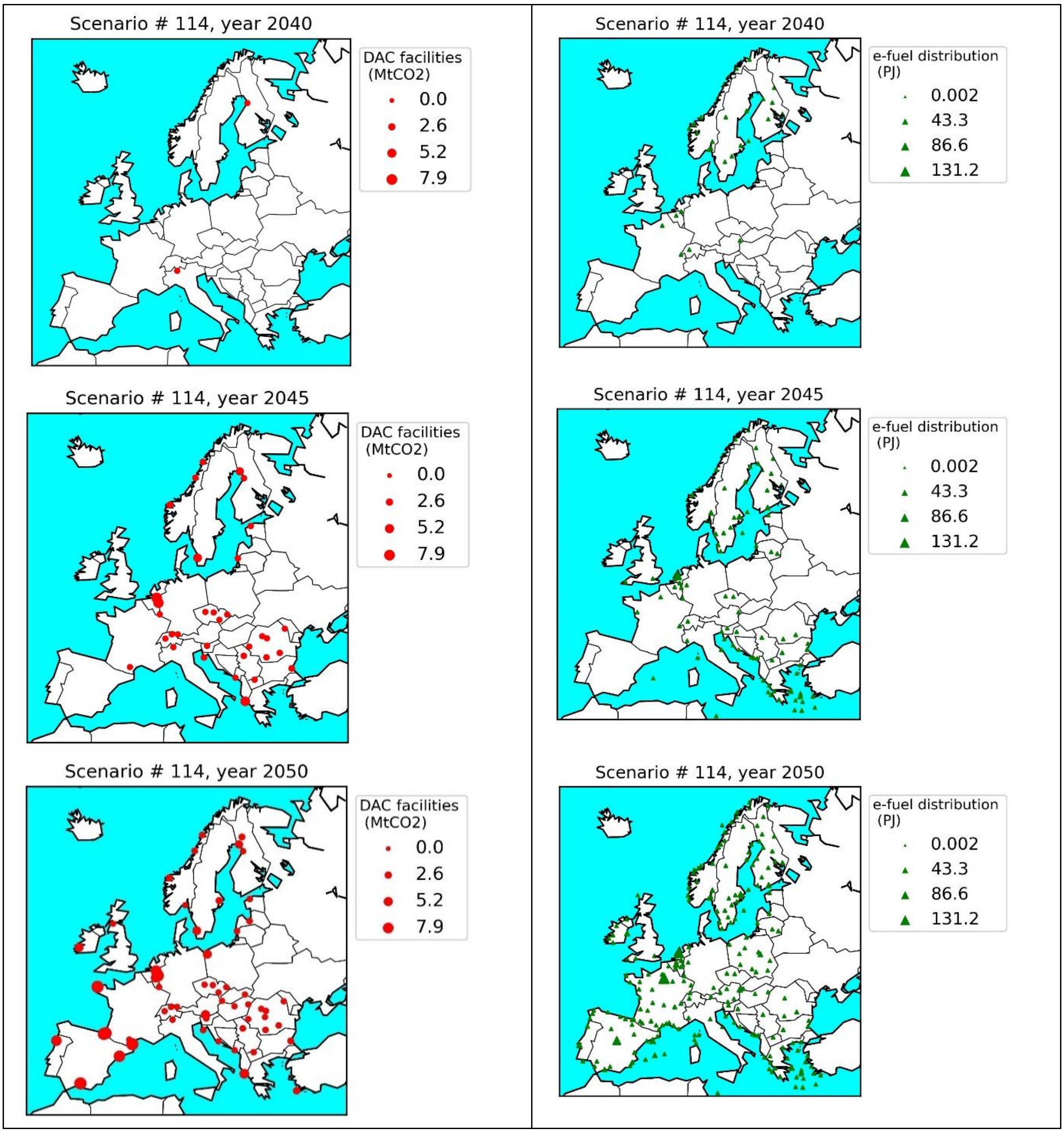


Figure 28: Development of DAC facilities (red dots) and the e-fuel distribution to the airports (green triangles) from 2040 to 2050. Assumptions: High fossil fuel cost, medium cost of DAC, Aggressive CO2 price, Blending mandate extreme, desalination plants allowed.

7 Techno-Economic Modeling: US case study

7.1 US input data

Like the European case study, the BeWhere model has been initialized with the following spatial data:

- Groundwater availability and price
- Desalination water potential facilities
- Location of airports across the US territory and corresponding e-fuel demand
- State level electricity availability derived from EDF and electricity price

7.2 Groundwater availability

The water data has been extracted from the global groundwater dataset from Greve et al., (2018). The dataset presents model estimates of both groundwater supply (that is, available water resources) and demand (that is, water withdrawal), which are both directly and indirectly influenced by climatic changes and socio-economic developments. The data used are provided on a 0.5° × 0.5° global grid and for five decadal climatologies from 2010 on a 10-year timestep. The corresponding net water availability has been calculated as the difference between supply and demand at grid cell level. The resulting groundwater is presented in Figure 29 from 2020 to 2050.

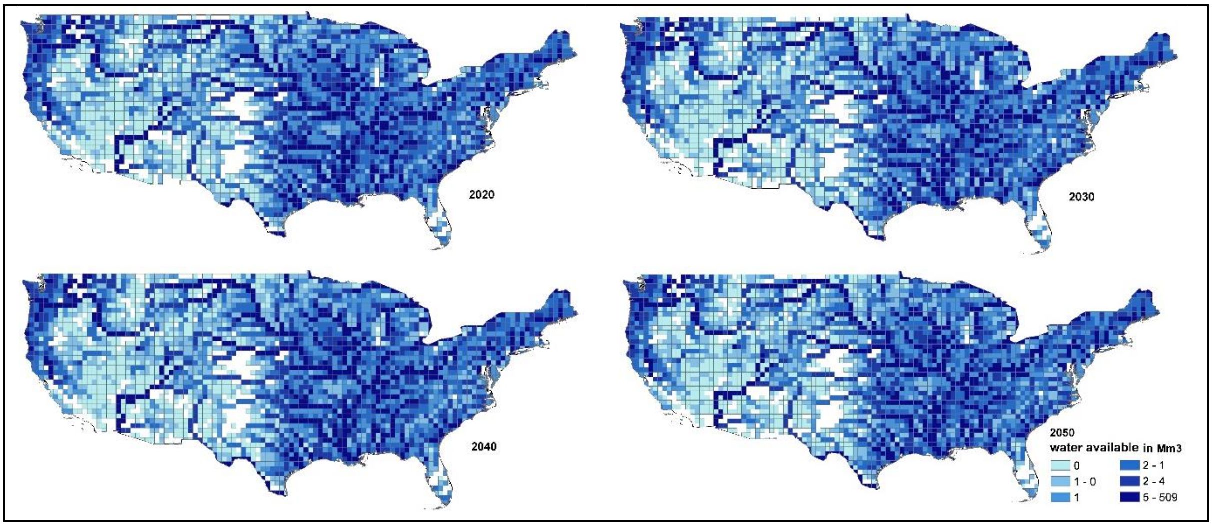


Figure 29: Groundwater availability for the USA from 2020 to 2050 in million m3 (Greve et al., 2018).

Figure 30 demonstrates that, overall, only a marginal fluctuation in water availability over time is expected to occur. Louisiana, Arkansas, Missouri and Michigan register the highest potential water availability, over 2,000,000 million liters, compared to the other states which potentials are lower than 500,000 million liters.

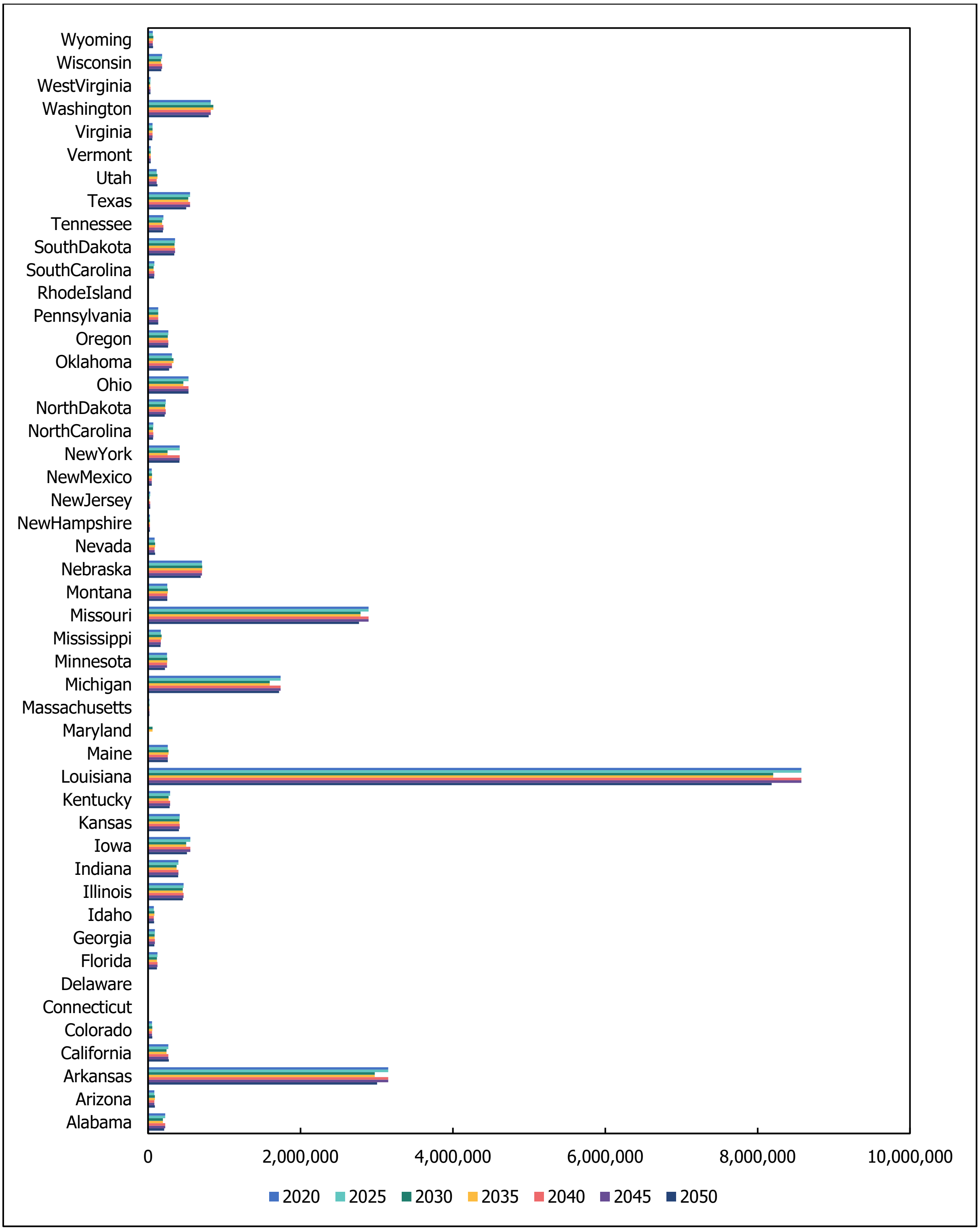


Figure 30: Ground water availability in million liter per state and from 2020 up to 2050 (Greve et al., 2018).

7.3 Airports distribution

The list of US airports has been compiled from three different online databases (Arash Partow, 2017; *List of US Airports*, 2020; *Open Data @ OurAirports*, 2021). The airports are categorized by their sizes (i.e., large, medium, and small) in terms of numbers of flights per year. Only the airports of large and medium sizes were used for the model, as presented in Figure 31. Based on the jet fuel demand at the state level from EIA (2021), (see Figure 32), the largest category of airports of each state are kept and assigned the corresponding jet fuel demand as presented in Figure 33. It is assumed the jet fuel demand to start at 5% of the full demand in 2025 and increases linearly up to 100% in 2050.

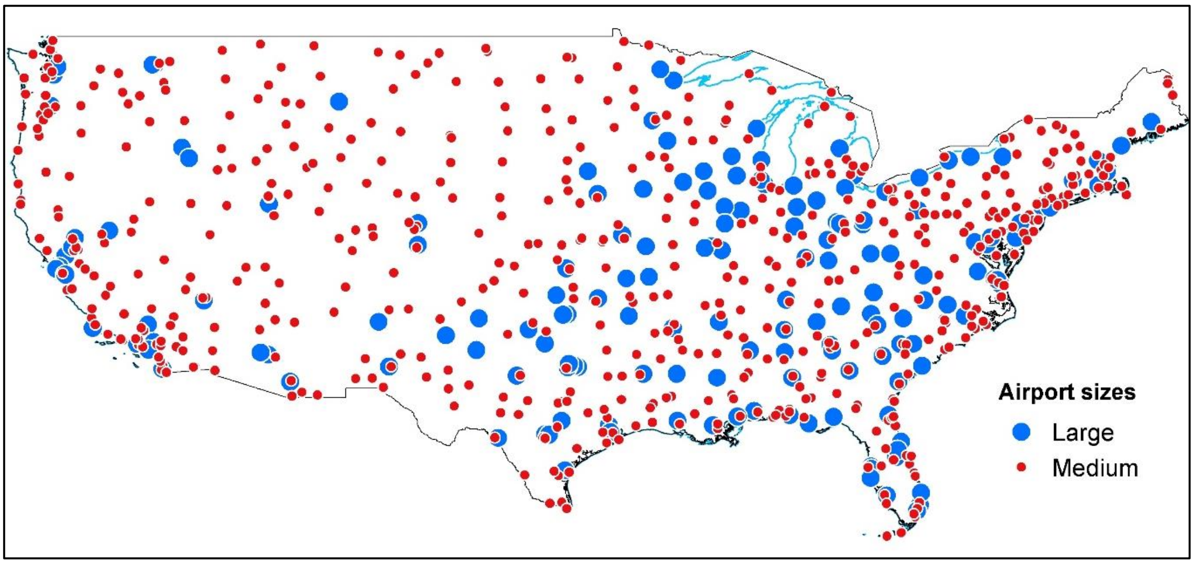


Figure 31: Distribution of the medium and large airports in the US. Only the larger airports per state will be kept for the analyses (Arash Partow, 2017; List of US Airports, 2020; Open Data @ OurAirports, 2021).

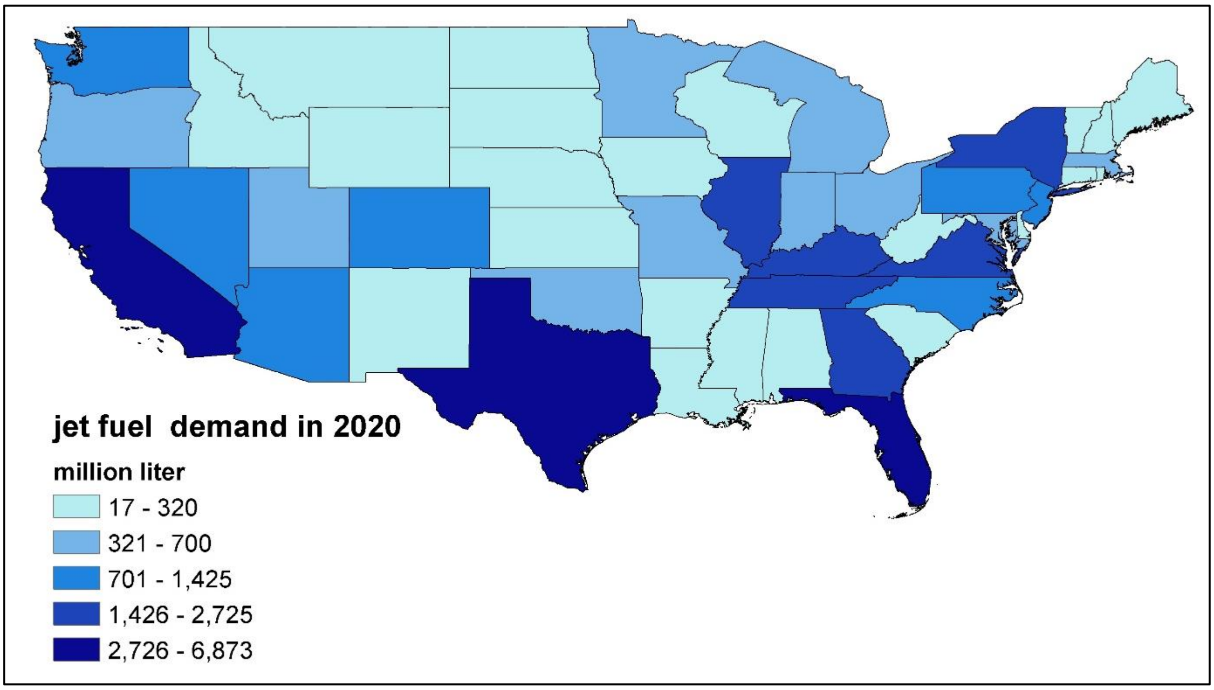


Figure 32: jet fuel demand as the state level in 2020 (EIA, 2021).

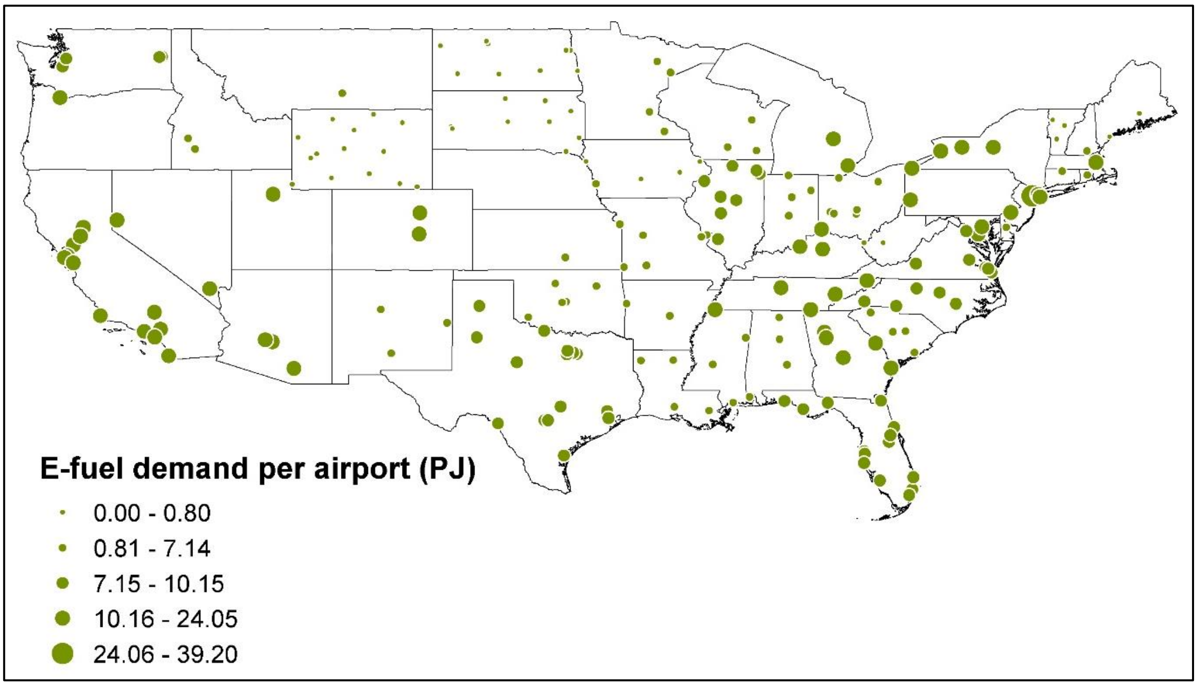


Figure 33: Distribution of the e-fuel demand per airport derived from the demand at the state level.

7.4 Candidate desalination plants

Beside the use of groundwater for electrolysis or DAC facilities, water desalination facilities can also be added in the model and would then decrease the stress on the use of groundwater. Figure 34 highlights the 47 US airports (in blue) that are close enough (withing a 100 km distance) to the coast and where desalination facilities could be setup.

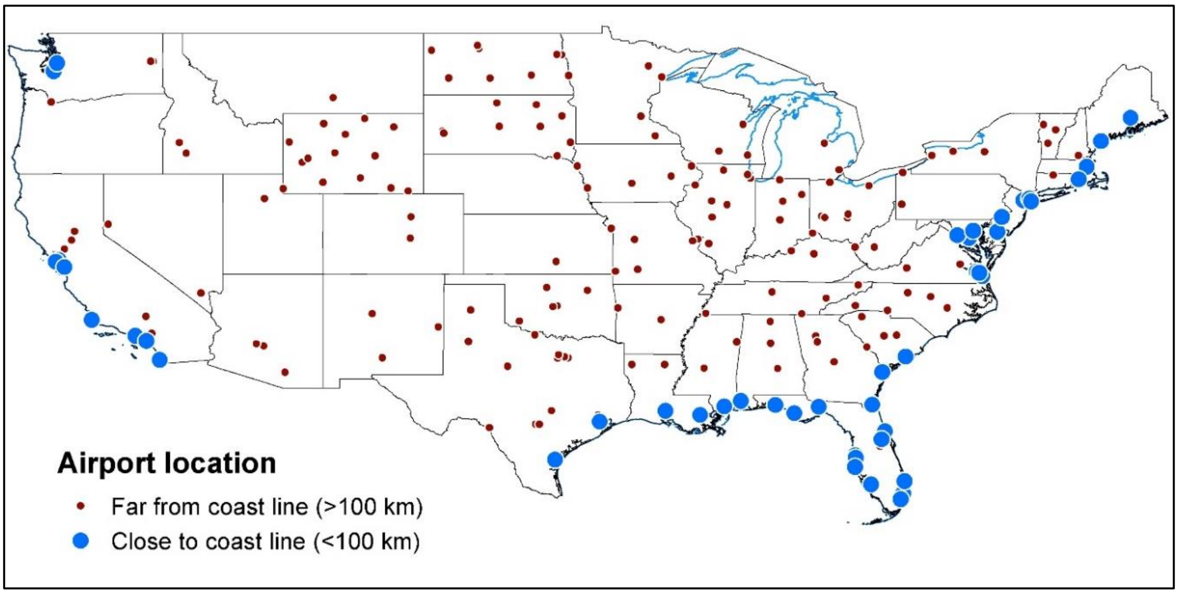


Figure 34: Distribution of the US airports by state, where the blue circles represent the airports close to coastline and able to use desalinated water.

7.5 Techno-economic assumptions

For each supply chain process step, e.g., CO_2 capture *via* DAC, electrolytic production of hydrogen, water desalination process, the model has been parametrized with the same capital cost assumptions adopted for the European analysis, assuming one USD is worth approximately 0.80 EUR. The variable operating costs are differentiated at the state level to reflect market price variations of the key commodities considered in the analysis such as water, the electricity and jet fuel (Figures 7-9). The fossil-based jet fuel price is directly taken from EIA (2021) at the state level, which is presented in Figure 35.

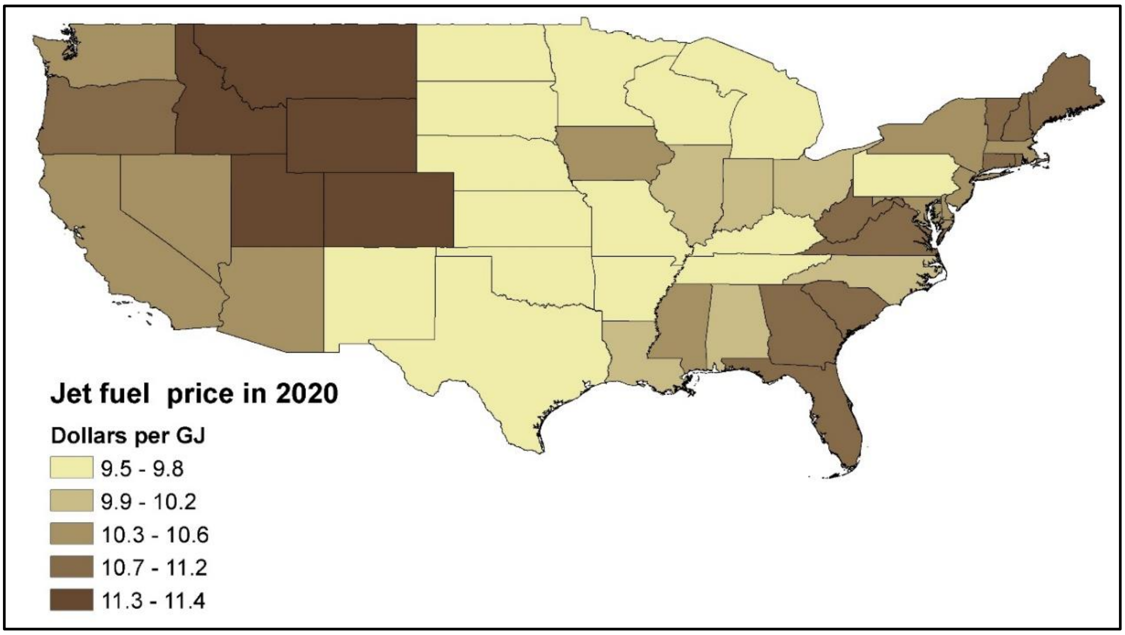


Figure 35: Fossil-fuel based jet fuel price in 2020 in $2020 per GJ (EIA, 2021).

State level water prices have been derived by combining two datasets. Bunch at al., have compiled a database of annual water prices for industrial applications, covering 30 U.S. States (Bunch et al., 2017). Given the limited geographic coverage of such analysis, we complemented the dataset with annual water cost data for household consumption (World Population Review, 2022). In states where both prices (industrial and household consumption) were available, the upper bound value was adopted for the modelling, so to provide a conservative estimate. As can be noticed from Figure 36 water prices exhibit large variations across states, i.e., between 0.033- 0.152 $c/liter.

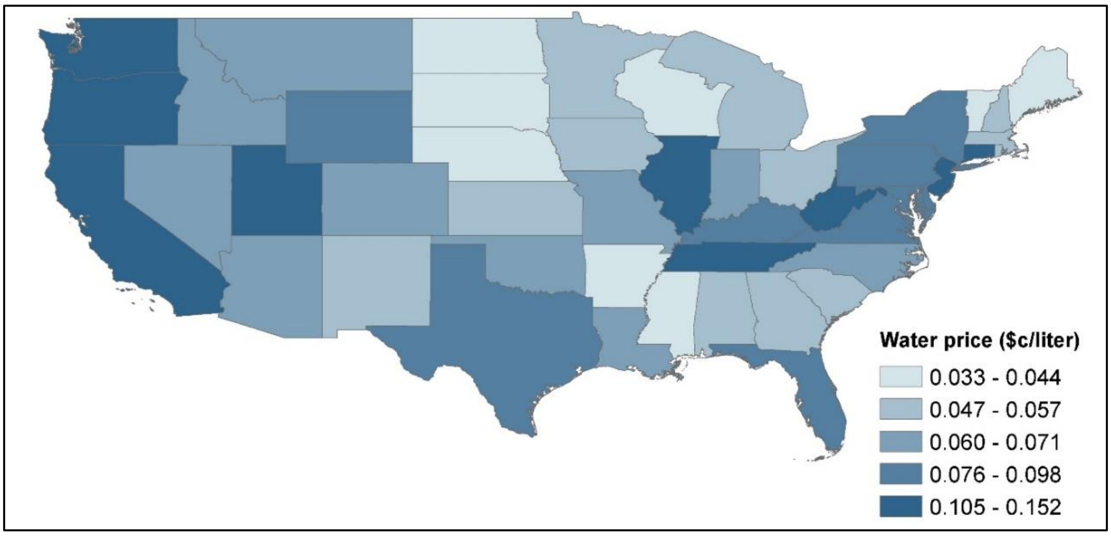


Figure 36: Water price per state in $c per liter.

The electricity availability has been derived from EDF as presented in Section 3 of this report. As the analysis assumes a constant electricity production cost of $0.01 per kWh, we adopted state level electricity prices from the U.S. Energy Information Administration database (U.S. Energy Information Administration, 2021). The final electricity production cost is presented in Figure 37. For the modeling it is assumed an electricity supply from a distance not further than 1,000 km.

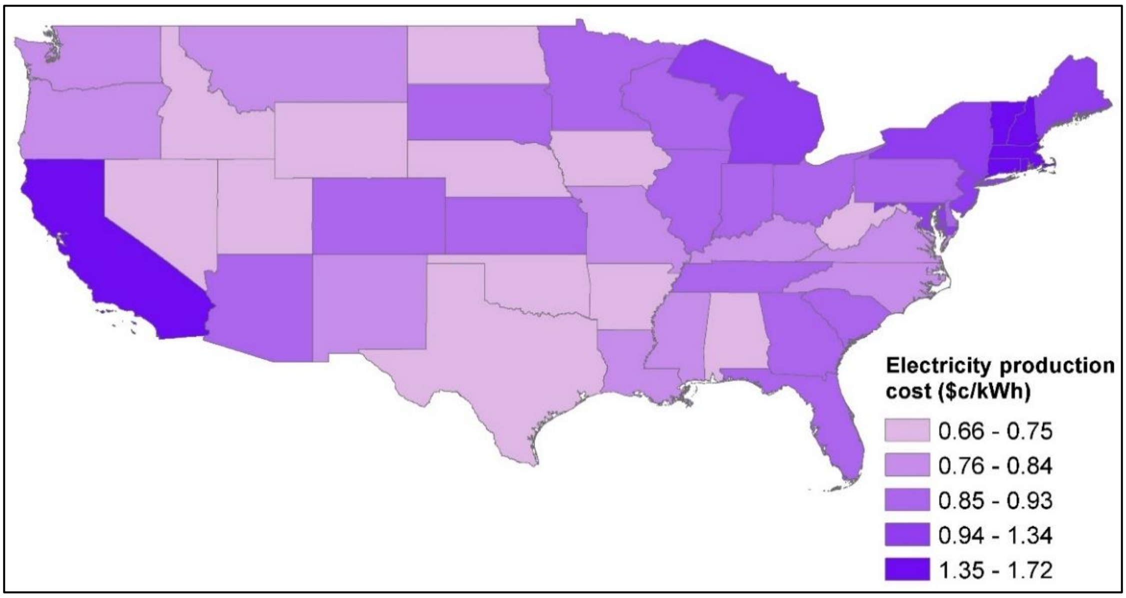


Figure 37: Adapted electricity cost at state level.

8 Results

8.1 e-fuel production and water access

The water availability is a parameter which is difficult to estimate. Water supply must be sufficient to meet demand from other activities, such as industrial, agriculture, and personal use. It is therefore assumed that a maximum of 5% of the total water available within each grid point, can be used for e-fuel production. Figure 38 presents the national e-fuel production at different level of water availability and accessibility, i.e., within maximum distances of reach of 100 km, 200 km, and 400 km. As can be seen, a 5% share water availability allows e-fuel production to meet the 2050 national jet fuel demand with a 100 km reach. There is, however, a direct correlation between water availability and accessibility, since even when assuming only 3% of local water being available, the 2050 fuel demand can be met, as long as the access to water is at least 200 km.

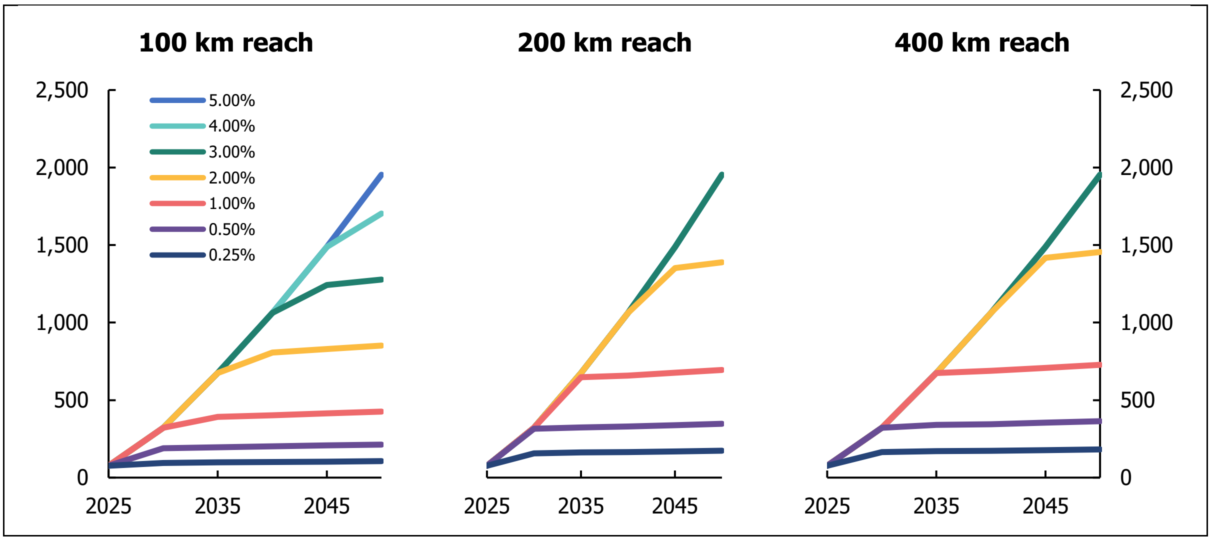


Figure 38: e-fuel production (in PJ) in respect to the water available expressed as share of the total ground water available, for three distances (100 km, 200 km, and 400 km) as the limit of water supply access. Assumptions: 0.1% of electricity available, high cost of fossil fuel, no desalination plant allowed and low cost of DAC facilities.

8.2 E-fuel production and electricity availability

Similar to water availability, electricity access and availability is unclear. It is assumed that the electricity used comes only from renewable resources (see Section 3) and that the share of electricity use at the grid level does not exceed 0.05% which is equivalent to 1,800 TWh of new electricity generated in the US. Such a share allows to meet the jet fuel demand in the U.S. as presented in Figure 39.

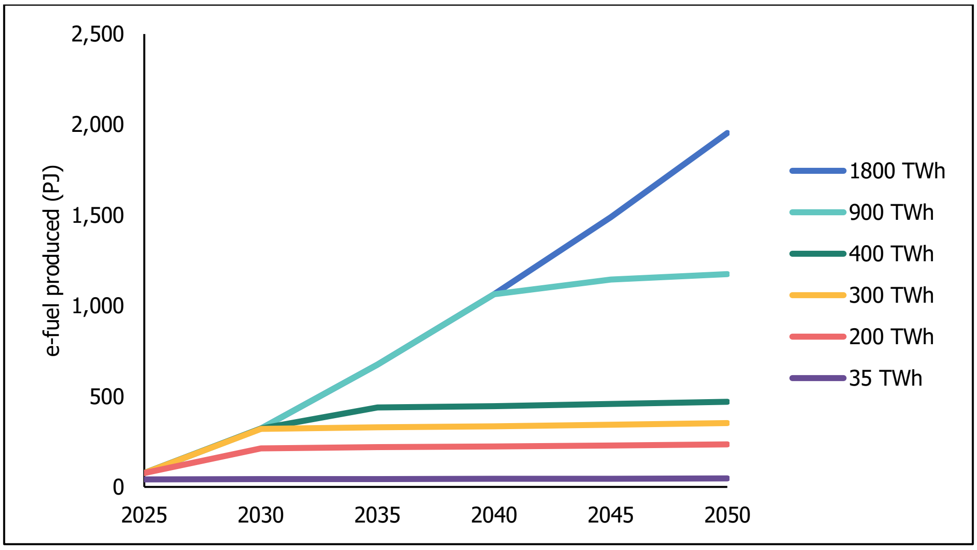


Figure 39: e-fuel production (PJ) in respect with the electricity available in TWh. Assumptions: 5% of groundwater available, high cost of fossil fuel, desalination plant allowed and low cost of DAC facilities.

8.3 Carbon scenario

The trend is the same for the U.S. as it was for Europe, when it comes to the impact of the carbon scenario on the production of e-fuel. As presented in Figure 40, the more stringent the carbon scenario is, the more e-fuel will be produced earlier: in an extreme carbon scenario, the e-fuel production would start 10 years earlier than a base case carbon cost scenario. This figure introduces the impact the use of desalination plants may have on the production of e-fuel. A groundwater availability is assumed to be of 2.5% which is not sufficient to produce the requested amount of e-fuel as illustrated in Figure 38. When the use of seawater (graphs on the right-hand side) is introduced, there are then no longer any constraints for meeting the demand from a water supply point of view, unless the carbon cost and the fossil fuel price are too low (e.g., graph on the bottom right corner).

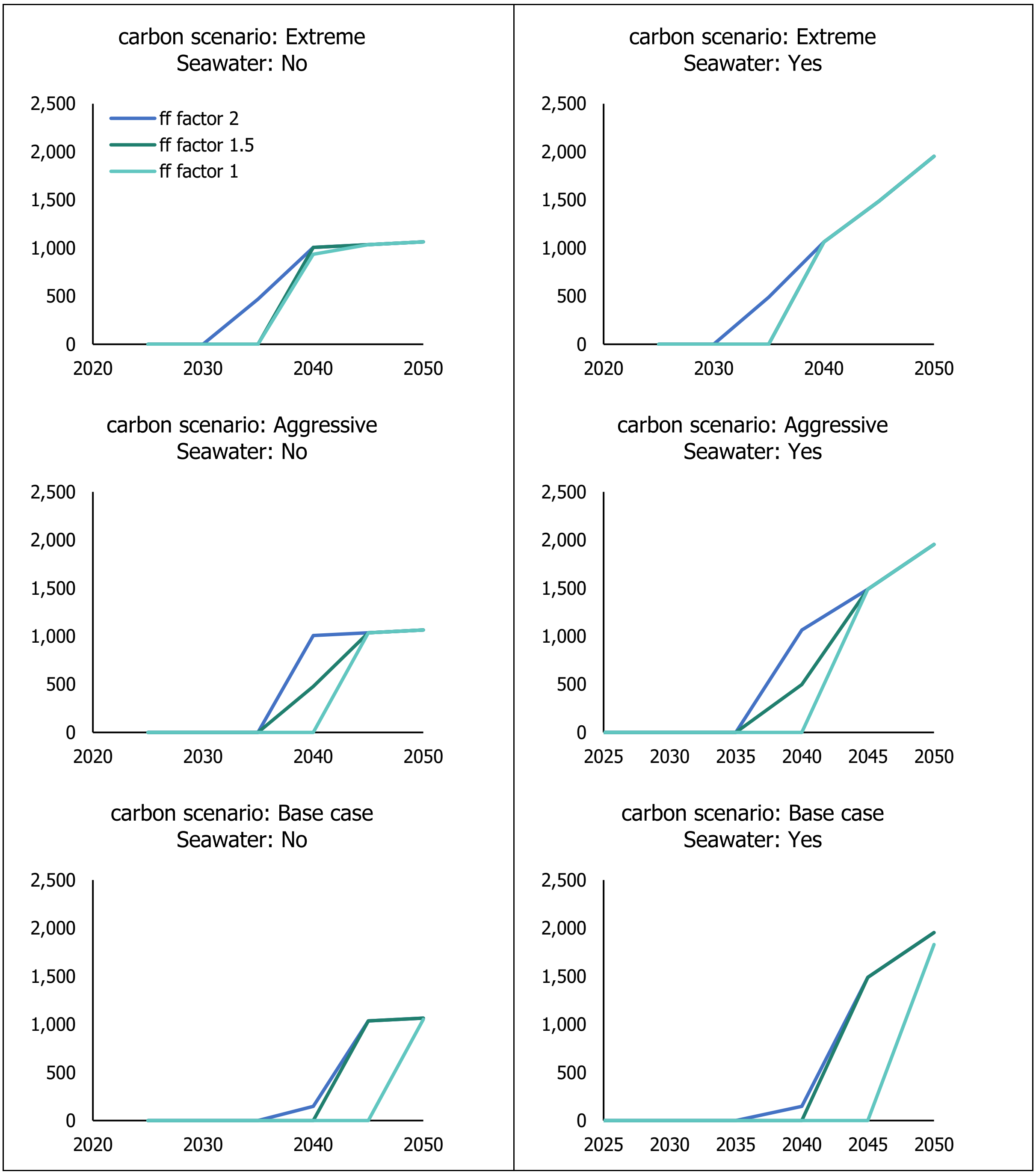


Figure 40: e-fuel production (PJ) for three carbon scenarios (Extreme, Aggressive and Base case) and the impact of the use of the desalination plants (denoted as "No" or "Yes") under different fossil fuel price factor denoted as "ff factor". Assumptions: 2.5% water availability, high cost of DAC facilities, 0.1% of electricity availability.

The production cost of e-fuel is summarized from all scenarios in Figure 41. The figure presents the possible values of production cost delimited by the production costs based on the higher and lower DAC technology cost. The production costs that would enter the market at a specific time depending on the fossil fuel cost: this is represented in the figure by the common area between the light grey fossil fuel price range and the orange technological cost. This common area would then represent the feasible competitive production cost and the time of penetration of the technology. If the carbon cost increases, represented by the dark grey triangle, the light grey area would then be shifted upwards per definition from the model (carbon cost is applied on the fossil fuel-based resources) and would then increase the common area between the fossil fuel price range and the production cost range. This would then mean that the higher the CO_2 cost, the larger the common area, and the earlier e-fuel would be produced. The early development of the technology would then occur when a high CO_2 cost occurs as indicated on the left-hand side of the figure, and the late development of technology would happen at a low CO_2 cost as indicated on the right-hand side of the figure.

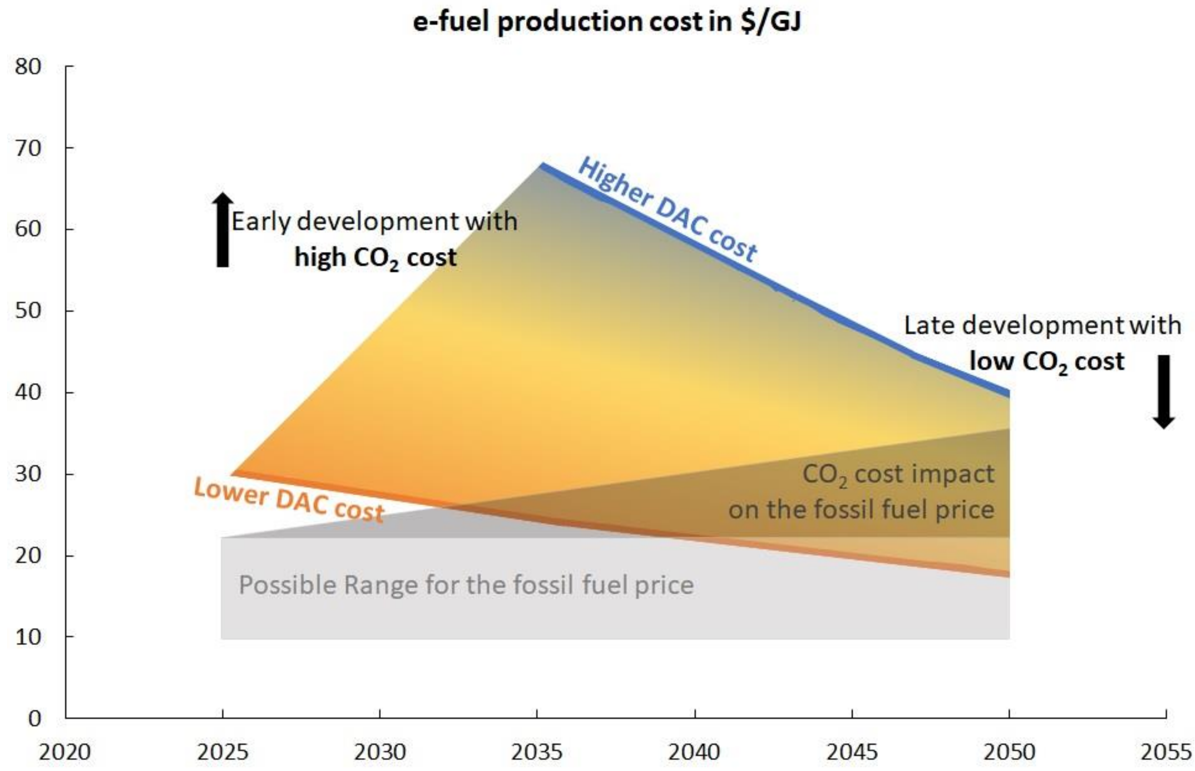


Figure 41: Possible range for the development of the e-fuel production cost.

8.4 Geographic distribution

The following maps (Figure 42) present the geographic distribution of the DAC plants depending on their capacities expressed in million ton of CO_2 as well as the distribution of e-fuel in PJ for the final year of the simulation, which is in 2050. The results start from a full coverage based on 1,800 TWh of excess electricity available down to a 200 TWh availability.

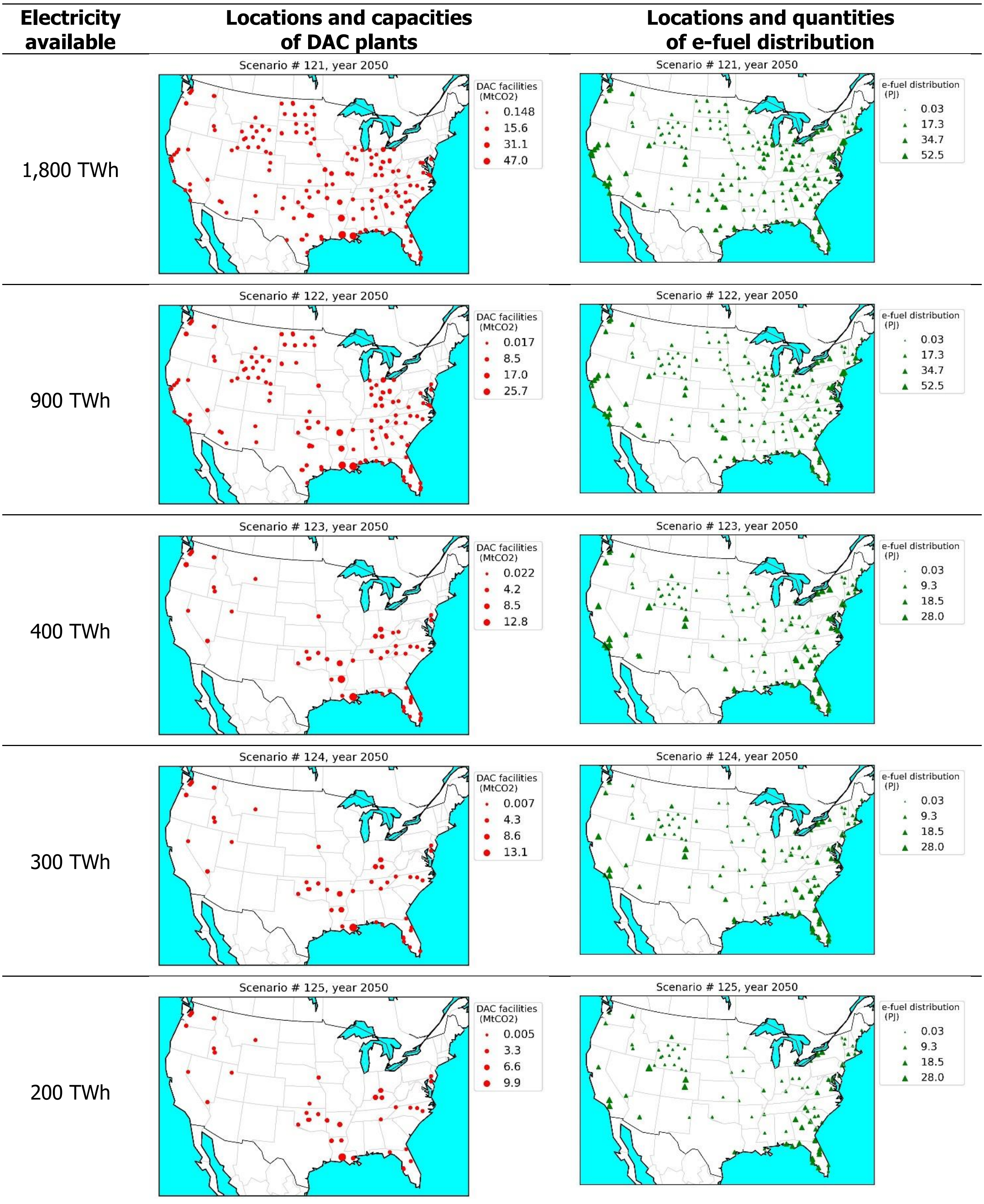
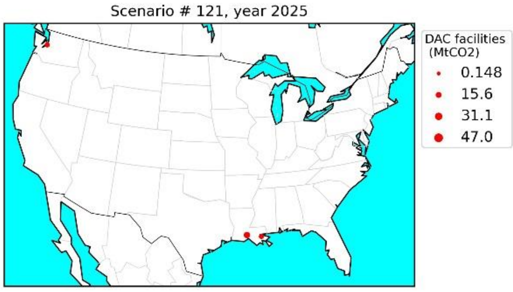
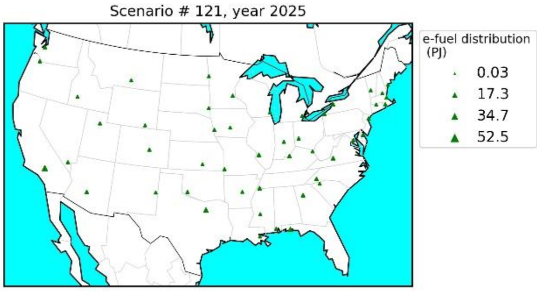
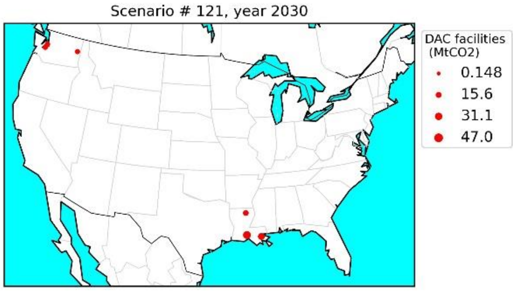
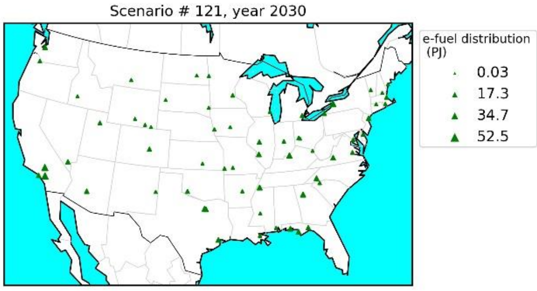
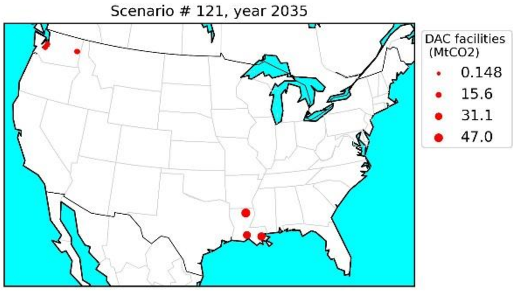
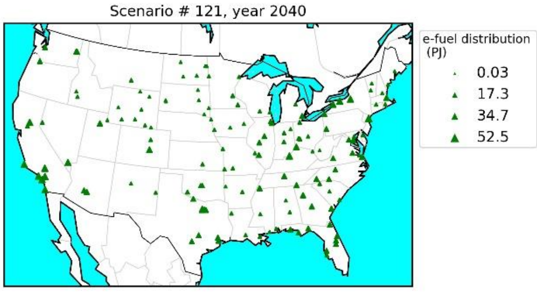
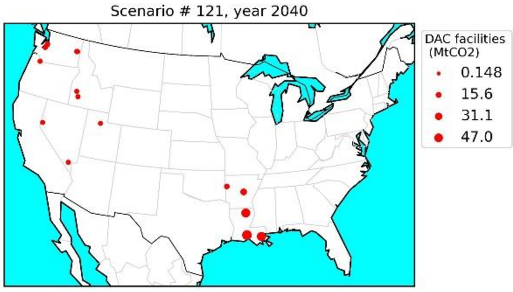
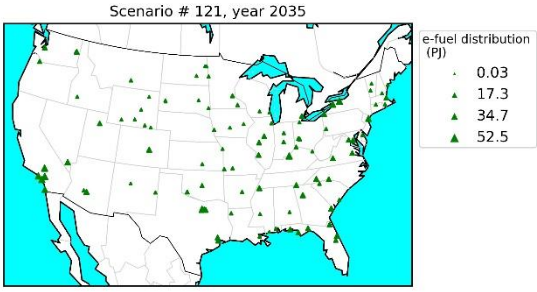
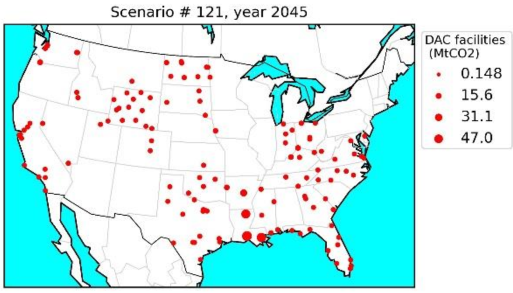
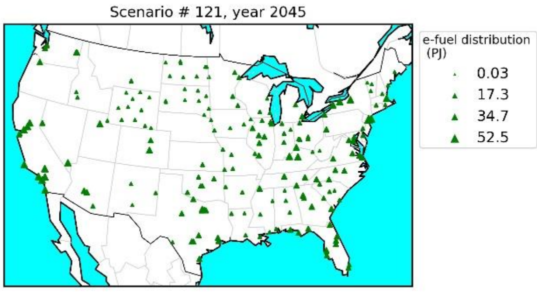


Figure 42: Distribution of DAC plants (red dots) and the corresponding e-fuel distribution (green triangles) for different electricity availability scenarios. Assumptions: low cost of DAC plants, high cost of fossil fuel, no desalination plants, 5% of water available.

It is important to identify where the first plant will be located as well as the largest ones. This seems to be a constant throughout the scenarios as can be identified from Figure 42 and Figure 43. The locations of the first plants happens to be in Louisiana and Washington. These facilities grow over a decade (i.e., scenario presented in Figure 43) before new smaller plants can be set up in diverse states of the country. It must be noted that the states of Louisiana and Washington have the highest potential of groundwater availability. These large facilities remain in the scenarios presented in Figure 43.

Year	Locations and capacities of DAC plants	Locations and quantities of e-fuel distribution
2025		
2030		
2035		
2040		
2045		

2050

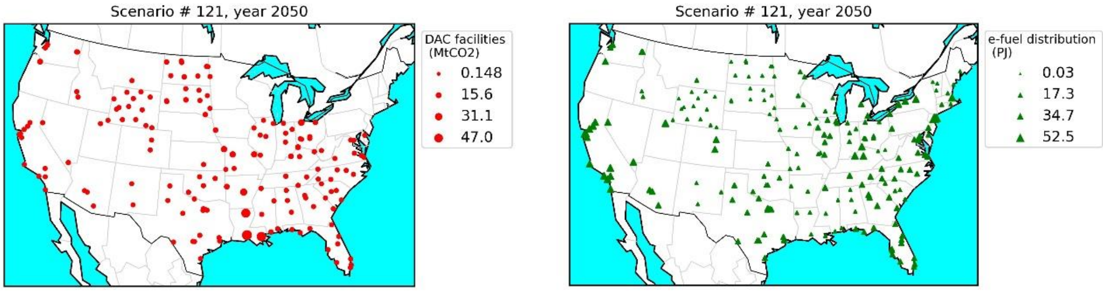


Figure 43: Distribution of DAC plants (red dots) and the corresponding e-fuel distribution (green triangles) over time from 2025 to 2050 for the first scenario presented in Figure 42. Assumptions: low cost of DAC plants, high cost of fossil fuel, no desalination plants, 5% of water available, 1,800 TWh excess electricity available.

9 Land use impact from the production of e-fuel in Europe and US compared to biomass-based biofuel production

Valin et al. (2015) reported the land use impact of the production of biofuel from for a variety of possible feedstock in the EU. The production potential per area of land varies between 15 GJ/ha and 145 GJ/ha for cereal straw ethanol and sugar beet ethanol (Figure 44).

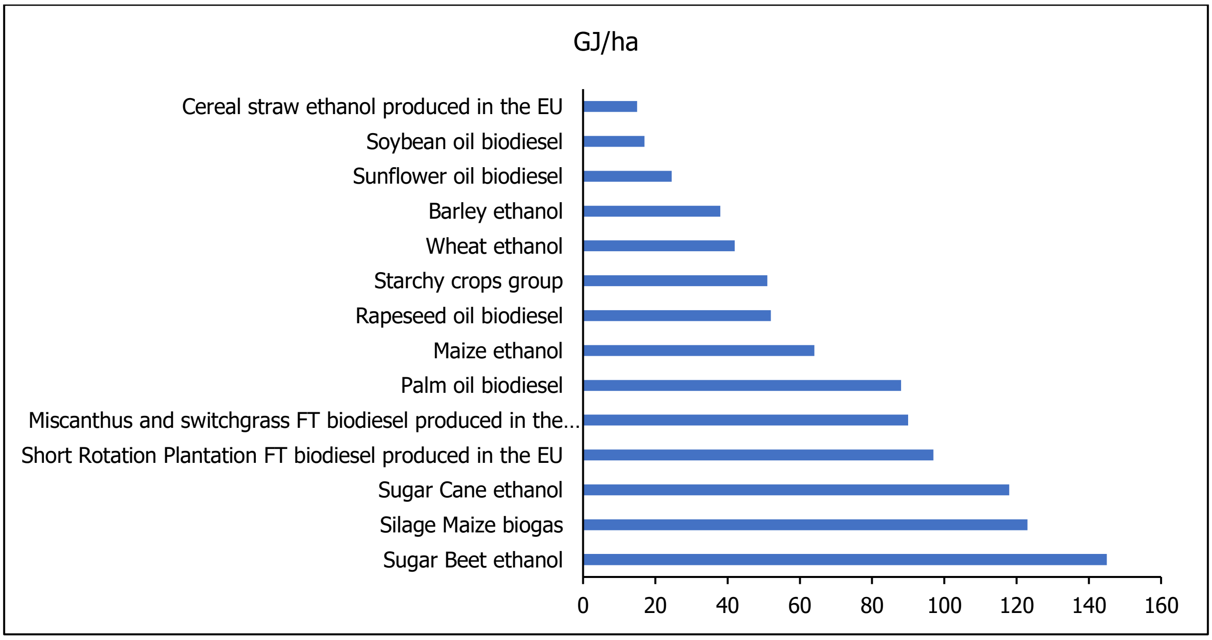


Figure 44 Production per area of biomass-based biofuel from different possible feedstock (Valin et al., 2015).

The results below present the results from the BeWhere model with the assumption presented in Table 13. The final land use for e-fuel production is presented in Figure 45. Note the electricity is both used for DAC and electrolysis facilities.

Water-requirement: https://roadmap2050.report/biofuels/water-land-biofuels/

Table 13: Assumptions on the amount of land needed for major facilities of the production of e-fuel.

Facility	**Unit**	**Range of values**	**Referenes**
Solar PV	MW/km^2	75(*)	(Breyer et al., 2018)
	$m^2/MWh/y$	6.3	(ICAO, 2022)
Wind energy	MW/km^2	8.4(**)	(Breyer et al., 2018)
	$m^2/MWh/y$	2.9-72	(ICAO, 2022)
Heat pumps	GW_{th}/km^2	1	(Breyer et al., 2018)
DAC units	$Mt_{CO2\ captured}/km^2/y$	2.5	(Breyer et al., 2018)
(*) a capacity factor is assumed to be 0.3 (Mesfun et al., 2018)			
(**) a capacity factor is assumed to 0.2 (Mesfun et al., 2018; Steffen et al., 2018)			

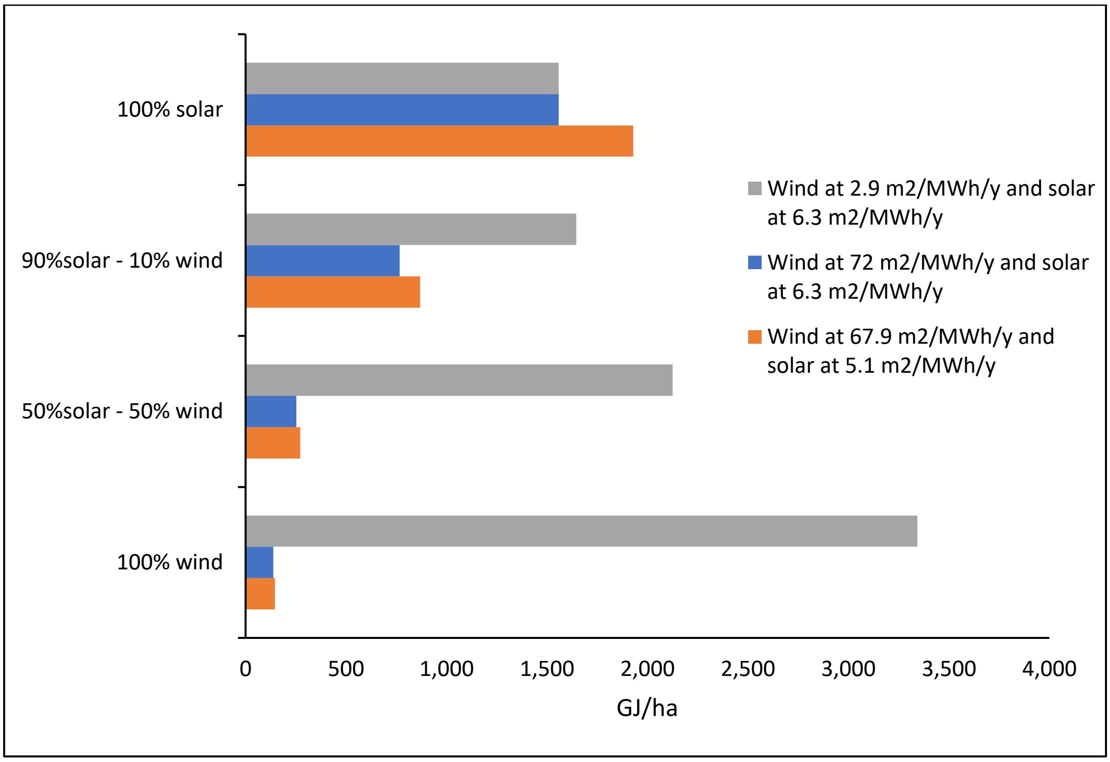


Figure 45: Production per land needed for e-fuel from DAC for four scenarios.

For the four scenarios presented in Figure 45, the share of the land is divided per production site (i.e., DAC unit, heat pump, solar PV and wind energy mills) and presented in Figure 46.

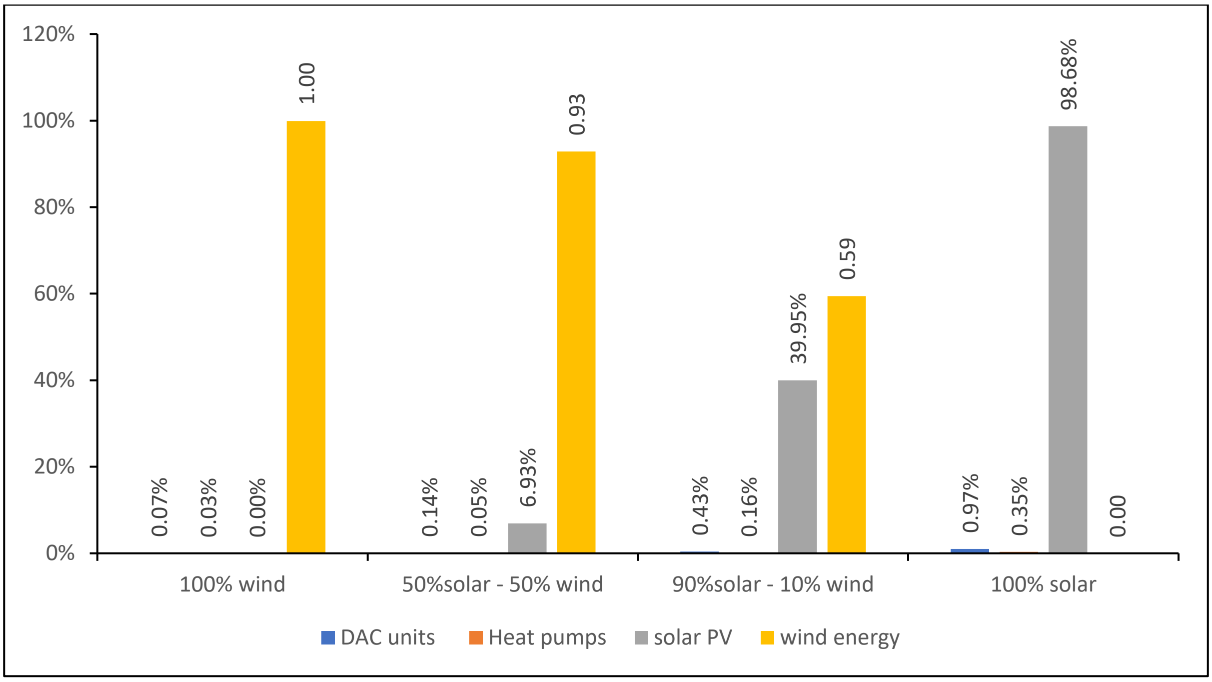


Figure 46: Share of the land in respect with the different production facilities for the e-fuel production.

Comparing the production of e-fuel with conventional biomass -based biofuel the land saved by the production of DAC-based e-fuel is of the order of magnitude of about 10 times less: looking at the exact spam of the range, it goes from a reduction from 1 to 150 times less, depending on the mix of wind and solar electricity generation. The highest uncertainty remains on the wind electricity generation which is dependent on various factors (e.g., capacity of the turbine, location, multi-purpose land).

10 Final remarks and future work

The potential of e-fuel both for Europe or U.S. very much depends on the availability and price of water and electricity. At the same time, the availability of water and electricity are two parameters with high uncertainties. Therefore, it can be concluded that for Europe, results indicate a higher dependency on the use of desalination plants, due to water access limitation. For the U.S., this seems to be less of a problem since at least four states have a relative high groundwater potential which can cover a large part of the freshwater demand for aviation-electro-fuel production from DAC. Finally, there is still some uncertainty about costs over the long-term, which depends on the rate of development of the technology. The cost of e-fuel can fluctuate between 20 to 45 US$/GJ in 2050 depending on the rate of development assumed for the respective technology, which in turn is dependent on policy measures applied, such as the carbon cost.

To elaborate this study further and build up on its insights, inter alia the incorporation of different DAC technologies (i.e., those technologies which are not that much water dependent) should be included in coming modeling work. Moreover, a special focus for further modeling work needs to be put on the technology development and integrating learning rates (which means entails that the cost development would become endogenous rather than exogenous as presently modeled). This would lead to substantially improved future cost estimates as well as have a direct impact on capacities and potentials. These improvements were not possible to be included in this research since it clearly exceeded scope and timeframe of the project. However, it should be given priority in a possible follow-up work.

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