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# The green energy transition in air transport – an analysis of supply chains for hydrogen and sustainable aviation fuels

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## Abstract

The aviation industry's transition to new energy carriers has only recently begun. Under the European Union's ReFuelEU Aviation Regulation, the use of Sustainable Aviation Fuels (SAF) is now mandated, with growing shares of SAF from biological and non-biological origins over time. In parallel, the industry is developing aircraft powered by hydrogen — either through combustion in turboprop or turbofan engines, or via fuel cells generating electricity for electric motors. These developments mark a shift away from today's petroleum-based jet fuels. Several studies have estimated future demand for hydrogen and SAF in aviation, but few have examined the supply chains dedicated to transporting these new energy carriers. As with crude oil and jet fuel today, a substantial share of Europe's future aviation energy demand is likely to be met by imports from regions with abundant, low-cost renewable energy. Based on existing techno-economic studies, this paper explores supply chain options for liquid hydrogen as well as alternative hydrogen carriers such as ammonia and liquid organic hydrogen carriers. It also examines supply options for synthetic SAF (renewable fuels of non-biological origin, RFNBO), which may involve also intermediate carriers like hydrogen, methanol, or syncrude. The central question is how to design an aviation energy supply chain for the EU that is both energy- and cost-efficient while minimizing dependence on external suppliers. The paper provides an overview of potential supply chains, offering a techno-economic assessment of various energy carriers and discussing the pros and cons of each. This analysis highlights the likely infrastructure needs at seaports, refineries, and in hinterland distribution to airports.

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## 1. Introduction

The transition of the aviation industry towards new energy carriers has only recently commenced. The European Union's ReFuelEU Aviation Regulation has mandated the introduction of Sustainable Aviation Fuels (SAF). The aeronautical industry is also engaged in the development of aircraft that utilize hydrogen as a fuel source, either through direct combustion in turboprop or turbofan engines or through the utilization of fuel cells to generate electricity for electric motors. Presently, the development of smaller regional aircraft, predominantly conversions from conventionally powered models, is underway (Gollnow, 2023). In contrast, the development of larger short- and medium-haul passenger aircraft with seat capacities of 200 passengers or more is currently in its infancy. Airbus, a leader in this field, anticipates that its ZEROe aircraft will not be operational until after 2040 (Perry, 2025).

The consequence of these developments is a medium- and long-term change in the energy carriers used in aviation, away from today's petroleum-based conventional jet fuels. A plethora of studies and forecasts have sought to estimate the demand for new energy carriers. As is evident in the present day, with crude oil and petroleum-based products such as jet fuel, it is probable that a significant proportion of the new energy carriers required for European aviation will be imported from regions of the world where renewable energy is consistently and cost-effectively available. A study conducted for the European Commission (2023) estimated that the aviation sector's demand in Europe for hydrogen could reach 0.4 million tonnes (Mt) in 2035, increasing to 2.6 Mt in 2040, 4.5 Mt in 2045, and finally reaching 6.1 Mt in 2050.

Grimme and Braun (2022) used a modelling framework analogous to that employed in the European Commission study, yet they adopted more conservative assumptions concerning fleet roll-over and the years in which hydrogen aircraft would enter service. The study assumes the existence of two distinct classes of hydrogen aircraft: a regional aircraft family with fuel cells and a capacity of 40–100 seats, and a short- to medium-range aircraft family with direct hydrogen combustion and a capacity of 160–250 seats. It is hypothesized that both aircraft classes could enter the market in 2040, utilizing liquid hydrogen as a fuel source. This results in a considerably lower projected hydrogen demand of 0.3 Mt in 2040, 1.9 Mt in 2045, and 3.3 Mt in 2050 for all departures of hydrogen aircraft from airports in the EFTA and UK.

EUROCONTROL has developed its FlyingGreen platform (EUROCONTROL, 2025). This tool facilitates the modelling of various scenarios pertaining to the future development of aviation, including but not limited to the growth rate of traffic, the renewal of fleets, the introduction rate of revolutionary propulsion concepts, and carbon pricing. Assuming a moderate set of assumptions, the required amount of hydrogen for the EFTA + UK is 0.9 Mt in 2035, increasing to 1.8 Mt in 2040, 2.8 Mt in 2045, and 3.8 Mt in 2050. However, should more optimistic assumptions be made regarding fleet renewal and revolutionary propulsion concepts, these figures would increase to 1.7 Mt in 2035, 3.5 Mt in 2040, 5.0 Mt in 2045 and 7.4 Mt in 2050, respectively.

While the prospects for the direct use of hydrogen in aviation remain uncertain, plans to achieve net-zero in aviation with SAF by 2050 are more concrete. The ReFuelEU Aviation Regulation (The European Parliament and the Council of the European Union, 2023) is the primary policy relevant for the uptake of SAF in the EU. Commencing in 2025, this regulation establishes mandatory requirements for the minimum levels of SAF, with incremental increases scheduled every five years. In accordance with the regulation, the proportion of jet fuel to be SAF is set to increase from 34% to 70% by 2040 and 2050, respectively, for flights departing from EU airports.

In 2030, the blending mandate for SAF will be at 6% of total jet fuel consumption. 1.2% of total fuel consumption must be renewable fuels of non-biological origin (RFNBO), otherwise referred to as power-to-liquid fuels (PtL). It is therefore possible that the short-term requirements for SAF can be met with SAF produced in the EU. Rising blending mandates for both biofuels and RFNBO will likely necessitate the import of SAF or feedstock in the long run to meet EU jet fuel demand (Shehab, Moshammer, Franke, & Zondervan, 2023). The EUROCONTROL FlyingGreen platform does not only provide information on hydrogen demand for aviation, but also for future jet fuel / SAF demand. In a scenario where hydrogen usage is moderate, the demand for conventional fossil jet fuel in Europe (EFTA+UK) would decline from 49.32 Mt in 2030 to 16.04 Mt in 2050. In a more optimistic scenario of hydrogen usage, the demand for conventional jet fuel would decline to 15.21 Mt in 2050. The comparatively negligible discrepancy in jet fuel demand forecasts between these scenarios indicates that EUROCONTROL anticipates a limited capacity for hydrogen aircraft to displace aircraft reliant on hydrocarbon fuels.

Meanwhile, the EUROCONTROL Flying Green Platform indicates a significant increase in SAF demand. According to the platform, the SAF requirements in Europe (comprising the EFTA countries and the UK) are projected to rise from 3.15 Mt in 2030 to 37.42 Mt in 2050 under a moderate hydrogen usage scenario, and from 3.14 Mt to 35.48 Mt under a high hydrogen usage scenario. Given the mandatory RFNBO sub-quota of 50% of all SAF to be consumed by 2050, the demand for synthetic SAF is projected to rise to almost 18 Mt by the same year.

The aforementioned studies provide a depiction of a future aviation system that is reliant on hydrogen and SAF; however, they do not address the logistics of supplying potentially millions of tons of new energy carriers to the aviation sector in Europe. It is widely acknowledged within the academic community and in political strategy papers that a significant proportion of new energy carriers will be sourced from regions globally where renewable energy is consistently and cost-effectively available (Ansari & Pepe, 2023; Federal Ministry for Economic Affairs and Climate Action, 2024; Lenivova, 2022). These could be regions with favorable conditions for wind power or photovoltaics. It is inevitable that energy carriers will have to be transported over considerable distances. This does generally not differ from today's energy imports from oil-rich countries, but substantial technological and economic challenges are nevertheless to be expected, due to the characteristics of the new energy carriers, which will require the adaptation of seaport terminals and distribution infrastructure.

With this paper, the authors contribute to closing this gap by reviewing techno-economic analyses on the provision of renewable energy carriers to be imported in Europe over long distances. The analysis is conducted from the perspective of the requirements of the aviation sector, which differ from those of other sectors. For instance, hydrogen to be used in aviation is likely to be in its liquid form in order to increase its volumetric energy density, which is required to achieve commercially viable aircraft ranges.

A focus is laid on hydrogen in section 2 and potential energy supply chains for the production of SAF are addressed in section 3. The transportation of hydrogen can be achieved in its liquid form, as ammonia, or in association with liquid organic hydrogen carriers. SAF could be imported in a form that is ready for immediate use and that meets the certification standards for jet fuel. Furthermore, it is possible to divide the supply chain of SAF production and import various feedstocks or intermediate products, such as hydrogen, methanol or synthetic crude oil. The paper concludes with a summary of findings and an outlook for further research.

## 2. Hydrogen-based Supply Chains

### 2.1. Liquid hydrogen

Hydrogen has a high gravimetric energy density of 120 MJ/kg. However, its volumetric energy content is remarkably low, with only 10.8 MJ of energy per cubic meter at standard pressure. An alternative option is to liquefy hydrogen, which increases its energy content to 8,496 MJ/m<sup>3</sup> and enables the transportation of large quantities of hydrogen over long distances. For the purpose of comparison, one cubic meter of jet fuel contains approximately 33,600 MJ (at a density of 800 kg/m<sup>3</sup> and an energy content of 42 MJ/kg). Two notable disadvantages associated with the transportation of liquid hydrogen (LH<sub>2</sub>) are the substantial cost and energy intensity of liquefaction, a process that necessitates cooling hydrogen to temperatures below -253°C and the relatively high boil-off during transport. Typically, end users consume hydrogen in gaseous form; therefore, liquid hydrogen must undergo re-gasification upon delivery. However, there is an exception in the space and aviation industries, where hydrogen is used in its liquid state, due to the aforementioned issues with energy density. For these users, a liquid hydrogen supply is optimal. Nevertheless, the minimization of boil-off during the transport and transfer process (for example, from an ocean-going tanker to barges, trucks, or railcars) will be challenging.

Existing hydrogen liquefaction plants are relatively small in scale due to the comparatively low demand for hydrogen, with a maximum reported capacity of 32 tons per day (Al Ghafri et al., 2022). A lack of incentives for improvements has also resulted in relatively low energy efficiency. The specific energy consumption of these systems range from 11.9 to 15 kWh/kg<sub>LH<sub>2</sub></sub> (Al Ghafri et al., 2022). The practical minimum specific energy consumption is estimated to be at 5.9 kWh/kg<sub>LH<sub>2</sub></sub> (Eckroll, 2017).

In the event of gaseous hydrogen being delivered to airports, the installation of hydrogen liquefiers at or in the immediate vicinity of these airports would be a prerequisite. Current estimates for large-scale liquefiers in the range of 200t/day estimate an investment cost of around €2,500 kg/day (Connelly, Penev, Elgowainy, & Hunter, 2019). For

an airport of the size of Hamburg, where demand for LH<sub>2</sub> is estimated to be around 70,000 t/year in 2050, the investment required for hydrogen liquefaction alone is estimated to be in the region of €500 million.

The energy requirements for hydrogen liquefaction are in addition to those necessary for its production. The most viable method for producing substantial quantities of hydrogen is water electrolysis. This process has been estimated to consume 42-62 kWh/kg<sub>GH<sub>2</sub></sub>, depending on the chosen technology (Panigrahy, Narayan, & Ramachandra Rao, 2022). The total energy consumption for the provision of 1 kg of liquid hydrogen is in the order of 50-75 kWh.

As demonstrated in the literature, the price of electricity has a significant impact on the production costs of hydrogen. In 2024, the average electricity price in Germany was 7.8 €-cents per kWh (excluding taxes and grid fees, Fraunhofer Institute for Solar Energy Systems ISE, 2025). Estimations indicate that the cost of electricity from renewable sources in regions with favorable conditions can be as low as 2 to 3 €-cents per kWh (Timilsina, 2021). This results in a substantial cost advantage for the production of liquid hydrogen.

Whether the long-distance transport of liquid hydrogen from regions with low electricity costs is preferential does not only depend on the cost differential of electricity, but also on the transport costs. These consist of the costs for the logistics and the boil-off losses during transport. Chen et al. (2025) estimated the levelized cost of hydrogen transported from West Africa to Rotterdam to be US-\$ 0.37 per kilogram and from Egypt to Rotterdam to be US-\$ 0.72 per kilogram. Schuler et al. (2024) have undertaken a meta study on the transportation cost forecasts of different energy carriers. Regarding LH<sub>2</sub>, they find an average of about €5.5/MWh on a 10,000 km journey in 2030, which corresponds to €0.54/kg LH<sub>2</sub>.

The long-distance transport of liquid hydrogen is expected to be accomplished with specialized tankers featuring insulated tanks to keep the hydrogen liquid and minimize boil-off losses. Evaporating hydrogen must be removed from the tanks to prevent over-pressurization. Boil-off losses are estimated in the literature between 0.2-0.5% per day (Kim, Oh, & Kang, 2025; You, Kim, & Lee, 2023). On an estimated 20-day-journey, the total boil-off loss could be in the order of up to 10% of the initial mass of hydrogen. While modern LNG tankers can re-liquefy gaseous boil-off LNG in excess of what is needed to propel the ship, the more complex liquefaction process and much deeper temperatures required for H<sub>2</sub>/LH<sub>2</sub> (-162°C vs. -253°C) make this impossible for the time being for LH<sub>2</sub>. Therefore, journey length and ship speed will substantially impact the economics of hydrogen transport. With the boil-off of liquid hydrogen being in excess of what is required to provide propulsion energy to the ship, the only remaining option would be burning of the excess hydrogen gas in order to avoid to let it escape with resulting climate impacts (Ocko & Hamburg, 2022). Still, with the transport costs and boil-off losses, the production of liquid hydrogen in the exporting countries seems to be economically preferential at an electricity price differential of 2 €-cents or more between the exporting and importing country. Various concepts for large-scale LH<sub>2</sub> tankers with a transport capacity of up to 280,000 m<sup>3</sup> or 20,000 tons have been proposed in the literature (Alkhaledi, Sampath, & Pilidis, 2022; You et al., 2023), reducing transportation costs due to economies of scale and making long-distance hydrogen transportation economically viable.

The extremely low volumetric energy density of hydrogen, even when liquefied, poses challenges for port infrastructure and logistics — a topic that has not yet received much recognition. The arrival of such a hydrogen supertanker would pose various challenges to port logistics for the distribution of hydrogen to the airports. A just-in-time logistics process will minimize boil-off, as every day of additional waiting time at the terminal will increase boil-off and would also require large-scale investments in intermediate storage facilities. Therefore, large-scale and quick ground transport by barges, railcars and trucks with direct access to the seaport terminal will be required. The challenges for landside distribution of liquid hydrogen coming in on a LH<sub>2</sub> super tanker are furthermore illustrated by the capacities of the different vehicles. Assuming the arrival of a tanker with 20,000t LH<sub>2</sub> will require either almost 100 cargo trains with 24 cars each with a capacity of 9t per car or almost 100 barges for inland navigation with a capacity of 210.6t each (Raab et al. 2024). These figures provide an indication of the requirement for a very well-orchestrated landside logistics and high capacity of railway lines to allow for the hinterland distribution.

## 2.2. Ammonia

In light of the logistical complexities associated with the transportation of liquid hydrogen, a proposed alternative involves the utilization of hydrogen in the form of ammonia (NH<sub>3</sub>) for long-distance transport. Ammonia is among

the most sought-after basic chemicals, with a wide range of applications in the production of nitrogen-containing chemicals, urea, and fertilizers. Recently, ammonia has garnered attention as a potential energy carrier for combustion engines on ships, with the objective of facilitating the decarbonization of maritime shipping (Al-Aboosi, El-Halwagi, Moore, & Nielsen, 2021). Ammonia can be stored in its liquid form at significantly higher temperatures compared to LNG and hydrogen. Specifically, ammonia becomes liquid at temperatures below  $-33^{\circ}\text{C}$ , whereas LNG requires temperatures of  $-156^{\circ}\text{C}$  and hydrogen requires temperatures of  $-253^{\circ}\text{C}$  to become liquid. Given its relatively elevated boiling point, ammonia exhibits a comparatively low boil-off rate of 0.02–0.04% per day (You et al., 2023). Despite its toxicity, ammonia is transported according to a standardized protocol and is currently transported on a large scale.

According to the literature, the lion's share of energy used for green ammonia synthesis is for water electrolysis (95%), while nitrogen separation and the Haber–Bosch ammonia synthesis account for an estimated 5% of the total energy requirement (Negro et al. 2023). The estimated electricity consumption for the production of one ton of green ammonia, inclusive of electrolysis, is 36 GJ/t (10 MWh/t) gross (34.4 GJ/t net, with 1.6 GJ/t utilized for steam in other processes or energy recovery). The energy efficiency of green ammonia synthesis, as determined by the LHV of ammonia ( $18.8 \text{ GJ/t} = 5.2 \text{ MWh/t}$ ), is estimated to be approximately 55%.

However, it should be noted that one ton of ammonia contains only 180 kilograms of hydrogen. Hence, the utilization of ammonia as a hydrogen carrier has specific implications for the transport efficiency. While the largest liquid hydrogen tankers are estimated to have a transport capacity of 20,000 tons of hydrogen, the largest ammonia carriers under construction have a capacity of 93,000  $\text{m}^3$  (Hine, 2023), equivalent to 63,000 tons of ammonia. Given the hydrogen content of 11,340 tons, approximately twice the number of voyages is necessary to transport the same quantity of hydrogen. This increase in the number of voyages results in additional ramifications, such as considerations of terminal capacity, the required number of ships, and associated costs.

Given the present utilization of ammonia in its original form, the efficiency of industrial-scale ammonia cracking to release hydrogen is relatively low. As stated by Negro et al. (2023), ammonia cracking requires high temperatures ( $400^{\circ}\text{C}$ ), and producing one ton of hydrogen from ammonia consumes 52 GJ (equivalent to 14 MWh). A design for an ammonia cracker by Makhloufi and Kezibri (2021) consumes 68.7 GJ/ton of hydrogen in the form of electricity, as well as ammonia and hydrogen as fuel, to create process heat (some of which can be recovered and reused).

Overall, the energy requirements for electrolysis, ammonia synthesis, and ammonia cracking are approximately 243 GJ/ton of hydrogen (67.5 MWh/ton of hydrogen). For comparison, the electrolysis and liquefaction of hydrogen fall within the same range, with an average of 67 MWh/t of hydrogen (assuming 55 MWh/t of hydrogen for electrolysis and 12 MWh/t of hydrogen for liquefaction). These figures must be considered in the context of hydrogen's energy content of 33.3 MWh/ton — meaning the energy efficiency of both processes is around 50% from well to tank. But if the ammonia pathway is used to supply aviation, liquefaction energy consumption of 12 MWh/t  $\text{H}_2$  at or near the airport must be added to the equation, putting ammonia at a disadvantage from the perspective of energy efficiency.

However, energy requirements represent merely a fraction of the overall equation; additionally, both capital expenditures (CAPEX) and operating expenditures (OPEX) must be taken into account. In the context of ammonia synthesis, transport, and cracking, substantial investments are required, in addition to those allocated for electrolysis and hydrogen liquefaction for the end users. In a meta-analysis of green ammonia production, Tully et al. (2025) identified a price range of 450 to 803 USD/t of green ammonia. In their study, Makhloufi and Kezibri (2021) calculated an ammonia cracking cost of €450 per ton of ammonia and an electricity cost of €60 per megawatt-hour, which results in a cost of compressed hydrogen of €4.83 per kilogram. However, for aviation applications, the costs associated with liquefaction must be incorporated into the overall equation, resulting in estimated costs of at least €7/kg  $\text{LH}_2$  at the airport. This is substantially higher than a range of estimations for hydrogen being transported in its liquid form, as outlined in section 2.1.

### 2.3. Liquid organic hydrogen carriers

Liquid organic hydrogen carriers (LOHC) are a class of chemicals that can absorb and release large quantities of hydrogen. Specifically, methylcyclohexane and toluene (MCH-TOL) can store up to 6.1% by weight in hydrogen, which is equivalent to 47 kg of hydrogen per cubic meter (Andersson & Grönkvist, 2019). LOHC are characterized by their ease of handling due to their high stability and non-toxic nature. These substances can be transported in conventional tankers, which are also utilized for the shipment of petroleum products.

The hydrogenation/dehydrogenation process is reversible; however, the reverse process, namely dehydrogenation, requires a significant amount of energy. Given the exothermic nature of hydrogenation, the integration of processes at the exporting location could prove advantageous. For instance, the heat generated by hydrogenation could be repurposed for high-temperature electrolysis. Melcher et al. (2021) state that approximately 3 kWh per kg H<sub>2</sub> must be input into the hydrogenation reaction to yield 9 kWh of heat from the exothermic process. The process of dehydrogenation requires 12 kWh of thermic energy per kg of hydrogen, which constitutes approximately 30% of the energy content in the released hydrogen.

Using LOHC, transport efficiency measured as hydrogen quantity carried per voyage would be relatively limited. Large-scale petroleum product tankers, for example, typically have a capacity of up to 115,000 tons. Using the hydrogen weight percentage of MCH-TOL, however, only about 7,100 tons of hydrogen could be shipped per voyage. From an economic perspective, transportation costs per unit of energy are influenced by two countervailing factors: the comparatively low hydrogen content and the relatively simple transportation methods employed. According to Schuler et al. (2024) the estimated transportation costs for a 10,000-kilometer journey amount to €10 MWh.

In the context of aviation, the transportation in the form of hydrogenated LOHC is very likely not to be preferential. This process is accompanied by a significant energy requirement in the importing country for LOHC dehydrogenation and subsequent liquefaction. As previously mentioned in section 2.1, a price difference in electricity costs between regions with abundant renewable sources and Europe is unlikely to offset the facilitated transport process and the avoidance of boil-off with LOHC as a hydrogen carrier for long-distance transport. Furthermore, from an economic standpoint, the capital expenditures and operating expenditures associated with hydrogenation and dehydration facilities could be circumvented when hydrogen is liquefied in the exporting region and directly transported.

### 3. Supply chains for hydrocarbon sustainable aviation fuels

In light of the constraints imposed by the availability of biogenic feedstocks, there is an increasing imperative for the development of PtL fuels to satisfy the demand for hydrocarbon energy carriers in the aviation sector. Moreover, the ReFuelEU Aviation regulation of the European Union stipulates an escalating requirement for RFNBO. By the year 2050, it is projected that 35% of aviation fuels will be RFNBO, with PtL fuels anticipated to account for a significant proportion of this share. According to the EUROCONTROL forecast, Europe will require between 17.7 and 18.7 Mt of RFNBO in 2050 (EUROCONTROL, 2025).

The PtL fuel production process necessitates a carbon source, ideally from a renewable source, and carbon-neutral hydrogen. Jet fuel is predominantly composed of medium-sized hydrocarbon chains with 12-16 carbon atoms (alkanes), in addition to ring-shaped cycloalkanes and aromatics. Assuming, for the sake of this analysis, that all jet fuel consists exclusively of alkanes, it can be deduced that the sum formula is C<sub>12</sub>H<sub>26</sub>. In this configuration, the mass percentage of carbon constitutes 84.6% of each molecule, whereas hydrogen makes up 15.4%. Consequently, to calculate the hydrogen demand required for PtL production, it is possible to use 15.4% of the PtL mass to determine the necessary amount of hydrogen. According to the EUROCONTROL forecast, the production of RFNBO/PtL fuels will necessitate 2.7 to 2.9 Mt of hydrogen. Consequently, even if direct hydrogen utilization will be limited in aviation, it becomes obvious that it is indispensable in the production of SAF.

The generation of PtL fuels necessitates considerable amounts of renewable electricity, not only for the production of hydrogen as an intermediary feedstock but also for the creation of hydrocarbons. Consequently, energy prices and availability are pivotal factors in the economic viability of PtL and the determination of its production location. Moreover, there are multiple PtL production processes, each with a distinct set of intermediate products. Among the most discussed production pathways of PtL fuels are the methanol-to-jet (MtJ) and Fischer-Tropsch (FT) processes.

Based on these findings, Fig. 1 shows several prospective supply chains for the production of PtL SAF and its transport to Europe. They differ in terms of the division of labor between exporting and importing regions and the types of energy carriers used for the long-distance transport, which will be typically done by ships.

Option 1 entails the transportation of liquefied hydrogen, a subject that was thoroughly examined in Section 2.1. The viability of this option hinges on the feasibility of long-distance maritime transport of LH<sub>2</sub> and the sufficiency of carbon availability in the export region to synthesize PtL SAF. While exporting regions may have sufficient low-cost electricity provision, they may lack the availability of carbon for PtL SAF power-to-liquid processes, e.g. when biomass availability is inadequate or where the economic and technical viability of large-scale atmospheric carbon

capture is not feasible. Subsequent PtL synthesis and jet fuel refining steps are conducted in the destination country or region. Option 1 necessitates the establishment of a LH<sub>2</sub> terminal at the importer's port. In contrast to the direct utilization of LH<sub>2</sub>, as outlined in Section 2.1, the hydrogen must undergo regasification, a process where at least some energy used for liquefaction can be recovered. In addition to the costs associated with liquefaction facilities in the exporting country and the boil-off losses during transport, liquid hydrogen (LH<sub>2</sub>) may not be the optimal choice for transporting hydrogen if it is not required in liquid form at the destination.

In the event that the transport of liquid hydrogen proves to be unfeasible, Option 2 presents a pragmatic solution to the challenges posed by the supply chain. In this instance, hydrogen is transported in the form of ammonia, a process that necessitates additional energy for synthesis and cracking (refer to the comprehensive discussion in Section 2.2). As in Option 1, other PtL synthesis and jet fuel refining process steps are retained within the importing country/region; however, energy losses associated with ammonia synthesis/cracking must be accepted. Moreover, the high costs associated with initial investments are likely to result in the establishment of facilities dedicated to ammonia synthesis and cracking.

Option 3 involves a distinct supply chain in which hydrogen for PtL production is transported to the destination region in the form of LOHC. This necessitates an additional logistics process for the dehydrogenation of the imported LOHC, which requires additional energy (as discussed in Section 2.3). Dehydrogenation should occur at or in close proximity to the port, as the tankers must be filled with dehydrogenated LOHC. The LOHC transport chain is a closed loop, and dehydrogenated LOHC must be refilled into the tankers at the importer's port and transported back to the exporting country, so it can be re-hydrogenated for the tanker's next voyage.

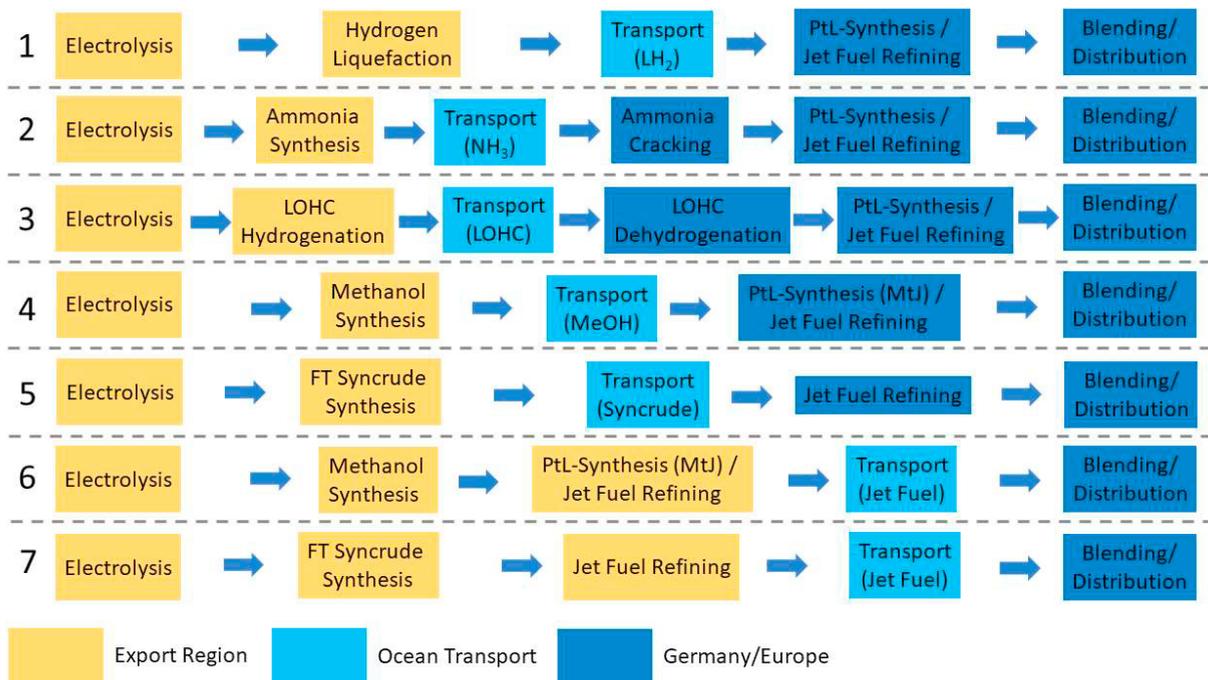


Fig. 1. Energy supply chain options for the production of PtL fuels

It is noteworthy that options 1, 2, and 3 are agnostic with regard to the ultimate PtL production process (i.e., the FT or MtJ process), given the necessity of hydrogen as a feedstock in both the MtJ and FT processes. However, option 4 focuses on the MtJ production route, in which methanol is synthesized in the exporting region. This could be a viable strategy because the transportation of methanol is inexpensive and uncomplicated. It is noteworthy that ships can be powered with methanol, thereby achieving a carbon-neutral supply chain. In order to ascertain the shipping costs of methanol, Schuler et al. (2024) controlled for its lower energy content of 20 MJ/kg and estimated the costs to be in the

order of €3.9/MWh for a 10,000 km voyage by ship. The logistics of importing methanol would be relatively uncomplicated. Due to its properties, it can be readily transported via various transport modes, including barges, railcars, and pipelines. The latter would be an optimal choice for transport from the seaport terminal to a refinery for MtJ fuel production. The MtJ production process necessitates the use of 1.5 to 2.5 tons of methanol for every ton of jet fuel produced. According to the estimates of EUROCONTROL, in conjunction with the ReFuelEU Aviation RFNBO mandates, the total demand for RFNBO in Europe is projected to reach approximately 18 Mt by the year 2050. Given the likelihood of a diverse array of feedstocks and production processes being necessary to meet this demand, the outlook for green methanol's use in aviation can be regarded as relatively optimistic. The processes of PtL synthesis and jet fuel refining will be executed within the importing region, necessitating significant energy resources. This option was also proposed by Thorsten Herdan of HIF Global, who cited the positive value added in existing refineries in Germany (airliners.de, 2025).

Option 5 involves the production of synthetic crude oil (syncrude) through the implementation of the FT process. The resulting intermediary product is subsequently transported to an import region for further processing into jet fuel. This process is very similar to the contemporary method of shipping fossil crude oil to refineries, such as those located in Germany, for the purpose of its refinement into a variety of petrochemical products, including jet fuel. The implementation of a syncrude-based logistics chain has the potential to contribute to the preservation of added value in Europe. Moreover, the processing of syncrude from multiple sources in European refineries has the potential to enhance resilience and risk diversification. As a further benefit, this strategy has the potential to reduce the necessity for investments in novel refinery capacities within exporting nations, as existing refineries in Europe could be easily adapted to the new production processes. However, it is necessary to evaluate the mentioned advantages against disadvantages, including the absence of heat integration. From an economic perspective, it appears to be a rational strategy to concentrate energy-intensive production steps in countries where the anticipated energy and electricity costs are the lowest. Nevertheless, ensuring a sufficient carbon supply remains a key challenge. In the context of the global energy landscape, nations that exhibit low electricity costs, a salient example being the Middle East-North Africa region, are inherently constrained in their potential to produce carbon from biomass. Consequently, the long-term capture of carbon from the atmosphere on a large scale appears to be a key prerequisite for integrated SAF production in exporting regions.

In comparison to Option 4, Option 6 offers a more advanced level of integration, as PtL synthesis and jet fuel refining will occur within the exporting region. The PtL jet fuel is then transported, a process that is well-developed, inexpensive, and uncomplicated. This process has the potential to enhance energy efficiency, particularly in scenarios where all process steps are conducted within a compact area of an integrated refinery. In such configurations, the process heat can be utilized in an optimal manner, leading to improved thermal efficiency and reduced energy expenditure. Furthermore, producers can capitalize on the lower electricity costs in the exporting region.

Finally, Option 7 is analogous to Option 5 in that both options involve the same Fischer-Tropsch synthesis process. However, in Option 7, the production of syncrude and the refining of jet fuel are integrated within a single facility. This approach offers potential benefits in terms of process integration and heat usage, similar to those offered by Option 6. The product that is shipped under this option is PtL jet fuel, which may undergo additional blending processes within the importer's region.

A potential challenge for options 4, 5, 6, and 7 could be the provision of a source of carbon in the exporting region. As previously discussed, in the absence of large-scale carbon capture from the atmosphere, a combined power/biomass-to-liquid process would be the only viable option if the objective is to avoid using industrial point sources of carbon. This has the potential to present a substantial challenge to regions that currently experience minimal electricity costs, such as the MENA region, Namibia, and Australia.

With the implementation of PtL SAF production facilities, a substantial amount of renewable electricity will likely be allocated to PtL fuel production. Therefore, the location of such facilities will largely depend on electricity prices, as producing one ton of PtL SAF requires about 43 MWh of electricity, assuming most of the necessary carbon comes from direct air capture (Drünert, Neuling, Zitscher, & Kaltschmitt, 2020). Assuming an energy content of 12 MWh/t in the final product, the overall energy efficiency of the process is relatively low at less than 30%. Under the assumption of an electricity price of 4.5 €-cent/kWh, one ton of PtL SAF could be offered for €1,800 to €3,100 in 2050. This is about 3-5 times higher than fossil-based jet fuel before carbon pricing. Table 1 summarizes the findings concerning the different supply chain options.

Importing energy carriers can be associated with geopolitical risks. In this regard, alternative energy carriers are no different from fuels based on crude oil. However, the risks of a resilient supply chain can be reduced to some extent. First, as Figure 1 shows, multiple supply chains can be established, which diversifies geopolitical and technological risks. Second, renewable energy sources can be geographically more diverse than crude oil sources. Various energy sources, such as wind, photovoltaics, concentrated solar power, hydropower, geothermal, and tidal, can be used to generate renewable electricity and, subsequently, chemical energy carriers. Nevertheless, areas that are conveniently located from a European perspective and that provide good prerequisites for photovoltaics or concentrated solar power in North Africa and the Middle East pose relatively high political risks. As Terrapon-Pfaff et al. (2022) analyzed, lower-risk locations are limited to countries such as Morocco, Jordan, the United Arab Emirates, and Tunisia. Other countries in the region pose a higher political risk, which translates into higher risk premia for financing, for example. Although politically stable countries are available for energy partnerships, they have a drawback from a European perspective due to the longer distances. Canada, Chile, and Australia, for instance, have stable political environments but are far away. This results in higher transport costs and, in the case of liquid hydrogen, potentially higher boil-off, making transport less attractive. Conversely, energy partnerships with politically and economically less stable countries present an opportunity to promote economic development when substantial gross value added remains in the exporting countries. Investments in these countries' energy infrastructure could contribute positively to economic development. The green energy transition should not result in a new form of "energy colonialism" (Müller, 2024) as has occurred in some oil-rich countries, where corruption, inefficiency, and foreign influence prevented the broader society from benefiting from their natural resources.

Table 1. Summarized overview for alternative energy supply chains for aviation

Category	Investment in Exporting Country	Investment in Importing Country	Handling and Transport	Energy Efficiency	Overall Assessment
Option 1 – Liquid Hydrogen (LH <sub>2</sub> )	High – hydrogen liquefiers	High when distribution as LH <sub>2</sub> / Medium when re-gasification is required	Very complicated / large tankers do not yet exist	Boil-off during maritime transport estimated 0.2-0.5% per day	Efficient choice when LH <sub>2</sub> is required by end users
Option 2 - Ammonia	High – ammonia synthesis	High – ammonia cracking	Uncomplicated in LNG tankers, but ammonia is a hazardous molecule and has a low hydrogen content (0.1765 kg H <sub>2</sub> per kg NH <sub>3</sub> )	Low boil-off, but energy losses for ammonia synthesis and cracking	Best used as direct energy carrier in shipping to avoid conversion losses from cracking to release hydrogen
Option 3 – Liquid organic hydrogen carriers	Medium/High – hydrogenation facilities with integrated high-temperature electrolysis	Medium - dehydrogenation facilities with considerable heat requirements	Uncomplicated in regular tankers	30% energy loss for de-hydrogenation	High volume shipments required due to low hydrogen content
Option 4 - Methanol	High – hydrogen and carbon supply needed	Medium – Methanol-to-Jet facilities	Uncomplicated in regular tankers	Efficiency losses due to separated methanol synthesis and methanol-to-jet refinery	Higher gross value added in importing country, multiple methanol sources possible

Option 5 - Syncrude	High – hydrogen and carbon supply + syncrude refinery	Low – existing refineries in Europe could be used to process syncrude	Uncomplicated in regular tankers	Efficiency losses, as syncrude production and jet fuel refinery are separated	Lower energy efficiency than options 6/7, but higher gross value added in importing country
Option 6 – Integrated Methanol Synthesis and Jet Fuel Refining	Very high – hydrogen and carbon supply + syncrude refinery + jet fuel refinery	Very low – use of existing fuel distribution logistics	Uncomplicated in regular tankers	Efficiency gains through integration of processes	Highest energy efficiency, but no gross value added in importing country
Option 7 – Integrated FT- Synthesis and Jet Fuel Refining	Very high – hydrogen and carbon supply + syncrude refinery + jet fuel refinery	Very low – use of existing fuel distribution logistics	Uncomplicated in regular tankers	Efficiency gains through integration of processes	Highest energy efficiency, but no gross value added in importing country

Another issue related to the global supply chains of renewable energy is the different sustainability criteria. For instance, while ICAO standards for CORSIA-eligible fuels allow a wide range of feedstocks of biological/agricultural origin, European regulations are much stricter, allowing only residual agricultural products for SAF production. Sustainability criteria for PtL fuels may also differ, e.g., regarding the additionality of electricity sources. If these criteria are not harmonized, the ability to create global supply chains with energy carriers made from renewable sources will be seriously impeded, and users will suffer from higher prices.

#### 4. Conclusions

The ReFuelEU Aviation Regulation and various ongoing projects to power aircraft directly with hydrogen indicate that the energy transition in aviation is already underway. The preferred supply chains and energy carriers for aviation are dependent upon many economic and technological developments. These include the development of hydrogen aircraft, the cost of renewable electricity in various regions of the world, the scaling up of direct air capture of carbon, and technological advances in hydrogen liquefaction and transport. In the short and medium term, until after 2040, hydrocarbon SAF appears to be the most relevant. Following the year 2040, the direct utilization of LH<sub>2</sub> could also become increasingly significant.

Both the academic literature and political strategy papers have reached a consensus that Europe will be reliant on imports of green energy, irrespective of the utilization of hydrocarbon SAF or hydrogen, due to constraints related to domestic cost and availability. Nevertheless, selecting the optimal supply chain and formulating and constructing the required infrastructure is a complex undertaking, due to the uncertainty surrounding pertinent factors. The ambiguity surrounding the regulatory environment, including sustainability criteria for imported SAF and technological advancements, such as the timeline for the entry into service of short- to medium-range aircraft with hydrogen propulsion, poses significant challenges to long-term planning for seaport terminals and fuel distribution infrastructure. The extant scientific literature offers no definitive conclusions regarding the optimal energy carriers and supply chains, as the outcomes of such analyses are contingent upon assumptions concerning future advancements in key parameters. Among the most important factors are energy costs. Consequently, from an efficiency standpoint, the production of energy carriers utilized in aviation could be predominantly situated in exporting regions.

In a future scenario in which aviation becomes a direct user of liquid hydrogen, it seems reasonable to import LH<sub>2</sub> directly in order to take advantage of the low energy costs in exporting regions. The implementation of this process would necessitate the establishment of LH<sub>2</sub> terminals. It is imperative to take into account the potential for boil-off during transport and transshipment to ensure the integrity and efficacy of the system. For users who do not require hydrogen in its liquid form, alternative supply chains could also be considered. LOHC is a particularly attractive solution in scenarios where the port or port region is capable of providing process heat for the dehydrogenation process. Green ammonia could be another option to provide hydrogen. However, due to conversion losses to release the contained hydrogen, it may be best used directly as fuel for ships and as a basic chemical.

In a future scenario in which a significant demand for hydrocarbon SAF emerges, the design of port infrastructure will be dependent on the distribution of the fuel production value chain. The viability of a highly integrated refinery exporting either syncrude or SAF will depend upon the availability of sufficient carbon in exporters' regions, either through large-scale direct air capture or a combined power/biomass-to-liquid process, and the presence of low electricity prices. In this scenario, the logistics of fuel distribution would remain relatively unchanged, as it would continue to be transported and distributed via seaports and refineries, much like the current practice involving fossil crude oil and conventional Jet A1. Conventional terminals, storage, and distribution facilities could be repurposed over time.

Feedstocks such as methanol, which are utilized in the MtJ PtL production route, can also be managed with minimal complexity, as they do not necessitate additional reforming or processing at the port. For instance, the transportation of methanol by pipeline, barge, railcar, or truck to facilities where it is subsequently reformed into SAF is a viable option. The necessity of proximity between these refineries and the port is not a prerequisite. These refineries do not necessarily need to be close to the port. In a future scenario where exporters' regions are unable to provide sufficient carbon for the synthesis of SAF or its intermediaries, such as methanol, it will be necessary to import larger quantities of green hydrogen to produce SAF domestically. However, the demand for green hydrogen may not be exclusively driven by aviation, as it is also required in the chemical, steel, and energy sectors. In this scenario, seaports would undergo substantial changes as they would require terminals for LH<sub>2</sub> re-gasification and distribution, as well as LOHC dehydrogenation facilities.

Overall, the energy supply chain strategy is not solely driven by techno-economic criteria. In recent years, resilience and risk management in the energy supply chain have received particular attention. A geographically and technologically distributed energy supply chain with different regions of origin and energy carriers could mitigate risks while acknowledging that imports will continue to play a major role in the European and German energy supply. This could be subject to further research, well beyond only techno-economic criteria on efficiency and costs.

## References

- airliners.de, 2025. Interview: "Die SAF-Produktion wird durch unnötig teure Regulierungen ausgebremst". Retrieved July 02, 2025, from <https://www.airliners.de/interview-hif-global-bringt-wind-sonne-uruguay-deutsche-raffinerien-e-saf/81103>
- Al Ghafri, S.Z., Munro, S., Cardella, U., Funke, T., Notardonato, W., Trusler, J.P.M., et al., 2022. Hydrogen liquefaction: A review of the fundamental physics, engineering practice and future opportunities. *Energy & Environmental Science*, 15(7), 2690–2731.
- Al-Aboosi, F.Y., El-Halwagi, M.M., Moore, M., Nielsen, R.B., 2021. Renewable ammonia as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, 31, 100670.
- Alkhalidi, A.N., Sampath, S., Pilidis, P., 2022. Economic analysis of a zero-carbon liquefied hydrogen tanker ship. *International Journal of Hydrogen Energy*, 47(66), 28213–28223.
- Andersson, J., Grönkvist, S., 2019. Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*, 44(23), 11901–11919.
- Ansari, D., Pepe, J.M., 2023. Toward a hydrogen import strategy for Germany and the EU: Priorities, countries, and multilateral frameworks. Retrieved August 15, 2025, from [https://www.swp-berlin.org/publications/products/arbeitspapiere/Ansari\\_Pepe\\_2023\\_Hydrogen\\_Import\\_Strategy\\_WP.pdf](https://www.swp-berlin.org/publications/products/arbeitspapiere/Ansari_Pepe_2023_Hydrogen_Import_Strategy_WP.pdf)
- Chen, P.S.-L., Fan, H., Abdussamie, N., 2025. Evaluation of hydrogen shipping cost for potential trade routes. *WMU Journal of Maritime Affairs*, 24(2), 315–338.
- Connelly, E., Penev, M., Elgowainy, A., Hunter, C., 2019. Current status of hydrogen liquefaction costs. Retrieved July 16, 2025, from [https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19001\\_hydrogen\\_liquefaction\\_costs.pdf?Status=Master](https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19001_hydrogen_liquefaction_costs.pdf?Status=Master)
- Drünert, S., Neuling, U., Zitscher, T., Kaltschmitt, M., 2020. Power-to-liquid fuels for aviation – processes, resources and supply potential under German conditions. *Applied Energy*, 277, 115578.
- Eckroll, J., 2017. Concepts for large scale hydrogen liquefaction plants. Norwegian University of Science and Technology. Retrieved July 02, 2025, from [https://ntnuopen.ntnu.no/ntnu-xmliui/bitstream/handle/11250/2454901/17110\\_FULLTEXT.pdf](https://ntnuopen.ntnu.no/ntnu-xmliui/bitstream/handle/11250/2454901/17110_FULLTEXT.pdf)
- EUROCONTROL, 2025. FLYINGGREEN: Supporting a sustainable future for aviation. Retrieved July 08, 2025, from <https://flying-green.eurocontrol.int/>
- European Commission, 2023. Market uptake and impact of key green aviation technologies – Final report. Publications Office of the European Union.
- European Parliament and Council of the European Union, 2023. Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation). *Official Journal of the European Union*.
- Federal Ministry for Economic Affairs and Climate Action (Ed.), 2024. Import strategy for hydrogen and hydrogen derivatives. Retrieved July 07, 2025, from [https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Hydrogen/Downloads/importstrategy-hydrogen.pdf?\\_\\_blob=publicationFile&v=1](https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Hydrogen/Downloads/importstrategy-hydrogen.pdf?__blob=publicationFile&v=1)

- Fraunhofer Institute for Solar Energy Systems ISE, 2025. Annual electricity spot market prices in Germany. Retrieved August 13, 2025, from [https://www.energy-charts.info/charts/price\\_average/chart.html?l=en&c=DE&interval=year&year=2024](https://www.energy-charts.info/charts/price_average/chart.html?l=en&c=DE&interval=year&year=2024)
- Gollnow, M., 2023. Passenger aircraft towards zero emission with hydrogen and fuel cells.
- Grimme, W., Braun, M., 2022. Estimation of potential hydrogen demand and CO<sub>2</sub> mitigation in global passenger air transport by the year 2050. *Transportation Research Procedia*, 65, 24–33.
- Hine, L., 2023. Does the rise of very large ammonia carriers spell the end of VLGCs? Enquiry ramps up for next not-so-new breed of gas carrier. Retrieved July 04, 2025, from [https://www.tradewindsnews.com/shipyards/does-the-rise-of-very-large-ammonia-carriers-spell-the-end-of-vlgs-2-1-1556996?zephyr\\_sso\\_ott=RKpFku](https://www.tradewindsnews.com/shipyards/does-the-rise-of-very-large-ammonia-carriers-spell-the-end-of-vlgs-2-1-1556996?zephyr_sso_ott=RKpFku)
- Kim, S., Oh, S., Kang, S., 2025. Techno-economic assessment of liquefied hydrogen tanker ships utilizing various propulsion systems. *Energy Conversion and Management*, 336, 119895.
- Lenivova, V., 2022. Potential development of renewable hydrogen imports to European markets until 2030. *OIES Paper ET: Vol. 08*. Oxford Institute for Energy Studies, Oxford.
- Makhloufi, C., Kezibri, N., 2021. Large-scale decomposition of green ammonia for pure hydrogen production. *International Journal of Hydrogen Energy*, 46(70), 34777–34787.
- Melcher, B.U., George, M., Paetz, C., 2021. Liquid organic hydrogen carriers – a technology to overcome common risks of hydrogen storage. Retrieved August 15, 2025, from <https://hysafe.info/uploads/papers/2021/5.pdf>
- Müller, F., 2024. Energy colonialism. *Journal of Political Ecology*, 31. Retrieved September 19, 2025, from <https://journals.librarypublishing.arizona.edu/jpe/article/5659/galley/5708/download/>
- Negro, V., Noussan, M., Chiaromonte, D., 2023. The potential role of ammonia for hydrogen storage and transport: A critical review of challenges and opportunities. *Energies*, 16(17), 6192.
- Ocko, I.B., Hamburg, S.P., 2022. Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, 22(14), 9349–9368.
- Panigrahy, B., Narayan, K., Ramachandra Rao, B., 2022. Green hydrogen production by water electrolysis: A renewable energy perspective. *Materials Today: Proceedings*, 67, 1310–1314.
- Perry, D., 2025. Airbus pushes back ZEROe timeline and ditches A380 fuel cell flight-test plan. Retrieved July 07, 2025, from <https://www.flightglobal.com/air-transport/airbus-pushes-back-zeroe-timeline-and-ditches-a380-fuel-cell-flight-test-plan/161718.article>
- Schuler, J., Ardone, A., Fichtner, W., 2024. A review of shipping cost projections for hydrogen-based energy carriers. *International Journal of Hydrogen Energy*, 49, 1497–1508.
- Shehab, M., Moshhammer, K., Franke, M., Zondervan, E., 2023. Analysis of the potential of meeting the EU's sustainable aviation fuel targets in 2030 and 2050. *Sustainability*, 15(12), 9266.
- Terrapon-Pfaff, L., Prantner, M., Ersoy, S.R., 2022. Risikobewertung und Risikokostenanalyse der MENA-Region: Bericht aus dem Teilprojekt B.I: MENA-Potenziale. Retrieved September 19, 2025, from [https://wupperinst.org/fileadmin/redaktion/downloads/projects/MENA-Fuels\\_Teilbericht8\\_Risikobewertung.pdf](https://wupperinst.org/fileadmin/redaktion/downloads/projects/MENA-Fuels_Teilbericht8_Risikobewertung.pdf)
- Timilsina, G.R., 2021. Are renewable energy technologies cost competitive for electricity generation? *Renewable Energy*, 180, 658–672.
- Tully, Z., King, J., Johnson, K., 2025. Hydrogen storage minimization under industrial flexibility constraints: A techno-economic analysis of off-grid green ammonia production. *International Journal of Hydrogen Energy*, 111, 12–21.
- You, Y., Kim, S., Lee, J.C., 2023. Comparative study on ammonia and liquid hydrogen transportation costs in comparison to LNG. *International Journal of Naval Architecture and Ocean Engineering*, 15, 100523.