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How Can Hydrogen Fuel Climate-Neutral Aviation in the EU?

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DESCRIPTION

The report is the outcome of two EPICO Policy Accelerator workshops, which took place in Brussels and Berlin in June 2024. Conceived by EPICO, the Policy Accelerator workshops adopt an interactive bottom-up approach, including a diverse range of key stakeholders on an operative and decision-making level to jointly develop policy mechanisms to overcome issues using an agile design thinking process.

DESIGN AND TYPE SETTING

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EXECUTIVE SUMMARY

This policy report examines the role that hydrogen can play in the future of climate-neutral aviation, in accordance with the EU's commitment to tackle climate change.

As one of the hardest-to-abate sectors, aviation's transition demands comprehensive policy frameworks, supportive financial mechanisms, and significant investment, to ensure a shift to sustainable alternatives. This paper primarily proposes policy recommendations centred around technological solutions, recognising the strategic importance of fostering innovation and advancing sustainability objectives. While the primary focus is on leveraging these technological pathways to reduce resource footprints, the anticipated scarcity of alternative fuels, particularly in the initial stages of deployment, is also acknowledged. Consequently, it is imperative to consider complementary strategies which investigate additional avenues for decarbonisation. Although complementary measures including demand-side management, rerouting, and changing flight altitudes lie beyond the scope of this analysis, these are all mechanisms which can and should be explored in parallel with hydrogen use, to help reduce the climate impact of the aviation sector.

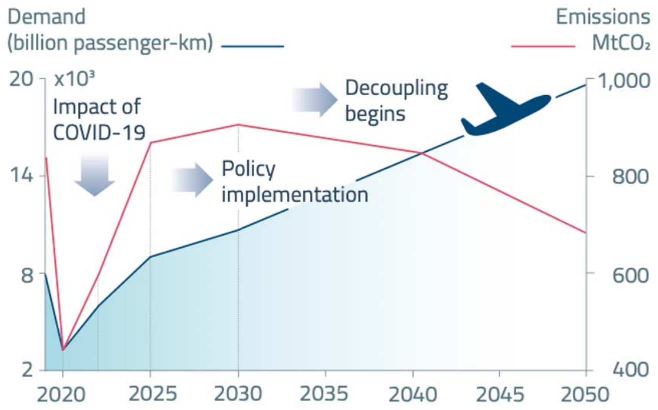
Policy recommendations for EU-level policymakers include:

1. Scaling finance and R&D for hydrogen development;
2. Developing the hydrogen market to ensure supply;
3. Ensuring infrastructural capabilities throughout the supply chain;
4. Levelling up the domestic and international playing field.

I.
AT A GLANCE

The aviation sector accounts for 2.5% of global CO_2 emissions, and about 5% of the EU's total greenhouse gas emissions (Future Cleantech Architects, 2024; ISAE Suaero 2022). As one of the fastest-growing sources of greenhouse gas emissions, with passenger demand expected to double before 2050 (Future Cleantech Architects, 2024), and air traffic predicted to double in the next 20 years (Airbus Global Market Forecast, 2024; Boeing Commercial Market Outlook, 2024), it is increasingly crucial to make the aviation sector climate-neutral in order to achieve global warming targets of 1.5°C, as decided under the Paris Agreement (Wasserstoff Kompass, 2022).

Figure 1: Projected global aviation demand (billion passenger-km) and emissions (MtCO2) growth to 2050 based on current implemented ambitions.



Source: Future Cleantech Architects. (2024, March).

As outlined in the European Green Deal, the EU aims to be climate-neutral by 2050. In Germany, the federal government seeks to reach climate neutrality by 2045, with interim ambitions to reduce total CO_2 emissions by at least 65% by 2030, compared to 1990 levels, as outlined in the Climate Protection Act (Klimaschutzgesetz, 2021).

Hydrogen-derived flights represent an opportunity to advance national and international climate ambitions. The versatile range of methodologies and usages of hydrogen in aviation enables a range of hydrogen applications. The authors' recommendations to overcome challenges of hydrogen in aviation focus on scaling up finance and R&D, addressing supply and demand issues, investing and developing hydrogen infrastructure, and advancing the international and domestic playing fields. These measures aim to facilitate the sector's shift towards climate neutrality.

TECHNOLOGICAL DEVELOPMENTS

All pathways to sustainable fuels require hydrogen at some point in their production (SASHA Coalition, 2023). Currently, there are three main applications for hydrogen in the aviation sector, which will be discussed in this paper:

1. **Hydrogen as a feedstock for synthetic SAF (Sustainable Aviation Fuels)/e-Fuels:** Synthetic-, e-SAF, e-Fuel or Power-to-Liquid (PtL) produced using green hydrogen and captured carbon dioxide. This method is currently the priority application for aviation decarbonisation considered by airlines and regulators to achieve climate-neutral aviation.

2. **Hydrogen-electric propulsion:** Hydrogen fuel cells create electrical energy, using liquid or compressed hydrogen, to power a propulsion system. This application functions entirely differently from commercial aircraft currently on the market.

3. **Hydrogen combustion as a direct fuel:** Hydrogen can be combusted, in the same way as traditional internal combustion, in either gaseous or liquid form, in a modified gas turbine to generate thrust.

Several industry players have started initiatives to bring hydrogen-powered aircraft to market, leveraging the primary applications of hydrogen across the EU and beyond.

The multinational European aerospace corporation Airbus is developing four hydrogen-powered aircraft as part of its ZEROe project. While three aircraft concepts use hydrogen combustion engines, one uses a hydrogen fuel cell to power electric motors. The project includes concepts seating 100 to 200 passengers, with ranges of approximately 1,000 to 2,000 nautical miles (1,852 to 3,704 kilometres). Both engines and fuel cells will be used in a modified A380 for flight tests scheduled for 2027 (Simple Flying, 2024). The goal is to introduce the world's first hydrogen-powered commercial aircraft by 2035 (Airbus, 2024).

Airbus also leads the Horizon Europe GOLIAT project (Ground Operations of Liquid Hydrogen Aircraft), comprising ten partners from eight countries. The project aims to support the adoption of liquid hydrogen transportation and storage solutions by developing refuelling technologies, trialling small-scale operations at three European airports, developing certification standardisation, and evaluating the hydrogen value chain for airport operations.

"Several industry players have started initiatives to bring hydrogen-powered aircraft to market, leveraging the primary applications of hydrogen across the EU and beyond."

Outside of the EU, British-American hydrogen-electric aircraft developer ZeroAvia is pioneering fuel-cell propulsion technology. ZeroAvia aircraft deployment aims to remove all emissions, including non-CO_2, with the exception of water vapour which is predicted to increase. To date, it has successfully demonstrated its technology using gaseous hydrogen in an aircraft seating 6 passengers and has matured technology for a 10- to 20-seat aircraft. Their long-term goal is to develop aircraft seating 200 passengers with a range of around 5,000 nautical miles by 2040 (ZeroAvia, 2024).

EXISTING POLICY FRAMEWORKS

Currently, several policy mechanisms are in place, both in Germany and at the EU level, to progress towards climate-neutral aviation. Intra-European Economic Area (EEA) flights have been included in the EU Emissions Trading System (ETS) since 2012. In June 2023, the EU adopted the ETS Reform to reach the objectives set out in the European Green Deal, which was announced in 2019 by the European Commission. The reform revises aviation rules: it further reduces the cap for aviation emission allowances and cuts free allowances by 25% in 2024 and 50% in 2025. From 2026, airlines will pay for all their CO_2 emissions. Previously, only 15% of aviation emissions between 2013 and 2020 had been auctioned (DG CLIMA, 2020). SAF allowances will also help aircraft operators cover 50% to 100% of the cost difference between traditional kerosene and SAF, depending on the type of fuel used. According to the reform, the EU will distribute 20 million allowances without charge until 2030 (European Commission, 2024). In October 2023, the EU adopted the ReFuelEU Aviation package, a regulation aimed at promoting the use of SAF. The regulation introduces percentage quotas for SAF, starting at 2% in 2025 and increasing to 70% by 2050. SAF allowances are only to be used on intra-EU flights, which represent about 40% of total aviation fuel use in the EU. The regulation covers over 95% of air transport departing from EU airports. ReFuelEU also includes a sub-mandate for synthetic fuels (e-fuels) of 35% by 2050. If successful, the policy mandate has the potential to reduce greenhouse gas emissions from aviation by around 38% by 2050 (Future Clean Architects, 2024).

The Fit for 55 Package also includes the adaptation of the Energy Taxation Directive (ETD) which taxes fuels based on their energy content and environmental performance and rules out exemptions for fossil fuels used for intra-EU air transport (CircuLaw, 2024). However, since this reform requires the Council's unanimous approval, it has stalled. Given low political capital, kerosene remains untaxed in commercial EU aviation. This places the EU behind other regions such as the US, Japan, India, Brazil, and Norway (Transport & Environment, 2019). Contrary to the popular belief, the Convention on International Civil Aviation (also known as the Chicago Convention) does not prohibit fuel taxation (European Commission, 2019). It only restricts taxing fuel that remains on board an aircraft departing from another country (Article 24).

The European Hydrogen Bank (EHB), launched by the Commission in 2023, aims to stimulate and support renewable hydrogen investment. This initiative seeks to expand domestic production and consumption of low-carbon and green hydrogen to replace traditional and other fossil energy for energy-intensive industries such as aviation. The EHB is the first financial instrument dedicated to developing a hydrogen value chain across the EU to reduce the cost gap and ensure market self-sufficiency by facilitating connections between producers and consumers and promoting project investment in the EU and beyond. All bids must include verifiable proof of early contracts with buyers (e.g. Memoranda of Understanding, Letters of Intent, or other forms of pre-contractual signed term sheets). In the first auction, which concluded on 30th April 2024, seven renewable hydrogen projects were awarded a total of €720 million. An additional €1.2 billion has been allocated for a subsequent auction. However, no awarded project had aviation as an end-use and/or offtaker for their renewable hydrogen in this first auction. Potential hydrogen producers participate in a "pay-as-bid" auction, where they bid for a specific subsidy per kilogramme of renewable hydrogen produced (EPICO, KAS, and Guidehouse, 2023).

The EHB builds upon the German H2Global initiative, which introduced an innovative double-auction model to drive the development and market adoption of green hydrogen and its derivatives. In this model, international hydrogen exporters offer the lowest possible supply price, while importers bid the highest price they are willing to pay. If a price gap arises, the government temporarily covers the difference until the market stabilises. In a significant development, the international pillar of the EHB, under the "Team Europe" approach, made H2Global available to all EU governments interested in conducting hydrogen auctions.

At the national level, Germany's federal government introduced the PtL Roadmap in 2021, as part of its National Hydrogen Strategy. The roadmap aims to expand sustainable PtL kerosene production, targeting at least 200,000 tonnes of PtL kerosene for aviation in Germany by 2030 (PtL Roadmap, 2021). Germany, alongside France, Sweden, and Norway, is positioned to become a leading producer of e-kerosene in Europe (Transport & Environment, 2024). The country benefits from several advantages in PtL development, including a robust industrial base (relevant for CO_2 as a by-product, and airlines as end-users) and advanced expertise in renewable energy and chemical engineering. However, the cost of this low-carbon electricity could play to Germany's disadvantage, when compared with Sweden or France, where prices are lower, and electricity is less carbon-intensive.

POLICY SHORTCOMINGS

A staple policy of climate-neutral aviation, ReFuelEU helps to provide greater certainty to aircraft operators and fuel suppliers by paving the way for scaled-up SAF production. Acceptable SAF under the regulation includes certified biofuels, renewable non-biofuels (hydrogen), and recycled carbon fuels. The policy also includes dedicated sub-targets for hydrogen-based electrofuels of 1.2% for 2030, and 35% in 2050. Despite percentage quotas, there are concerns that production will fail to meet demand, resulting in pulling back on targets in order to avoid crippling EU aviation companies (Clean Sky 2 & FCH 2, 2020; ISAE Supaero, 2022; Mission Possible Partnership 2022; Future Cleantech Architects, 2024).

However, climate experts fear that the targets do not go far enough or act quickly enough to spark the vast infrastructural developments necessary for hydrogen in aviation in any of the primary uses. These include aircraft retrofitting and/or remodelling, as well as transportation, storage, and electrolyser facilities (Alliance for Zero-Emission Aviation, 2024). The development cycle for aircraft, encompassing design, rigging, demonstration, certification testing, and entry into service, typically spans 15 to 20 years. This means that traditional kerosene-powered planes produced in the coming years will still be in operation in 2050, making ambitious and timely targets imperative to match ambitions.

"The current policy focus remains largely on biofuels, with insufficient emphasis on, for example, renewable hydrogen as a more sustainable alternative to help make the sector climate-neutral."

Moreover, the current policy focus remains largely on biofuels, with insufficient emphasis on, for example, renewable hydrogen as a more sustainable alternative to help make the sector climate-neutral. ReFuelEU primarily targets liquid fuels but incorporating policies and targets for hydrogen as a direct fuel, and hydrogen-electric propulsion systems, could significantly accelerate the sustainable transition, utilising a multitude of hydrogen applications. Although the framework allows for the direct use of hydrogen in percentage quotas, there is a lack of real incentives to accelerate hydrogen technology development at the speed necessary to be ready for 2050. In order to scale to the size and efficiency required, the technology readiness level (TRL) of the hydrogen applications discussed in this paper (SAF, electric-propulsion, and combustion) require further support for deployment also given the nature of stringent safety regulations in the aerospace industry.

Furthermore, the EU ETS is incomplete, as it does not cover extra-EU flights, small aircraft (e.g. some private jets), or non-CO_2 aviation effects. The ETS captured 22% of emissions from intra-EU flights (164.5 megatonnes of CO_2) in 2023, equating to €3 billion in EU allowances (Homaio, 2024). On non-CO_2 effects, the European Commission only plans to introduce a Monitoring, Reporting, and Verification (MRV) system for now, starting from January 2025 (ETS Monitoring and Reporting Regulation, 2024). International coordination on aviation climate neutrality needs to be addressed. The lack of coverage of international flights in the EU ETS omits a vast proportion of the highest-emission flight paths operating in and out of the European airspace, such as intercontinental and transatlantic flights, which equate to over 50%.

II.

ADVANTAGES OF HYDROGEN IN AVIATION

CLIMATE MITIGATION

The main benefit of using hydrogen in aviation is its potential to cut CO_2 emissions, while simultaneously reducing non-CO_2 effects. Clean hydrogen is produced using low-carbon energy sources, including wind, solar, hydropower, nuclear, and tidal energy. Unlike grey hydrogen, which is derived from fossil fuels, green hydrogen is the only type considered capable of steering aviation towards climate neutrality. However, as of June 2024, only 3.6% of low-carbon hydrogen production projects in the EU planned for 2030 reached the Final Investment Decision (FID), resulting in just 0.6 MtH2, with two-thirds of this hydrogen still originating from fossil fuels with carbon capture (so-called 'blue' hydrogen) (European Roundtable on Climate Change and Sustainable Transition (ERCST), 2024). The latter might therefore be important for the aviation sector as an interim bridge, until the EU scales its green hydrogen production.

"The main benefit of using hydrogen in aviation is its potential to cut CO_2 emissions, while simultaneously reducing non-CO_2 effects."

The other most common climate-neutral application is Bio-SAF, which includes fuels like Hydroprocessed Esters and Fatty Acids (HEFA) derived from plant oils, animal fats, and waste biomass. Bio-SAF, however, faces supply limitations and a lack of environmental credibility. HEFA, despite currently being the most common form of SAF, requires extensive land use that can lead to deforestation, biodiversity loss, and significant water and resource consumption. Due to the extensive amount of land required to produce the quantities of Bio-SAF necessary for climate-neutral aviation, hydrogen is both a promising and logical alternative to drive the transition.

All applications of hydrogen in aviation reduce CO_2 impact, however non-CO_2 impact is often left out of the equation. According to the German Environmental Agency, non-CO_2 effects, which include soot, nitrogen oxide (NOx), and sulphur oxide (SOx), are responsible for about two-thirds of the climate impact of aviation (Umweltbundesamt, 2019).

E-SAF reduces direct CO_2 emissions compared with kerosene and is expected to burn with a lower aromatic content and therefore reduce NOx emissions, water vapour, and contrail formation (Deutsches Zentrum für Luft- und Raumfahrt, 2021). According to a McKinsey study for the Clean Sky 2 & FCH 2 (2020), e-SAF has the potential to reduce climate impact by 30-60%.

Hydrogen fuel-cell propulsion could reduce impact by 75-90% (Clean Sky 2 & FCH 2, 2020). It has the potential to fully eliminate CO_2 from its in-flight emissions, nearly eliminate soot and NOx emissions, and potentially decrease contrail formation by 60-80% (ibid; Tiwari, Pekris, and Doherty, 2024). It does, however, increase water vapour by 150%.

According to the same study, hydrogen combustion can reduce its emissions by an estimated 50-75% (Clean Sky 2 & FCH 2, 2020). In more detail, hydrogen combustion can cut in-flight CO_2 emissions by 100%, and NOx emissions by 50-80%, although it could increase water vapour by 150%, while reducing contrails by 30-50%.

Synthetic SAF or e-SAF will have high costs at the dispensation stages. However, the systemic costs will be lower in the long run, due to the fact that they are drop-in fuels that do not require novel aircraft design and manufacturing, or large-scale infrastructure redesign at airports. This makes them the preferred option for the coming years, with targets starting from 2030. Hydrogen propulsion, on the other hand, may have higher systemic costs because of the requirement for novel aircraft designs and large-scale infrastructure redesign at airports. The University of Leeds developed the Resource to Climate Comparison Evaluator for the Aviation Environment Federation (RECCE, 2024), which finds that, among hydrogen options, hydrogen fuel-cell propulsion is the cleanest hydrogen application for use in aviation.

Figure 2: Comparison of climate impact from H2 propulsion and synfuel compared to kerosene-powered aircraft, timeframe until 2010. Compared to kerosene-powered aircraft, timeframe until 2010.

Ongoing scientific debate about full climate impact, in particular:

- Contrail/cirrus formation
- Aggregate measure

Total climate impact could be 2 to 4 times compared to CO_2 emissions alone

	Change of in-flight emissions and emission related effects[1]				Climate impact reduction potential[4]
	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus	
Synfuel	-0% / -100% (Net)[3]	-0%	-0%	-10-40%	-30-60%[3]
Hydrogen turbine	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%	-75-90%

1. Assuming decarbonized production and transportation of fuels in 2050
2. 10 times lower climate impact than from CO_2 emissions
3. Net CO_2 neutral if produced with CO_2 captured from the air
4. Measured in CO_2 equivalent compared to full climate impact of kerosene-powered aviation

Source: McKinsey & Company & Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU. (2020, May).

III.

CHALLENGES OF HYDROGEN IN AVIATION

FINANCE AND R&D

Successfully deploying hydrogen-powered aircraft in Europe will require an estimated €300 billion in investments (Transport & Environment, 2023). However, the high capital expenditure (CAPEX) requirements, long investment cycles, and regulatory uncertainties pose significant challenges to attracting investment opportunities. Scaling hydrogen technologies demands substantial research, development, and safety and inspection certification to prepare it for commercial viability. For all applications of hydrogen in aviation, aircraft and infrastructure modifications will need to take place. The technological barriers and long certification process add an investment risk-dimension.

> *"Scaling hydrogen technologies demands substantial research, development, and safety and inspection certification to prepare it for commercial viability."*

Regulatory uncertainty regarding the implementation of policies that ameliorate these risks exacerbates investment hesitancy. The ambiguity surrounding the specific methods and applications of hydrogen in aviation further contributes to this reluctance. Combined with high CAPEX and long investment cycles, these factors result in a lack of FIDs from the private sector, as incumbents fear potential market share loss. For example, the German government's initial attempt to facilitate industry access to e-SAF through the state purchase programme (H2 Global) was unsuccessful, as investors found the regulatory framework "too ambiguous and risky" (Tagesspiegel Background, 2024).

RENEWABLE HYDROGEN SUPPLY

A significant challenge to commercialising hydrogen in aviation is securing a reliable supply of renewable hydrogen. Currently, domestic hydrogen production in the EU is insufficient to meet the demand. The production of renewable hydrogen heavily relies on renewable energy but, given the current capacity and competing demands from other sectors, this reliance is a strain on production. To supply renewable hydrogen at scale, imports from outside of the EU will be necessary, but will have to be counterbalanced with criteria surrounding resilience and energy security, as well as exposure to supply chain disruptions, geopolitical instability, and environmental and economic costs, including conversion losses (Pepe, Ansari, & Gehrung, 2023). To minimise energy use and conversion losses, imported hydrogen should be transported in liquid form, with future deliveries to high-demand users, such as large airports, potentially through dedicated pipelines (Alekseev et al., 2023).

Competition for renewable hydrogen with other hard-to-abate sectors, which are considered more essential and are arguably more important to most national European economies, and more price-sensitive, presents another barrier to ensuring sufficient hydrogen supply for aviation. Supply constraints and competition for renewable hydrogen access, without support for production, could drive up costs, making hydrogen a less attractive solution for decarbonising the aviation sector. Policymakers must balance the needs of different sectors, prioritising CO_2 abatement potential and costs. As a result, hydrogen use should be optimally directed toward hard-to-abate sectors such as ammonia, steel, aviation, and shipping, and excluded for heating and short-haul road transport, as recommended by the International Renewable Energy Agency (International Renewable Energy Agency, 2024).

Furthermore, while Europe is working to increase its electrolyser capacity to over 40 GW by 2030, the current pace of production is insufficient compared to the amount needed, not only for aviation but also for other sectors looking at the possibility of hydrogen as a decarbonisation solution (European Roundtable on Climate Change and Sustainable Transition, 2024). Moreover, around two-thirds of all manufacturing capacity projects of electrolysers are still in a pre-FID stage with a significant risk of cancellation, delay, or relocation (Hydrogen Europe, 2023). Another main issue is that electrolysis currently operates at an efficiency rate of around 60–70% under optimal conditions. This means a significant portion of the electrolyser input energy is lost, and that efficiency improvements need to be developed to maximise output.

INFRASTRUCTURE AND SUPPLY CHAIN LOGISTICS

Transporting hydrogen to airports presents the first set of logistical challenges in the post-electrolysis supply chain. The mode of transporting hydrogen will largely depend on the size, location, and demand of the airport to which it is being delivered – either 1) through gaseous hydrogen pipelines; 2) liquid hydrogen tanker deliveries; or 3) a potential scenario where demand necessitates hydrogen production and liquefaction in or around the airport vicinity (Aerospace Technology Institute, 2022). All three options pose logistical hurdles, including traffic congestion, grid pressures, and infrastructural development. Bespoke planning will be required to ensure a swift and safe hydrogen supply.

> *“Robust refuelling infrastructure is critical to ensuring speedy and safe delivery of fuel to aircraft.”*

Furthermore, the vast amount of hydrogen being supplied to airports will require storage facilities. The most obvious way to store hydrogen would be in liquid form, which has three times the energy-per-unit mass of traditional aviation fuel, but a lower volumetric density. This necessitates increased storage capacity in cryogenic storage tanks insulated at a temperature of -253°C. Although this will require significantly less land use than gaseous hydrogen storage, it will still require the construction of numerous cryogenic tanks close to refuelling sites, as well as a vast amount of energy to cool it to such temperatures.

Robust refuelling infrastructure is critical to ensuring speedy and safe delivery of fuel to aircraft. To handle hydrogen, the carrier – whether it be a bowser or piping system – used to transport the hydrogen from the storage site to the refuelling stations will require cryogenic insulation to keep the hydrogen in a liquid state to avoid boil-off. To ensure that airports are ready for the uptake of hydrogen-compatible aircraft, they will need to prove that they can tackle all the infrastructural and logistical challenges necessary to swiftly and safely refuel fleeting aircraft.

REGULATION AND SAFETY

The aviation sector adheres to some of the most stringent safety regulations in the world, undergoing rigorous certification processes to ensure aircraft meet the highest safety standards. As a highly explosive chemical element, hydrogen poses a number of safety concerns both for transporting hydrogen and for in-flight use. Hydrogen leakage, including from renewable hydrogen, also generates emissions, and contributes to global warming due to hydrogen's role as an indirect greenhouse gas as it reacts with hydroxyl radicals and nitrogen oxides, leading to extended lifetime of methane and ground-level ozone, both of which are potent greenhouse gases with much higher heat-trapping potential than CO_2 (Columbia Center on Global Energy Policy, 2022).

In the future, a critical consideration for the sector will be the social acceptance and consumer confidence in the use of hydrogen in aviation, especially when using novel applications such as hydrogen-electric propulsion and hydrogen combustion. Given that hydrogen is highly explosive, and in view of its historical associations, we can anticipate a degree of flight anxiety among some members of the public (IFPEN Economic Papers, 2023).

Addressing these concerns will be an essential component for airlines to ensure consumer confidence and encourage hydrogen flight uptake. In order to get to the stage at which safety concerns need to be addressed, however, a number of strategies need to be implemented to take hydrogen use in aviation forward.

IV.
POLICY RECOMMENDATIONS

1. SCALE FINANCE AND R&D FOR HYDROGEN DEVELOPMENT

Regulatory sandboxes

The EU should establish a dedicated framework within aviation policy, specifically addressing the development and integration of hydrogen technologies by creating regulatory sandboxes in the EU, taking examples from provisions of the Net-Zero Industry Act (NZIA). This framework should facilitate regulatory support, streamline certification processes, and promote standardisation across the industry to ensure commercial readiness. The UK Civil Aviation Authority is implementing a regulatory sandbox approach, aimed at ensuring that regulatory frameworks are fit for the introduction of hydrogen fuel in aviation. This approach seeks to identify and address potential regulatory challenges early in the development process. ZeroAvia's hydrogen-electric propulsion technologies were selected as part of the Civil Aviation Authority's 'Hydrogen Challenge' to leverage the potential of hydrogen as an alternative zero-carbon emission fuel in aviation (ZeroAvia, 2024).

To ramp up R&D funding for large-scale use of hydrogen applications still at a lower TRL, such as hydrogen combustion and electric propulsion, the EU should make more of its funding available through various R&D initiatives, including Horizon Europe projects and the Innovation Fund. Additional funds should also be accessible through the EU's other lending institutions, such as the European Investment Bank (EIB) group. Currently, the main EU-level funding dedicated to hydrogen-powered aircraft is through the Clean Aviation Joint Undertaking (CAJU), with a budget of €4.1 billion. Funding for hydrogen infrastructure at European airports is provided by the Alternative Fuels Infrastructure Facility (AFIF) under the Connecting Europe Facility, which has granted over €1.3 billion since 2021 (European Commission, 2024). The aforementioned GOLIAT project is funded by the Horizon Europe Framework Programme.

> *"The EU should establish a dedicated framework within aviation policy, specifically addressing the development and integration of hydrogen technologies by creating regulatory sandboxes."*

Public-private partnerships

Public-private partnerships (PPPs) or Joint Undertakings (JUs) will be imperative to aid expansion of commercial-level production and utilisation of hydrogen in aviation. A number of PPPs and JUs already exist in hydrogen and aviation. In 2021, the EU set up the Clean Hydrogen Partnership (formerly Fuel Cells and Hydrogen 2 JU), aimed at accelerating fuel cell and hydrogen technologies, and the Clean Aviation JU (formerly Clean Sky 2 JU), to create a network of SMEs to develop innovative technologies to reduce aircraft CO_2 emissions, respectively.

In Germany, the Federal Ministry for Economic Affairs and Climate Action set up a hydrogen PPP in 2023, entitled "International Hydrogen Ramp-up Programme" to support SMEs in preparing and implementing green hydrogen pilot projects using German technological expertise in third countries with the establishment of import-export relations. To ensure the development of applications which do the most to reduce emissions in aviation, the EU should look at setting up a PPP or JU dedicated solely to the development of hydrogen technologies in aviation. In order to prevent exacerbating global inequality, the price paid for green hydrogen production in third countries will need to be higher than the base cost of energy/production, in order to account for fair export revenues received by the country of origin.

2. DEVELOP THE HYDROGEN MARKET TO ENSURE SUPPLY

To make Europe an attractive place for innovation and investment, particularly in hydrogen technologies like fuel cells and hydrogen combustion, several financial strategies should be deployed to enable the development of novel technologies for the aviation sector. Investing in hydrogen fuel cell technology not only benefits the aviation sector but also has the potential to revolutionise many other industries. Advantages include higher efficiency, lower emissions, and the ability to integrate renewable energy sources, for energy storage and backup power, for grid balancing and long-haul road travel. Additionally, cryogenic liquid hydrogen could enable the cooling or supercooling of equipment, providing further efficiencies across various applications.

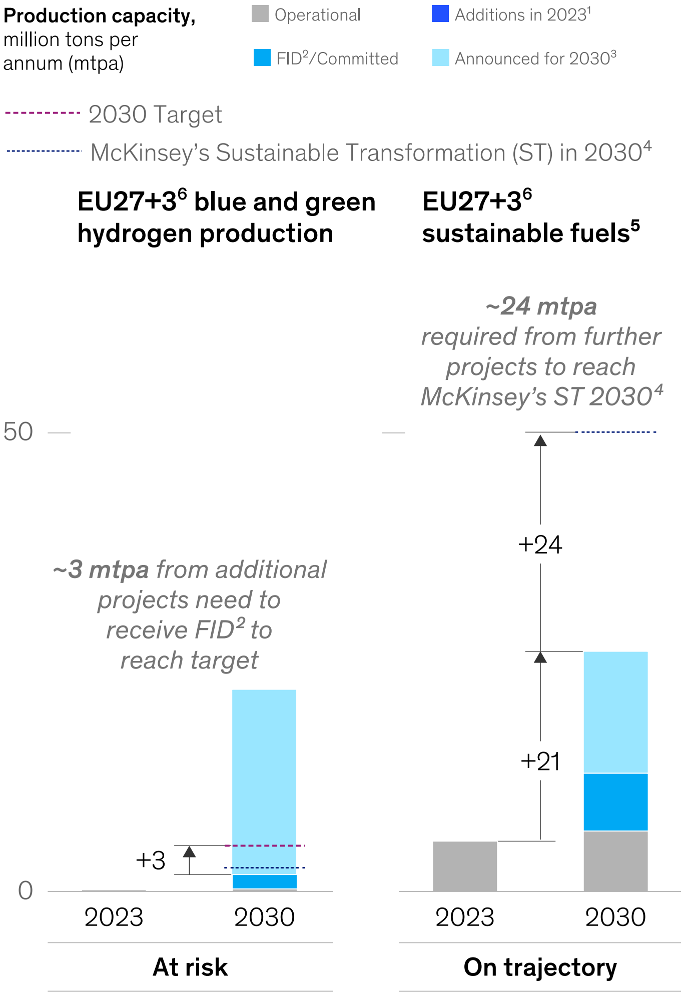
"Investing in hydrogen fuel cell technology not only benefits the aviation sector but also has the potential to revolutionise many other industries."

Ramp up hydrogen production

Given the imperative role of hydrogen for sustainable fuel production, the lack of concrete hydrogen projects risks throwing sustainable fuel expansion off track (McKinsey, 2024). The situation for renewable hydrogen production in the EU is critical: only 3.6% of hydrogen production projects planned for 2030 have reached the FID stage, resulting in just 0.6 MtH2, with a mere 0.2 MtH2 being renewable (ERCST, 2024). The European Court of Auditors has made several key recommendations to address this issue, including: updating the hydrogen strategy to incorporate market incentives, funding priorities, and geopolitical considerations; using a scoreboard to monitor progress; and assessing the effectiveness of EU funding arrangements for hydrogen development (European Court of Auditors, 2024). The European Commission's decision to embrace these recommendations marks a positive step forward for the hydrogen economy. However, new political, regulatory, and financial focus should be directed towards the North and Baltic Seas, where direct conversion of energy into hydrogen is expected to be more profitable than offshore wind electricity as highlighted in our upcoming study "Connecting Borders Through Offshore

Hydrogen: Infrastructure and Financing in the North Sea".

Figure 3: Many hydrogen projects may not materialise, putting non-biobased sustainable fuels at risk



[1]Operational GW capacity added in 2023. [2]Announced projects that have reached the final investment decision. [3]Includes announced projects and prefinal investment decision. [4]Continued momentum scenario. [5]Hydrotreated vegetable oil (HVO)/hydroprocessed esters and fatty acids (HEFA), advanced middle distillate, methanol. [6]EU27 + Norway, Switzerland, and the United Kingdom.
Source: Hydrogen Insights Project tracker, McKinsey's Sustainable Fuels Project database

Source: McKinsey & Company. (2024, August).

Incentivise private investment

Currently, 80% of European venture capital is directed towards American projects (European Commission, 2022). To counter this trend, Europe should utilise tools such as first-loss loans and sector-specific loan guarantees to boost investment. Additionally, offering temporary tax credits for investments, and encouraging alternative financing such as green credit guarantees, can further attract investors. Re-enacting the European Fund for Strategic Investments, which provides a guarantee to the EIB, would allow for the financing of higher-risk projects, enhancing Europe's innovation landscape and investment appeal for domestic hydrogen (EPICO, 2024).

Offtake Agreements

To de-risk the market for exponential hydrogen uptake in the coming years, the development of offtake agreements, supported by government incentives, presents a strategic pathway. Offtake agreements involve airlines committing to purchase hydrogen prior to its market availability, ensuring predictable demand for hydrogen producers, and enabling substantial investments to scale up production capacities. However, airlines have been reluctant to engage in these agreements due to a combination of insufficient incentives and an underdeveloped business case. One potential strategy could involve government procurement of e-SAF and hydrogen-powered flight options for state-related air travel, setting a benchmark for the industry and significantly advancing these technologies.

> *"To de-risk the market for exponential hydrogen uptake in the coming years, the development of offtake agreements, supported by government incentives, presents a strategic pathway."*

In addition to governmental offtake and procurement initiatives, Member States could consider implementing Contracts for Difference (CfDs) or Carbon Contracts for

Difference (CCfDs), as mentioned in the UK Sustainable Aviation Fuels Revenue Certainty Mechanism (UK Department for Transport, 2024). These government mechanisms cover part of the cost difference between cheaper fossil fuels and low-carbon alternatives. Unlike traditional CfDs, CCfDs are specifically designed to support industrial decarbonisation by factoring in savings from carbon pricing. In the aviation sector, this approach would involve governments subsidising the adoption of hydrogen, thereby closing the cost gap, and providing price security and stability for airlines. However, this mechanism should be temporary, with a sunset clause, serving as a bridge until the ETS is fully implemented without free allowances.

Governments have historically supported the aviation sector during crises due to its critical economic role. For example, the German federal government provided €3.8 billion in loans to Lufthansa through its Economic Stabilisation Fund, while the French and Dutch governments extended €10.4 billion in loans to Air France-KLM, and the Austrian government allocated €150 million to Austrian Airlines during the pandemic (Bundesregierung, 2021; European Commission 2020a; 2020b; Der Standard, 2024). However, this aid was provided without significant conditions. In contrast, implementing conditional CCfDs would not only support aviation's role in national economies but also incentivise the reduction of the sector's growing climate impact.

3. ENSURE INFRASTRUCTURAL CAPABILITIES THROUGHOUT THE SUPPLY CHAIN

Electrolysis development

One of the challenges facing the use of hydrogen in aviation is securing a sufficient supply of renewable energy. As well as ramping up the number of electrolysers in the EU, substantial technological development is needed in the electrolysis process to increase its efficiency and therefore use less renewable supply. To cement a European supply chain, the EHB should consider increasing its budget and integrating resilience criteria, as suggested by various stakeholders in the hydrogen value chain (Letter to President von der Leyen, July 2024). The same criteria should be present in public procurement, the use of EU funds such as the cohesion and structural funds, and also the Modernisation and the Innovation Funds (Defard et al., 2023).

Airports as 'lead markets'

Support should be put in place for airports to act as 'lead markets' to encourage offtake agreements, prioritise access to infrastructure, and enhance EU-wide cooperation on transport technology, cryogenic storage, and refuelling infrastructure. An initial option could be to utilise private jet airports, which are smaller and more regional than commercial airports, and therefore good starting points for development before being rolled out on a larger and more international scale. These efforts should build on the provisions for ensuring robust refuelling infrastructure under the Alternative Fuels Infrastructure Regulation (AFIR).

> *"The future hydrogen backbone should consider 'lead market' airports […] and incorporate progress made within the 'hydrogen valleys' projects to develop full-scale hydrogen ecosystems."*

Furthermore, the future hydrogen backbone should consider 'lead market' airports in defining pipeline infrastructures, and incorporate progress made within the 'hydrogen valleys' projects to develop full-scale hydrogen ecosystems to establish initial hubs for hydrogen aviation and refuelling stations. Existing commercial examples include Groningen Airport in the Netherlands and Toulouse Airport in France. However, this can be developed to include transport hubs across Europe as hydrogen in the aviation sector develops.

Airlines must be confident that airports possess the necessary infrastructure to transport, store, and refuel their aircraft before committing to offtake or purchasing agreements. Additionally, as one of the sectors with the most stringent safety regulations, airports must ensure that the substances are being handled safely. It will be crucial to conduct comprehensive life cycle analyses (LCAs) for all types of alternative fuels and focus on minimising hydrogen leakages to ensure environmental sustainability in and around the airport vicinity.

4. LEVEL UP THE DOMESTIC AND INTERNATIONAL PLAYING FIELD

Expand the ETS

To realistically achieve climate-neutral aviation, the EU must collaborate with global partners, upholding stringent norms for social and ecological sustainability and ensuring fair revenue distribution among major emitters. To standardise compliance for flights entering and leaving its airspace with those within the EEA, the EU could extend the ETS to include extra-EEA flights, as it does for shipping entering EU-exclusive economic zones. The EU should also strengthen the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) mechanism through partnerships under International Civil Aviation Organization (ICAO), promoting global standards for hydrogen fuel cells, hydrogen combustion, and e-SAF.

"To realistically achieve climate-neutral aviation, the EU must collaborate with global partners, upholding stringent norms for social and ecological sustainability and ensuring fair revenue distribution among major emitters."

Despite a carbon price of €100/tonne of CO_2-e translating to a €0.25/litre increase, and a kerosene price of €0.75/litre, the e-SAF price of €2.30/litre maintains a cost premium exceeding 50%. The EU ETS should also start monitoring non-CO_2 aviation effects from all flights in 2025, and price them as soon as possible afterwards. This should especially be the case if pure H2 aircraft reduce non-CO_2 effects; in this scenario they should benefit from non-CO_2 integration under the ETS. EU Member States should consider a higher, unified EU carbon price for kerosene due to its high warming potential, and the fact that only 15% of ETS allowances have been traded since 2012 (Directorate-General for Climate Action, 2024). Revenue from auctioning these allowances should support the transition from conventional kerosene to alternative fuels. While the first e-SAF projects in Europe are anticipated to begin in 2027, hydrogen technologies in combustion and fuel cells are not expected to be commercially viable before 2030, highlighting the increased support required for these disruptive technologies to scale effectively (Transport & Environment, 2024).

Uphold the Green Claims Directive

Member States should fully and swiftly implement the Green Claims Directive, underlining its vital link to hydrogen. This directive is designed to combat greenwashing by ensuring clearer and more credible claims about environmental benefits. By curbing deceptive practices, the directive will promote a more trustworthy market, enhancing the effective use of renewable hydrogen resources. Improved transparency and reliability are crucial for advancing sustainable energy solutions and meeting wider environmental objectives. Thorough monitoring and evaluation processes need to be uniformly conducted across Member States. This will ensure that claims are certified and ambitions are on track across the domestic and international playing field.

V.
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EPICO is an independent climate and energy policy think tank based in Berlin and Brussels. Founded in 2021 by Dr Bernd Weber, EPICO has a social market-oriented approach to promote a socially cohesive and environmentally sustainable transition to climate neutrality. Supported by its broad-based Advisory Council, EPICO provides a platform and network for diverse stakeholders from politics, academia, industry, and civil society to exchange and find majorities for ambitious climate policies.

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