The cost of hydrogen aviation

Making hydrogen aircraft cost competitive

May 2023

Summary

€299 billion would be needed between 2025 and 2050 to develop and run the hydrogen aviation value chain in Europe, with 83% of costs for hydrogen production, distribution and liquefaction. These are the main findings of an economic analysis on deploying hydrogen aviation for intra-European flights by 2050, commissioned by the European Climate Foundation (ECF) and Transport & Environment (T&E), and conducted by Steer.

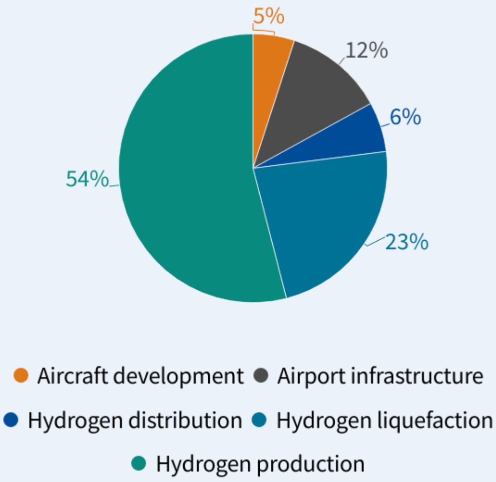

Figure 1. Share of costs

The study, which assumes the entry into service of an aircraft with a 2000 nautical miles range by 2035, finds that the bulk of hydrogen aviation costs come from hydrogen production (54%) and liquefaction (23%). Hydrogen distribution accounts for 6%, with airport infrastructure amounting to 12% of the total. Aircraft design is only 5% of the overall cost, but should happen before 2035 to ensure the success of hydrogen for intra-European flights.

The baseline scenario considers a yearly traffic growth of 1.1%. But if leisure and business traffic remained respectively at 100% and 50% of 2019 levels, **total costs would go down to 190€ billion**.

The study finds that operating **hydrogen aircraft can be cost competitive but only if adequate taxation and carbon pricing policies are in place**. By 2035, the operating costs of a 1000 nautical miles flight for a hydrogen aircraft would be 7.7% higher than for a jet aircraft using an untaxed Sustainable Aviation Fuel (SAF)/jet fuel blend, but 2.1% lower if the SAF/jet fuel blend is taxed. The same flight on a hydrogen plane in 2050 would be 3.0% more expensive than on a jet aircraft with an untaxed SAF/jet fuel blend, and 0.5% cheaper than with a taxed blend.

To ensure a successful deployment of hydrogen aviation, ECF and T&E recommend the following measures:

- Kerosene taxation in the Energy Taxation Directive (ETD)[1], and pricing of carbon emissions in the Emissions Trading System (ETS) for aviation, to make fossil kerosene more expensive and foster the uptake of cleaner solutions
- Recycling part of the carbon and kerosene tax revenues to support the development of zero emission aircraft
- Strengthening the EU's green taxonomy criteria for aviation to focus on truly disruptive solutions such as zero emission aircraft
- Progressive decarbonisation targets for routes suited for hydrogen aircraft operation, using instruments such as the Air Services Regulation or Public Service Obligations (PSOs)

1. Introduction

Hydrogen-powered aircraft are one of the key technologies that can help the aviation industry achieve its ambition of sector decarbonisation by 2050. The direct use of hydrogen on aircraft holds a lot of potential, as it can be more energy efficient than using e-kerosene, and more scalable than bio-based Sustainable Aviation Fuels (SAF).

The low energy density of liquid hydrogen relative to kerosene means that a larger volume is required for the same amount of energy. This factor limits the range of these aircraft compared to their kerosene-powered counterparts, but hydrogen planes can still provide a viable alternative to decarbonise regional and short/medium haul routes, which represent 50% of total CO_2 aviation emissions in Europe[2].

However, besides new aircraft technology, hydrogen aviation would also require the timely development of an ecosystem comprising hydrogen production and distribution, and airport infrastructure.

The aim of this study was to quantify the costs associated with development, deployment and operation of hydrogen-powered aircraft and the supporting infrastructure within the top-100 airports in Europe by 2050. The results identify the main cost components, the impact on operating costs, the cost-competitiveness of hydrogen aircraft versus kerosene-powered alternatives, and the main measures that can be put in place to ensure that hydrogen aviation successfully takes off in Europe.

2. Scope and assumptions

In order to quantify the cost of deployment and operation of the hydrogen aviation ecosystem in the top-100 European airports by 2050, the study models a rollout scenario of hydrogen aircraft, followed by an estimation of the required hydrogen production and distribution facilities and airport infrastructure. The scope, rollout scenario and assumptions of the study are explained below.

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[1] The ETD proposal by the European Commission would tax fossil kerosene at €10.75/GJ - approx. €0.37/L

[2] Analysis in T&E's 2022 Decarbonisation Roadmap, based on ICAO emissions calculation methodology and PlaneFinder AIS data. Flights below 2000 nautical miles (3700 kilometres) represent half of CO_2 emissions

2.1. Hydrogen aircraft technology

There are three main propulsion technologies currently envisaged for hydrogen aircraft:

- Hydrogen turbofan: similarly to existing turbofan engines, this propulsion system burns hydrogen in a jet engine to create thrust for the aircraft
- Hydrogen fuel cells: this system uses a fuel cell to obtain electricity, which then powers an electric propulsion system
- Hybrid propulsion: a combination of the previous two systems

A number of companies are currently developing technologies for hydrogen aircraft. Universal Hydrogen and Zero Avia are working on retrofit solutions for existing regional planes, and aim for an entry into service by 2025. Airbus, on the other hand, has announced the goal to explore three different concept designs under its ZEROe project, and to develop one of them for entry into service by 2035.

The selected aircraft design for this study is a hydrogen jet engine aircraft, with a range of 2,000 nautical miles (3,700 km), and an energy efficiency[3] assumed to be the same as existing turbofan aircraft. This representative design is similar to one of the three Airbus ZEROe concepts, and it would be able to operate 99% of intra-European routes.

2.2. Air traffic projections

The baseline scenario considers an air traffic growth rate as per the European Commission's 2020 EU Reference Scenario[4]. The study analyses as well a low traffic scenario in line with Transport and Environment's Roadmap to climate neutral aviation in Europe[5], where business and leisure air traffic in 2050 stay respectively at 50% and 100% of 2019 levels.

2.3. Rollout scenario

The study assumes an entry into service of the hydrogen aircraft in 2035, with the fleet size growing from 127 in that first year to 3,521 in 2050 for the baseline scenario. Similarly, the analysis considers 20 airports to be equipped with hydrogen supply infrastructure by 2035, followed by a progressive rollout until the top-100 European airports are hydrogen-ready by 2050.

With the previous assumptions, 65% of the flight routes below 2,000 nm between the top-100 European airports would be covered by hydrogen aircraft by 2050, representing 48% of total intra-European traffic.

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[3] The energy efficiency is measured in megajoules per revenue passenger kilometer (MJ/RPK), i.e. the amount of energy required to transport one unit of payload for one kilometer

[4] https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

[5] Transport and Environment's Roadmap to climate neutral aviation in Europe

2.4. Hydrogen production

Although several pathways to produce hydrogen are available, the only meaningful production method to decarbonise the aviation sector is green hydrogen from electrolysis powered by renewable electricity.

The study assumes that all the hydrogen is obtained from renewable sources, and produced in four sites:
- Two in Northern Europe (UK and Denmark), powered mainly by wind power
- Two in Southern Europe (Spain and Italy), using mostly solar photovoltaic power

The required hydrogen demand is derived from the previously described traffic projections. For the baseline scenario, the study finds that 6.7 Mt/year of green hydrogen would be needed to power the hydrogen aircraft flying in 2050. In the low traffic scenario, the demand for hydrogen is reduced to 4.0 Mt.

2.5. Hydrogen distribution

Once the hydrogen has been produced in the four sites described above, it can be transported to airports in a variety of ways, for example as gaseous or liquid hydrogen via pipeline, as liquid hydrogen via truck or ships, or as liquid ammonia or using liquid organic hydrogen carriers (LOHC).

However, the selected hydrogen aircraft design would use pure, liquid hydrogen, and the two more viable distribution technologies to achieve hydrogen distribution at the required scale are the following:
- The hydrogen is liquefied at the production site, and then distributed In liquid (LH2) form via trucks and ships
- The hydrogen is distributed in gaseous (CGH2) form via pipeline, with liquefaction taking place at or close to the airport after transportation

The study considers liquid distribution for small hydrogen volumes. Once the hydrogen demand reaches 36 tonnes per day (the equivalent of approximately 20 average flights), the supply switches to gaseous distribution via pipeline and liquefaction at or near the airport. The projected ramp-up of hydrogen aircraft and the associated hydrogen demand means that the share of gaseous distribution would increase from approximately 50% by 2035 to 99% by 2050.

2.6. Airport infrastructure

The use of hydrogen aircraft will require new transportation and storage infrastructure facilities, separate from the existing ones for jet fuel.

Depending on the distribution method used for hydrogen delivery to the airport, the study considers two possible solutions:
- When hydrogen is distributed to the airport in liquid form, a bowser (fuel tanker vehicle) is used to distribute the liquid hydrogen to the aircraft
- When hydrogen is distributed in gaseous form via pipeline and then liquefied at or near the airport, the study considers that liquid hydrogen is distributed to the aircraft via hydrants (pipes)

Pipeline and hydrant capacity are assumed to gradually increase in accordance with the increase in hydrogen aircraft operations at the airport.

3. Cost quantification

After the definition of the scope and assumptions set out in the previous section, the study quantified the cost projections required to meet the demand for hydrogen aviation between 2035 and 2050. These costs include capital expenditures (CAPEX) incurred as upfront investment costs, starting from 2025 onwards, while the relevant asset or infrastructure is being constructed; and operational expenditures (OPEX) to operate the asset or infrastructure, which start in 2035.

Cost projections are based on models by Steer, Doig and Smith and Hamburg University of Technology[6][7].

3.1. Total costs

The study finds that the total costs to deploy and operate the expected air traffic demand of hydrogen aviation by 2050 are **€299 billion**, to be incurred between 2025 and 2050. **In the low traffic scenario**, the lower demand for hydrogen and the reduced need for infrastructure result in total costs of **€190 billion**, i.e. a 36% decrease versus the baseline.

Figure 2 shows the relative contribution of hydrogen production, distribution and liquefaction, airport infrastructure and aircraft development to the total costs for the baseline scenario.

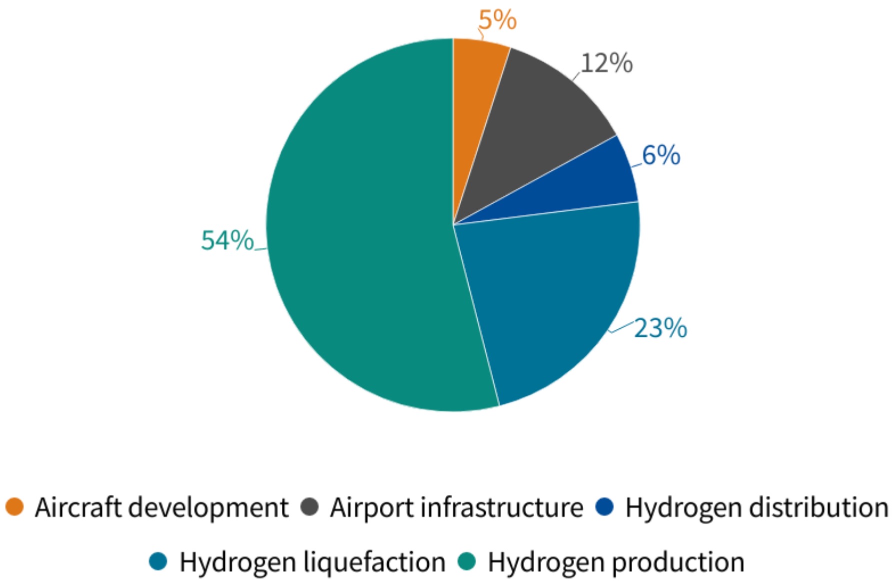

Figure 2. Share of costs

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[6] Cost minimized hydrogen from solar and wind – Production and supply in the European catchment area

[7] Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 – A techno-economic well-to-tank assessment of various supply chains

3.1.1. Hydrogen production

The total projected production costs are **€161 billion**. These include the necessary infrastructure and operating costs of the water electrolysis and renewable energy to power it, on-site storage prior to distribution, and additional production to account for boil-off losses throughout the supply chain.

3.1.2. Hydrogen distribution

Fuel distribution costs are estimated at **€18 billion**, comprising liquid transportation on trucks and ships, gaseous transportation via on and offshore pipelines, and storage within the supply chain.

3.1.3. Hydrogen liquefaction

The total costs of liquefaction are projected to be **€68 billion**. This includes the liquefaction infrastructure either at the production site (for liquid distribution) or at/near the airport (for gaseous distribution), and the renewable energy required to power the liquefaction process.

3.1.4. Airport infrastructure

The costs needed for the rollout of the required airport infrastructure amount to **€37 billion**, covering liquid hydrogen storage, the distribution of hydrogen to aircraft via fuel tankers or pipelines and hydrants, and the required renewable energy to run these systems.

3.1.5. Aircraft development

The cost of developing a short/medium haul hydrogen aircraft is modelled to be **€15 billion**. This figure is an estimate based on previous new aircraft developments, and includes the non recurring costs of aircraft design, testing and certification. The study assumes that the recurring costs of production for hydrogen-powered and kerosene-powered aircraft are the same, so they are not included in this figure.

3.1.6. Cost scenarios

All the costs detailed above are from the baseline scenario, which assumes median values of the TUHH's cost optimisation model for technological, financial and economic parameters. To complement this baseline scenario, the study performs a sensitivity analysis, by considering more progressive (optimistic) and conservative (pessimistic) scenarios.

In the progressive scenario, a faster technology development and more favourable environment reduce the overall costs to €219 billion. On the contrary, costs would rise to €423 billion in a conservative scenario, with a slower technology development and a disadvantageous context.

3.2. Unit and operating costs

In order to provide a better understanding of the results, the analysis projects the total costs previously presented to unit costs and operational costs for an average intra-European flight.

3.2.1. Fuel unit costs

The analysis considers the total costs of hydrogen production, distribution and liquefaction, and translates them to the unitary cost per kilogram of hydrogen. This cost is forecast to evolve from €3.90/kg in 2035 to €3.45/kg in 2050. The study factors in as well the aircraft energy efficiency, to assess fuel costs per revenue passenger kilometer (RPK).

To compare the economic viability of hydrogen as an energy carrier for aviation, the study analyses several cost projections for fossil kerosene, including a possible taxation scenario, and for SAF.

By 2035, the fuel cost of the hydrogen plane would be €0.034/RPK. For comparison, the projected cost of a representative fossil kerosene/SAF blend[8] would be €0.031/RPK, if the fossil part of the blend pays a carbon price of €127/tonne. This cost would go up to €0.040/RPK if, on top of the carbon price, the fossil part of the blend is taxed as per the European taxation directive (ETD) proposal.

By 2050, the hydrogen fuel costs would go down to €0.030/RPK. For a representative SAF blend[9], the costs would be €0.031/RPK assuming a carbon price of €200/tonne, and €0.035/RPK with that carbon price and a fossil kerosene tax.

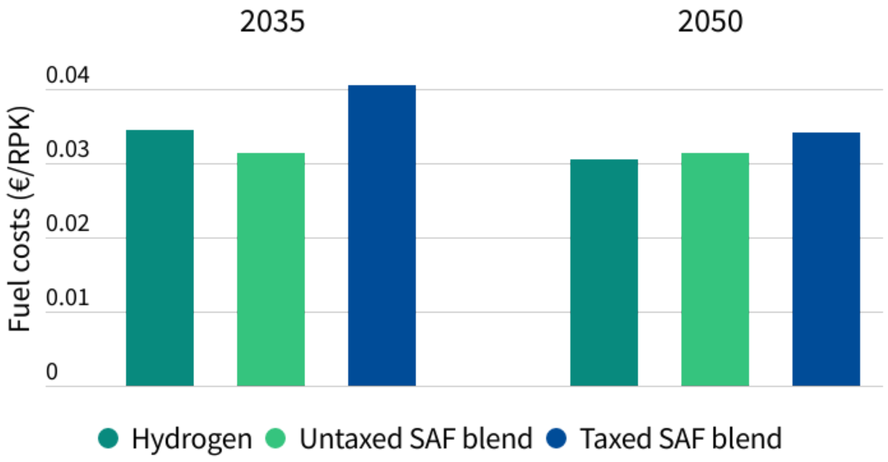

Figure 3. Fuel costs for 2035 and 2050

3.2.2. Operating costs

As early as 2035, using hydrogen as an energy carrier for aviation can be a cost competitive alternative to kerosene-powered aircraft using a SAF/fossil kerosene blend, provided that adequate taxation and carbon pricing policies are in place for fossil kerosene.

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[8] 2035 representative blend: 80% fossil/15% bio-based/5% synthetic kerosene (from ReFuelEU SAF mandate).

[9] 2050 representative blend: 30% fossil/35% bio-based/35% synthetic kerosene (from ReFuelEU SAF mandate).

Besides the price of the fuel, hydrogen aviation incurs additional costs compared to kerosene-powered aircraft. One of them is the purchase of hydrogen aircraft, which impacts the ownership cost. The other is airport infrastructure, which the study assumes to be passed on to airlines in the form of airport fees[10].

The study analyses a 1000 nautical miles flight, and compares the three components adding to the operating cost of hydrogen aircraft - hydrogen fuel, which represents the bulk of the cost, aircraft ownership and airport fees - against the operating costs of a kerosene-powered aircraft using 100% fossil kerosene with no tax or carbon price, used as baseline. The analysis concludes that the operating costs of a hydrogen aircraft would increase by 25.10% by 2035, and by 20.01% by 2050.

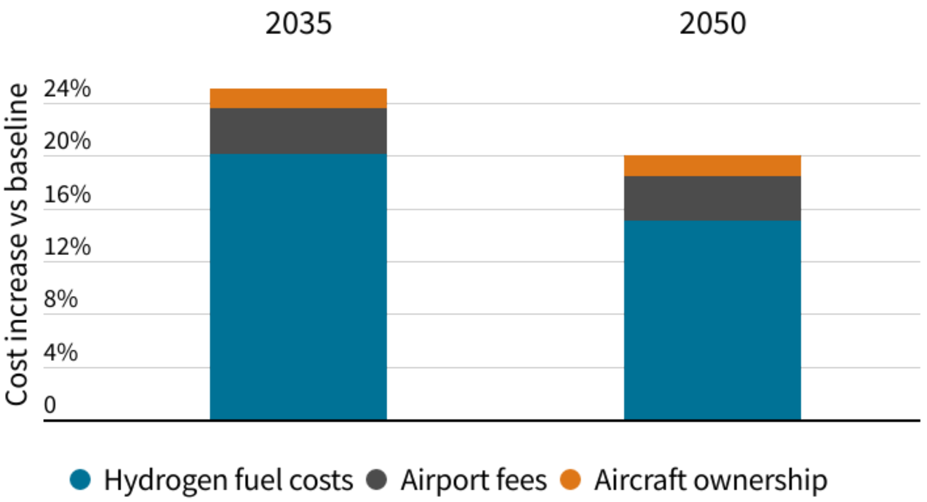

Figure 4. Extra operating costs for hydrogen aircraft vs baseline (100% fossil kerosene with no tax and no carbon price)

The analysis then compares the operating costs of a hydrogen aircraft to those of a kerosene-powered aircraft using the fuel blends presented in section 3.2.1 , also for a 1000 nautical miles flight.

In 2035, operating a hydrogen aircraft would be 7.7% more costly than a kerosene-powered aircraft using an untaxed fossil kerosene/SAF blend. However, the cost would be 2.1% lower if the blend is taxed.

For 2050, the operating cost of a hydrogen aircraft would be 3.0% higher than for a kerosene-powered aircraft using an untaxed fossil kerosene/SAF blend. If the blend is taxed, the operating costs of the hydrogen aircraft would be 0.5% higher.

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[10] The analysis assumes that 100% of airport infrastructure costs are borne by airport fees on hydrogen aircraft.

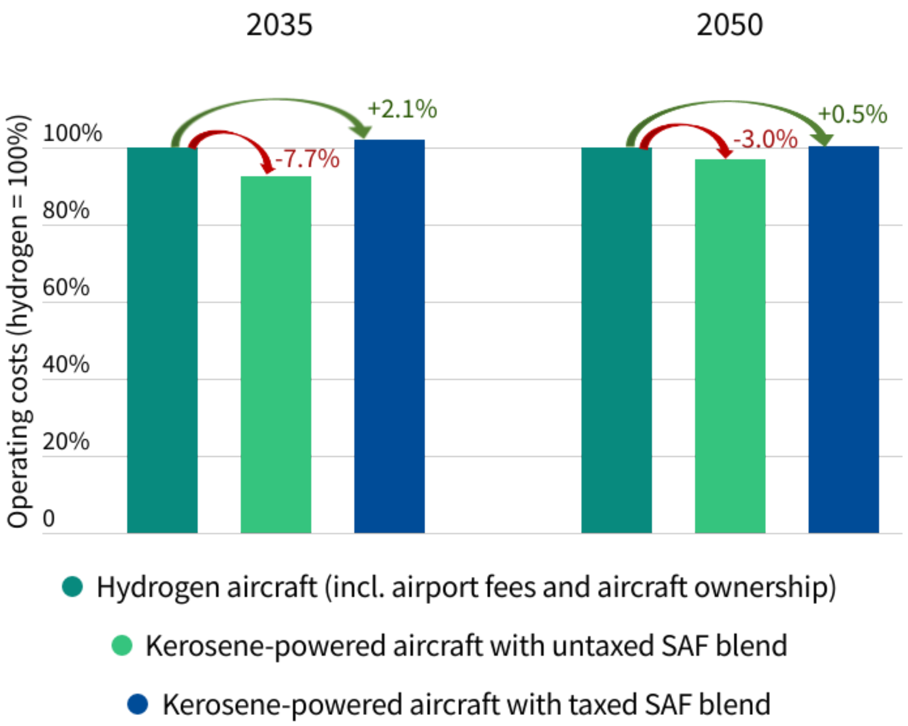

Figure 5. Comparison of total operating costs for different aircraft and fuels

These results highlight that **hydrogen aircraft can be a cost competitive technology** to decarbonise the sector as early as 2035, **only if the fossil jet fuel is adequately taxed and carbon-priced**.

4. Conclusions and policy recommendations

Hydrogen aviation can be a promising technological pathway to help decarbonise the aviation sector. This study finds that deploying hydrogen aircraft for intra-European flights would cost €299 billion, including aircraft design, hydrogen production and distribution and airport infrastructure. The study showcases as well the economic viability of flying hydrogen aircraft if the right policy and investment frameworks are in place.

4.1. Securing a timely development of hydrogen aviation

The first step would be to focus on aircraft development. The analysis estimates that designing and certifying a short/medium haul hydrogen aircraft would only require 5% of the total costs, but this must happen before 2035 to maximise the decarbonisation potential of hydrogen aviation by 2050.

Once hydrogen aircraft enter into service by 2035 and start to replace old, kerosene-powered jets, the challenge will lay in scaling up the production and distribution of green hydrogen to power the growing hydrogen aircraft fleet. This would take 83% of the costs associated with hydrogen aviation by 2050, and would require investments in the wider hydrogen economy.

Airport infrastructure, accounting for 12% of the total costs, must accompany aircraft uptake, so that it does not become a blocking point for hydrogen aviation growth.

Europe must therefore support the swift deployment of hydrogen aircraft; adopt policies to speed up their uptake; and secure the development of a green hydrogen economy to power aviation (through direct use and SAF production), other transport means such as shipping, and industry applications.

4.2. Cost competitiveness

Once the overall costs of hydrogen aviation are translated into operating costs, the analysis concludes that flying hydrogen aircraft can be cost competitive with traditional, kerosene-powered planes right from their entry into service. For this to happen, however, the fossil kerosene used by traditional planes must be adequately taxed and carbon-priced.

The adoption of a tax on fossil kerosene such as the one proposed in the Energy Taxation Directive (ETD) can play an essential role in securing a successful deployment of hydrogen aviation. This tax would help make hydrogen flights competitive compared to polluting fossil kerosene, especially important to secure a good market penetration in the early years of the technology.

Moreover, setting decarbonisation targets or mandating the use of zero emission aircraft on suitable routes can be a very effective way to foster the market uptake of hydrogen aviation. This can be achieved through instruments such as the Air Services Regulation, or including environmental performance requirements on routes operated under Public Service Obligations (PSOs).

To secure a successful deployment of hydrogen aircraft and the decarbonisation of the aviation sector, Europe must make sure that polluting fossil kerosene pays for its climate impact through fuel tax and carbon pricing, and that part of those revenues are invested into clean solutions.

4.3. Policy recommendations

To achieve a successful deployment of hydrogen aviation in Europe, T&E and ECF recommend the following measures:

- Kerosene taxation in the Energy Taxation Directive, and pricing of carbon emissions in the Emissions Trading System (ETS) for aviation, to make fossil kerosene more expensive and foster the uptake of cleaner solutions
- Recycling part of the carbon and kerosene tax revenues to support the development of zero emission aircraft
- Strengthening the EU's green taxonomy criteria for aviation to focus on truly disruptive solutions such as zero emission aircraft
- Progressive decarbonisation targets for routes suited for hydrogen aircraft operation, using instruments such as the Air Services Regulation or Public Service Obligations (PSOs)

Further information

Carlos López de la Osa
Aviation Technical Manager
Transport & Environment
carlos.lopez@transportenvironment.org
Mobile: +34 626053843