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Europe's future aviation landscape

The potential of zero-carbon and zero-emissions aircraft on intra-European routes by 2040

July 2023





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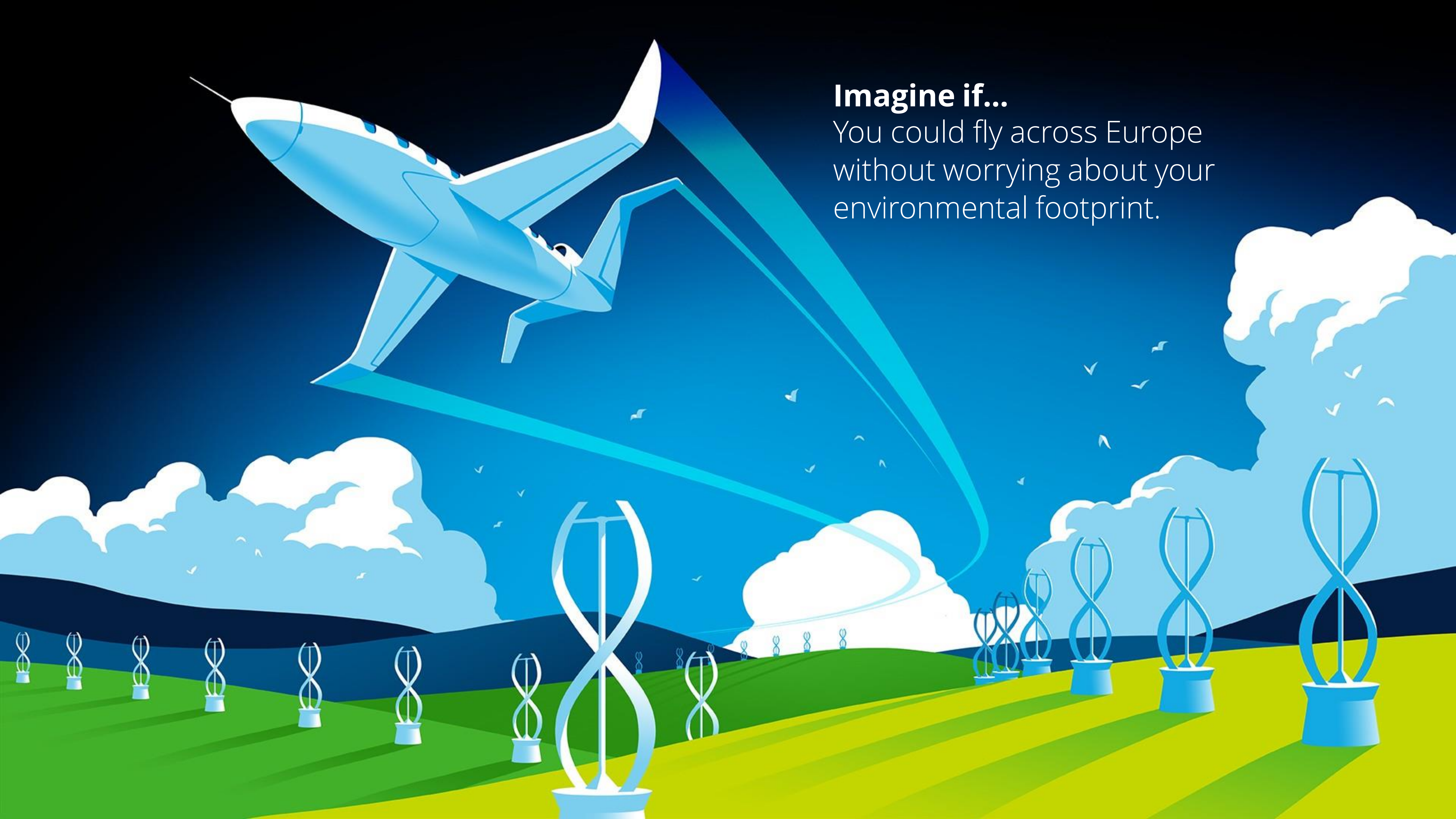
Imagine if…
You could fly across Europe without worrying about your environmental footprint.

The context for the decarbonization of the aviation sector

The need for disruption

Globally, aviation connectivity is a strong driver of economic growth, jobs, trade and mobility. At the same time, the growth in air traffic demand needs to be concomitant with maintaining high standards of aviation safety as well as reducing aviation's environmental footprint. The aviation industry is one of many industries that has a heavy impact on global human-made emissions. **While aviation accounts for 2-3% of global carbon emissions today, if no changes are made in the sector this will increase to as much as 27% by 2050.**[1] Based on planned reductions and "more efficient" fossil fuel technology, the industry is still projected to consume over 12% of the annual CO_2 budget.

Increased public pressure

The past few years have seen an increase in public pressure on the sector, especially in Europe, with a growing media attention given to the "flight shaming" movement as well as discussions within different European governments about promoting a significant shift towards more sustainable modes of transport, such as rail. Under increased scrutiny, and following pledges made by other emission-intensive sectors, the European aviation sector adopted several resolutions to significantly reduce its emissions and a proposed approach to reach carbon-neutrality by 2050.[2] To achieve these targets, the aviation industry is currently shifting from focusing solely on technological and operational improvements towards developing new systems and alternatives to kerosene to significantly reduce the emissions of the sector.

Powering aircraft sustainably

Energy efficiency improvements to current technologies, operations and infrastructure are part of the solution to decarbonize the aviation sector, but incremental improvements of existing systems won't suffice to reach the decarbonization ambitions put forth by the EU Commission in its European Green Deal within reasonable timelines. As most of aviation emissions are related to the combustion of kerosene, it is crucial to focus on how airplanes are powered and uncover new and sustainable ways to propel aircraft.

Replacing kerosene with sustainable alternatives (also called Sustainable Aviation Fuels, or SAFs) could help reduce the net-emissions of air travel, even in the short term. Indeed, technologies using biomass to produce jet fuels are already existing and several airlines started using biofuels (or a kerosene-biofuel blend) on different routes, including long-haul ones.[3] However, scaling up the production of biofuels significantly (which currently represents less than 1% of global jet fuel demand) will increase the biomass demand, which in turn will lead to a critical competition for feedstock, land use, and water with other industries, such as food and feed production.

A solution potentially scalable would be to produce synthetic SAFs through the reaction of hydrogen and CO_2. Hydrogen will need to be produced by using renewable energy to split water into hydrogen and oxygen, whereas CO_2 will need to be captured from the air or as an output of industrial processes. However, the underlying technologies are yet to become cost competitive and it will take several years before the production of sustainable synthetic fuels is available at large-scale.[4]

Most importantly, the combustion of SAFs still causes in-flight CO_2 and NOx emissions that are similar to those of kerosene-powered aircraft and consequently SAFs only partially solve the sector's environmental challenge. Scalable and truly sustainable innovation is required to reduce emissions from aviation and decrease the industry's GHGs footprint in the long-term.

Batteries and hydrogen

Promising technologies have emerged to help decarbonize the aviation sector in the long-term.

The first one leverages recent advances in the automotive industry and consists of using batteries to power electric motors and spin propellers or ducted fans to generate thrust. While today's battery energy densities can only power small aircraft for a short period of time, the current rate of improvement will make it possible for larger passenger aircraft to be powered by batteries for journeys of several hundreds and even thousands of kilometres in the future.[5] **The development of this technology is crucial, as battery-powered aircraft don't produce any in-flight emissions, therefore removing any in-flight global warming effects.** For a truly carbon neutral cycle, batteries need to be charged with renewable electricity.

Another promising solution to decarbonize aviation is to use hydrogen-based technologies. While hydrogen has been studied for decades, the growing share of renewable energy production has led to a particular interest in hydrogen[6] as it can be used as an effective energy carrier or storage medium to mitigate the intermittent effects of solar or wind energy production. Hydrogen could therefore become the link between renewable energy and energy intensive industries, such as aviation.

Hydrogen can be used in two main ways to power aircraft: either in a fuel cell to provide electricity for electric motors (the same way as batteries), or by combusting it in modified jet engines to generate thrust. Hydrogen propulsion could significantly reduce the climate impact of the aviation industry by completely eliminating carbon emissions. It is, however, important to note that hydrogen propulsion technologies still emit water vapour and NOx (in case of combustion), which both promote non-CO_2 related global warming effects (see dedicated section on the next page).

The busy short-haul mobility ecosystem

The current aviation technology roadmap suggests that such **battery- and hydrogen-powered commercial passenger aircraft (also designated as zero-emissions and zero-carbon aircraft, respectively) will enter into service by 2040, with expected performances that would allow them to compete on the short-haul market segment** (with different key sub-segment for battery-[5] and hydrogen[7] -powered aircraft). Given this, synergies with the road and rail sectors need to be considered.

From a road perspective, the recent progress in electric vehicle technologies has greatly extended the range and flexibility of EV cars and intercity buses. Whereas their potential for long-distance travel is limited, their immediate availability offers a concrete and cost-effective solution to reduce the climate impact of the transport sector. **From a rail perspective, the development of the high-speed train network is likely to impose a significant competitive pressure on air transport.** Furthermore, from an environmental point of view, current short-haul flights are typically much more carbon-intensive per kilometre than rail as a large proportion of an airplane's fuel is burnt during the take-off and climbing phases (which represent a greater part of the flight on short routes). However, the extent to which the rail network can support a significant shift of passenger volumes from air to rail travel is uncertain and important infrastructure investment would be required to increase the network capacities.

The need for (EU & public) investments

On top of the ongoing discussions around the climate impact of aviation, the Covid-19 crisis highlighted the benefits of empty skies and highways on air quality and reinvigorated the debate on whether governments should use public money to bail out polluting industries, aviation included. While certain governments incorporated requirements to cut emissions in their funding agreements with airlines,[8] or even ban flights shorter than 2 hours and 30 minutes where rail is available,[9] public bailouts also need to address airlines' unprecedented liquidity difficulties and long-term solvency challenge. Additional investments and policies supporting the development of zero-carbon and zero-emissions technologies for the aviation sector are therefore needed. However, support for these measures might compete with funds potentially allocated to the development of other sustainable transport or policies advocating for a modal shift, for example towards rail transport. While the current arguments in favour of electric vehicles and rail rely on their low climate footprint, the advent of zero-carbon and zero-emissions aircraft could significantly impact the discourse and drive government support for the aviation sector.

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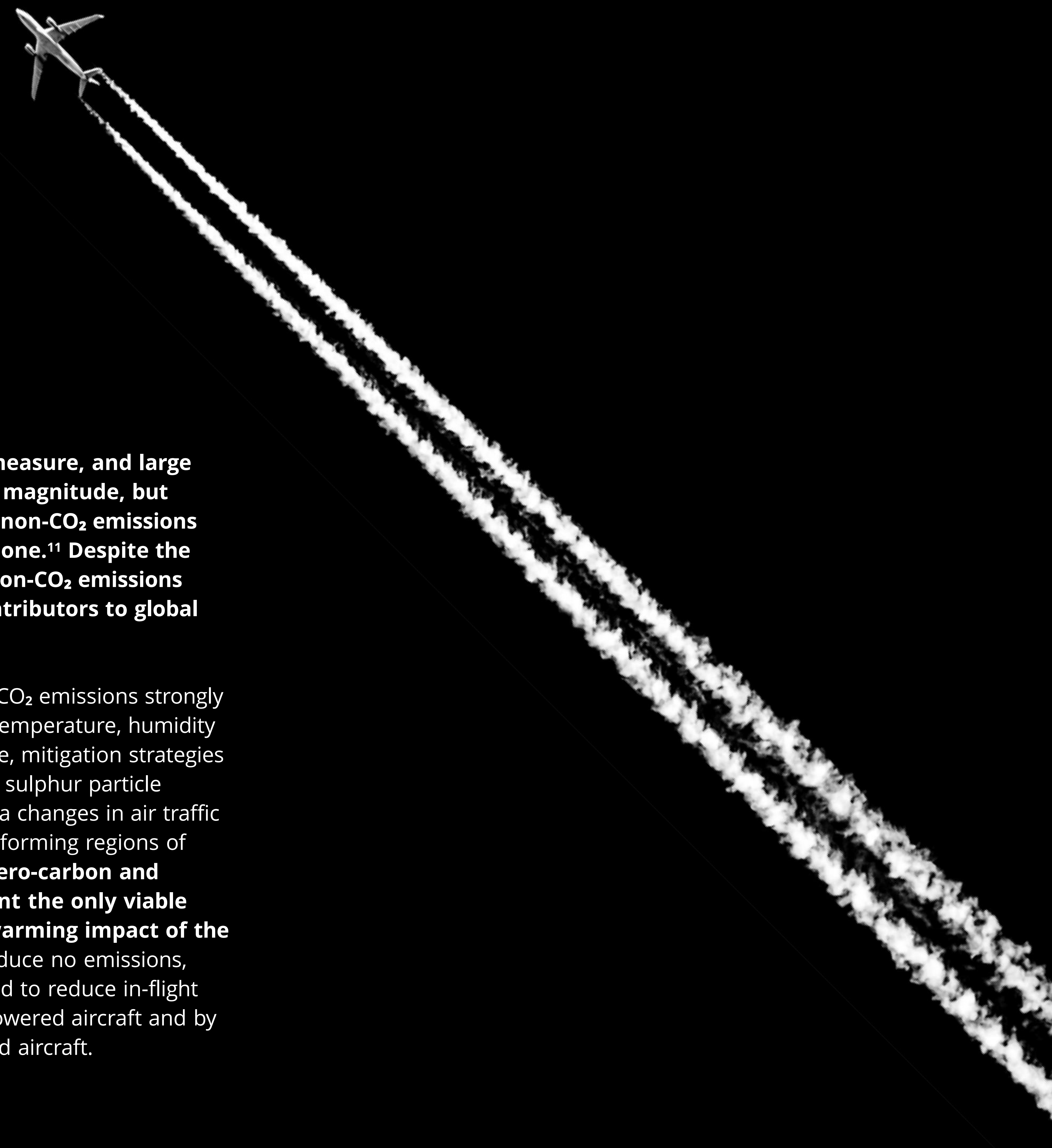
The non-CO_2 global warming effect of aviation



The climate impact of kerosene aircrafts' non-CO_2 emissions is estimated to be from 2 to over 4 times that of CO_2 alone

The global warming impact of the aviation sector due to its CO_2 emissions is well known. However, other emissions arising from the combustion of kerosene have been identified as significant contributors to global warming: nitrogen oxides (NOx), soot particles, oxidized sulphur molecules (SOx), and water vapour. These emissions result in changes in the chemical composition of the atmosphere and influence the formation of clouds, a combination which results in a net positive radiative warming force.[10]

Most of the impact of these non-CO_2 emissions occurs during the cruise phase of a flight, when an aircraft flies at high altitudes. For example, contrails, which are the lines of cloud that can be observed behind a moving airplane, are formed when water vapour from its exhaust condenses on particle emissions (such as soot or sulphur particles). These contrails then slowly spread to form cirrus-like clouds that trap and release it into the atmosphere. The emissions of nitrogen oxides also have a global warming effect: NOx emissions promote the rapid formation of ozone – a strong greenhouse gas (GHG), but also the decomposition of methane particles (CH4, another GHG), however at a lower rate compared to the creation of ozone, resulting in a net warming effect.

Most of these phenomena are difficult to measure, and large uncertainties remain regarding their exact magnitude, but recent studies estimate that the impact of non-CO_2 emissions ranges from 2 to over 4 times that of CO_2 alone.[11] Despite the uncertainties, it is therefore evident that non-CO_2 emissions and their related effects are significant contributors to global warming.

It is important to note that the impact of non-CO_2 emissions strongly depends on atmospheric conditions, such as temperature, humidity and local concentrations of particles. Therefore, mitigation strategies could be adopted,[11] mainly: reducing soot and sulphur particle emissions by using cleaner aviation fuels, or via changes in air traffic management, such as avoiding contrail cirrus-forming regions of the atmosphere. **Ultimately, the advent of zero-carbon and zero-emissions propulsion systems represent the only viable options to significantly reduce the global warming impact of the aviation sector.** Battery-powered aircraft produce no emissions, and hydrogen propulsion systems are expected to reduce in-flight climate impact[12] by 75% to 90% for fuel-cell-powered aircraft and by 50% to 75% for hydrogen combustion-powered aircraft.

Focus of this report and key questions to be answered

In this context, this report aims at providing clarity regarding several questions surrounding the future of zero-carbon and zero-emissions aircraft in Europe, in order to understand the true potential of these technologies and the place they should occupy in European mobility roadmaps, policy frameworks, and investment strategies. In order to do this, the report looks at the projected aviation technology roadmap and expected performance, as well as the distance segments that could be captured by zero-carbon and zero-emissions aircraft in the intra-European passenger travel market[i] in 2040, the date by which these new aircraft are expected to enter into service. Zero-carbon and zero-emissions aircraft are then compared to other conventional modes of transport (air and ground) to better understand the benefits and trade-offs associated with these new technologies in terms of climate impact, travel costs per passenger, and overall travel time.

Notes: i) i.e., excluding: flights from or to an airport outside the EU, freight transport and VTOL aircraft

What role should zero-carbon and zero-emissions aircraft play in European mobility strategies towards 2040?

Aviation Technology Roadmap by 2040 (for short-haul flights)

1. What is the current technology roadmap for zero-carbon and zero emissions propulsion technologies (for short-haul flights)?
2. What are the key features of zero-carbon and zero-emissions airplanes?

Intra-EU Market Potential for Passenger Air Travel in 2040

3. What market segments can be captured by zero-carbon and zero-emissions aircraft in 2040?
4. How many passengers could be transported with zero-carbon and zero-emissions aircraft in 2040?
5. What is the climate impact reduction potential of zero-carbon and zero-emissions aircraft in 2040?

Comparing Modes of Transport

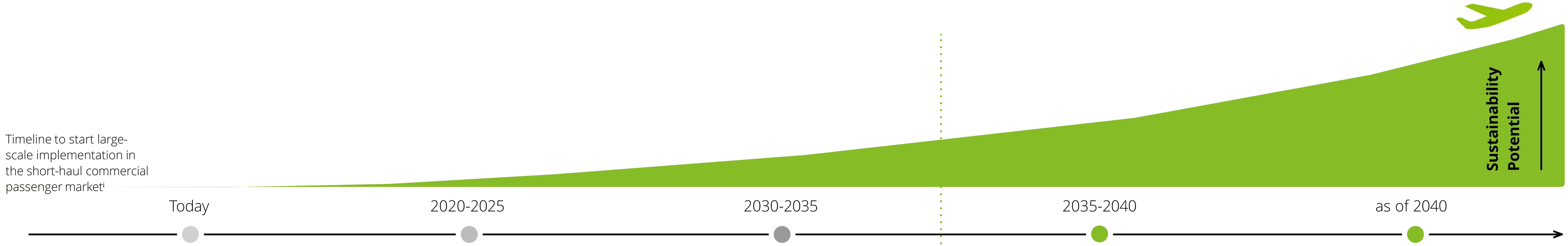
6. How do zero-carbon and zero-emissions aircraft compare to other modes of transport in terms of:
   - Climate impact?
   - Travel time?
   - Travel price?

Aviation Technology Roadmap by 2040 (for short-haul flights)

Battery and hydrogen propulsion technologies represent the most promising paths towards a zero-carbon and zero-emissions aviation industry.

The road to zero-carbon and zero-emissions commercial passenger aircraft on intra-European short-haul routes

The road to truly zero-emissions aviation will take incremental steps, from making current aircraft more efficient, to replacing kerosene with hydrogen or integrating all-electric propulsion systems into new aircraft designs, while offsetting equivalent GHG emissions and introducing hybrid systems along the way. The different technologies will coexist for a certain period of time until a complete switch towards zero-carbon and zero-emissions aviation can be achieved.



I. Efficient aviation

Reduce GHG emissions through technological and operational efficiency, such as propulsion system and aerodynamic efficiency improvements, electrification of control systems, optimized flight patterns and optimized taxi operations (or use of electric systems).

II. Net-zero aviation

Offset equivalent GHG emissions via carbon offsetting investments (e.g. renewable energy, carbon sequestration) or reduce net emissions by replacing kerosene with sustainable aviation fuels (e.g. biofuel from biomass or waste, or power-to-liquid fuels synthesized from hydrogen and CO_2).

III. Hybrid-electric aviation

Implement hybrid-electric powertrains to partially reduce GHG emissions. Done via the integration of electric motors powered by batteries or fuel cells to complement a combustion engine or via the use of a combustion engine to drive an electric generator powering an electric motor.

VI. Zero-carbon aviation[ii]

Replace kerosene with non-carbon emitting fuels (e.g. hydrogen), which can be combusted in modified turbines or reacted in fuel cells to power an electric powertrain. For a truly zero-carbon cycle, hydrogen must be produced without emitting carbon.

Hydrogen-based propulsion aircraft

V. Zero-emissions aviation[ii]

Replace all propulsion systems with fully electric propulsion systems. Combustion engines are replaced by electric motors powered by batteries to drive propellers or ducted fans. Electricity must be produced without emitting carbon.

Battery based propulsion aircraft

Out of scope

Focus of this publication[iii]

Notes:
i) The timeline indicates dates at which the first pilot projects or new propulsion systems are expected to be implemented by commercial passenger airlines.
ii) Zero-emissions (battery-powered) aircraft are expected to have the energy capacity to serve the short-haul market, whereas zero-carbon (hydrogen-powered) aircraft have the potential to serve long-haul routes. These technologies are therefore expected to coexist for the foreseeable future.
iii) The developments in net-zero and hybrid-electric technologies are not covered in this publication as they primarily represent transitional solutions towards true zero-carbon and zero-emissions technologies.

Key features of zero-carbon and zero-emissions aircraft by 2040

Battery and hydrogen propulsion technologies represent the most promising paths towards a zero-carbon and zero-emissions aviation industry. While there is no all-round answer to decarbonize aircrafts' operations, batteries and hydrogen can offer sustainable solutions across the different distance segments of the market. Therefore, this combination of technologies has the potential to greatly decrease the overall climate impact of the aviation sector.

	Zero-carbon aviation		Zero-emissions aviation
	Hydrogen-powered combustion aircraft **Up to 2000 km** Distance range	**Hydrogen fuel cell electric aircraft** **Up to 1000 km** Distance range	**Battery-powered electric aircraft** **Up to 500 km** Distance range
Technology overview	Hydrogen, and oxygen captured from the air, are combusted in modified engines to generate thrust	hydrogen is reacted in a fuel cell to provide electricity to electric motors than spin propellers or ducted fans to generate thrust	Electric batteries are used to power electric motors that spin propellers or ducted fans to generate thrust
Performance indicators[i, ii]	**– 50-75%** Climate impact reduction potential **+ 5-15%** Flight time **+ 10-35%** Ticket price	**– 75-90%** Climate impact reduction potential **+ 20-30%** Flight time **+ 0-15%** Ticket price	**– 100%** Climate impact reduction potential **+ 20-30%** Flight time **+ 0-20%** Ticket price
Benefits	✓ No carbon emissions (water and NOx are still produced) ✓ Scalable technology derived from conventional aircraft designs and engines ✓ Economies of scale benefits from synergies with other hydrogen dependent industries	✓ Near-Zero emissions (water is still produced) ✓ Quieter engines ✓ Economy of scale benefits from synergies with other hydrogen dependent industries	✓ Zero emissions ✓ Quieter engines ✓ Reduced maintenance costs (fewer moving parts) ✓ Economy of scale benefits from synergies with other battery dependent industries
Constraints	→ The low energy density of battery and hydrogen propulsion systems will decrease the flight range and optimal cruise speed compared to conventional kerosene systems	→ By 2040, higher energy costs (hydrogen), capital costs (energy storage, propulsion system) and maintenance costs (landing gear, battery replacement) of hydrogen and battery aircraft compared to conventional kerosene aircraft will lead to increased ticket prices. However, these costs are expected to decrease with the large-scale implementation of hydrogen and battery technologies.	
Required development	1. Significant increase in sustainable hydrogen production capacities 2. Development of large-scale hydrogen supply chains (transport) and required airport infrastructures (storage) 3. Important Innovations required to adapt aircraft for the use of liquid hydrogen as a fuel (adapted aircraft designs and engines, power-dense fuel cells, light hydrogen storage systems)		1. Further improvement of battery technologies, especially in terms of energy density 2. Significant increase in renewable electricity production 3. Innovations required to adapt aircraft to large battery systems (design, electrical systems, electric motors)

Notes: i) Comparisons are made for similar routes and aircraft within the mentioned distance segments
ii) Ticket prices do not consider potential increase in carbon tax until 2040

Sources:
– Schäfer et al. (2018), Technological, economic and environmental prospects of all-electric aircraft. Nature Energy
– European Commission. Fuel Cells and Hydrogen Joint Undertaking (2020), Hydrogen-powered aviation - A fact-based study of hydrogen technology, economics, and climate impact by 2050

Intra-EU Market Potential for Passenger Air Travel in 2040

Zero-carbon and zero-emissions airliners are expected to mainly serve short routes due to limited flight ranges. The intra-European market therefore represents a great opportunity for these technologies.

The key market segments for zero-carbon and zero-emissions aircraft in 2040

By 2040, the energy and power density of battery- and hydrogen-based propulsion technologies will still be lower than existing kerosene-based systems, resulting in zero-carbon and zero-emissions aircraft being limited in terms of passenger capacity and flight range.

However, configured to best maximize the passenger-range ratio, battery- and hydrogen-based airplanes can be operated on key market segments where both passenger demand and climate impact reduction potentials are the highest.

Based on expected technology advancements and the development roadmap announced by aircraft manufacturers, it is possible to determine what aircraft designs could be available by 2040 (i.e., entry into service around 2040), as well as their performance and seating capacity.

Following the assumption that the use of aircraft with the highest climate impact reduction potential needs to be maximized, battery-powered airplanes should serve routes up to 500 km, followed by hydrogen fuel-cell-powered planes from 500 km to 1000 km, and hydrogen combustion airplanes covering distances between 1000 km and 2000 km (based on performance and limitations expected by 2040, these ranges are expected to be extended with further technology developments).

Battery-powered electric aircraft

- **Up to 500 km** Distance range
- **– 100%** Climate impact reduction potential
- **9 - 19** Seat capacity*

Hydrogen fuel cell electric aircraft

- **Up to 1000 km** Distance range
- **– 75-90%** Climate impact reduction potential
- **60 - 100** Seat capacity

Hydrogen-powered combustion aircraft

- **Up to 2000 km** Distance range
- **– 50-75%** Climate impact reduction potential
- **100 - 180** Seat capacity

* Higher seat capacity for battery-powered electric flights could be achieved in case of breakthrough in battery technology in the future.

Source: Wright Electric, Airbus, CleanSky2 & FCH2, Deloitte Analysis

The intra-EU passenger air travel market in 2040

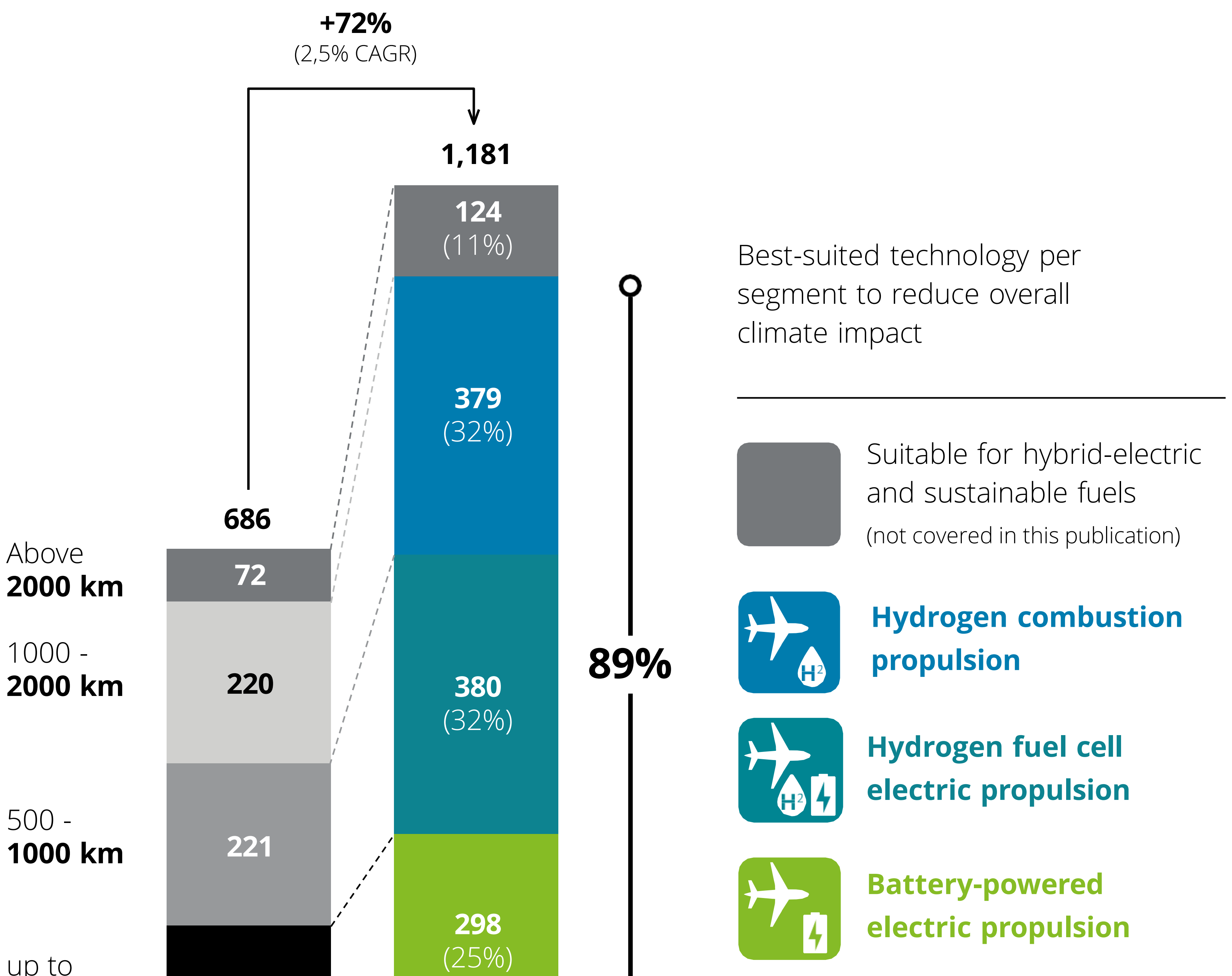
Almost 90% of intra-European passenger air transport would fall into the operating segments of zero-carbon and zero-emissions aircraft in 2040.

As explained previously, zero-carbon and zero-emissions aircraft are expected to mainly serve short routes due to limited flight ranges. The intra-European market (i.e. flights from and to an EU airport) therefore represents a great opportunity for these technologies. Boosted by seamless airport operations and low-cost offerings, the European population has increasingly chosen air transport to travel within Europe and the demand for flights between EU airports will continue to increase.

As presented earlier, different distance segments could be served by battery- and hydrogen-powered aircraft. Taking the total number of intra-EU passengers forecasted for 2040, flights up to 500 km would absorb 25% of passengers, while routes of up to 1000 km and 2000 km would cover 47% and 89% of demand, respectively (see figure on the right). **These numbers show that, despite allowing shorter flight ranges than kerosene-powered aircraft, zero-carbon and zero-emissions airliners have the potential to absorb a significant part of the intra-European passenger market.**

It is important to note that with the first deliveries of hydrogen- and battery-powered passenger aircraft expected between 2035 and 2040, the complete renewal of the fleet might take decades (the current average lifetime of an aircraft is 25 years). As shown in the past, and again with the Covid-19 crisis, the renewal rate can be accelerated by different factors[12] – mostly economic, such as: increasing fuel prices, variation in air traffic demand, higher maintenance costs, and the availability of more fuel-efficient aircraft. **Furthermore, the implementation of stricter environmental regulations and financial incentives by governments to influence these factors can play a fundamental role in accelerating the replacement of kerosene airplanes with zero-carbon and zero-emissions alternatives.**

Number of passengers (in millions) on intra-EU flights, per flight distance segments



Sources:
- Passengers in 2018: Eurostat. News release. 6 December 2019. Air passenger transport in the EU
- Forecasted CAGR: Eurocontrol. (2018). European Aviation in 2040 - Challenges of growth (Annex 1 - Flight Forecast to 2040) – "Regulation & Growth" Scenario
- Flight distance distribution: Electric Leap. (2020). Zero-emissions Commercial Air Transport – Let's get started

The climate impact reduction potential of zero-carbon and zero-emissions aircraft in 2040

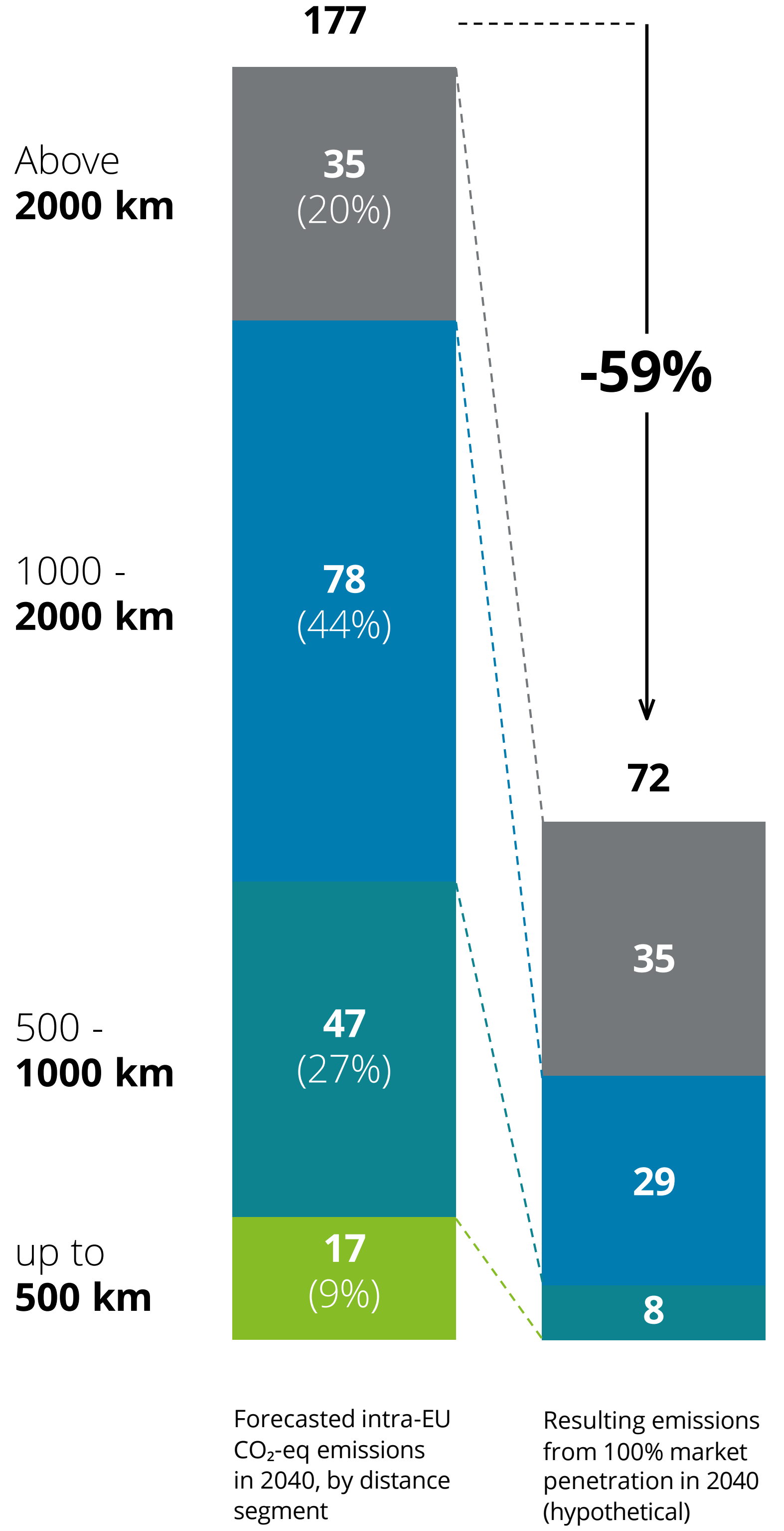
In 2040, replacing all kerosene aircraft with zero-carbon and zero-emissions alternatives could decrease the intra-EU climate impact by up to 59%

Looking at the intra-EU passenger air travel market in 2040, up to 80% of the forecasted CO_2-equivalent emissions fall into the operating segments of future hydrogen- and battery-powered airplanes (see figure on the right, first column). **Replacing all aircraft in those segments with zero-carbon and zero-emissions variants would represent a substantial decrease of 59% in emissions.** With conventional aircraft development cycles of 15-20 years, **it is crucial to invest significant effort into developing propulsion technologies and to optimize the time to market of zero-carbon and zero-emissions aircraft in order to ensure their entry into service by 2040.** To do so, several technological advancements are required: a significant increase in the energy and power density of battery and fuel cell systems, a major weight reduction of liquid hydrogen storage tanks, the development of powerful light-weight electric motors and hydrogen compatible engines, the redesign of aircrafts' fuselage to fit these new technologies, the development of safe and reliable high-voltage electricity and liquid hydrogen distribution systems, and the integration of ground infrastructure for battery charging or swapping, as well as hydrogen supply and refuelling systems.

To achieve these technological breakthroughs, a sector-wide roadmap aligning the private and public sectors needs to be agreed upon to foster research and innovation activity and funding, as well as the implementation of an adequate policy framework and optimized certification processes for these new technologies.

This roadmap should also promote intermediary technologies, such as hybrid-electric and sustainable aviation fuels (SAFs), both representing important transitional solutions to reduce emissions until zero-carbon and zero-emissions technologies take over the entire sector. The development of smaller battery- and hydrogen-powered aircraft will also play an important role in demonstrating the feasibility of such systems, as well as gauging the certification processes. The aviation industry also needs to support the increase of renewable energy production needed to charge batteries and produce green hydrogen, which is essential to truly guarantee the overall climate impact reduction potential of these technologies.

Climate Impact (in $MtCO_2$-eq) of Intra-EU passenger flights in 2040



Most suitable technology per segment to reduce overall climate impact

Emissions from flights above 2000 km could be further reduced with hybrid technologies (hydrogen or electric) and sustainable aviation fuels

Hydrogen combustion propulsion
– 49 $MtCO_2$-eq
(avg. –62.5% emissions)

Hydrogen fuel cell electric propulsion
– 39 $MtCO_2$-eq
(avg. –82.5% emissions)

Battery-powered electric propulsion
– 17 $MtCO_2$-eq
(–100% emissions)

Notes:
- The data illustrates the direct in-flight climate impact, taking into account CO_2 and non-CO_2 related climate impact (other GHGs, water vapour, high altitude contrails) translated to CO_2 equivalent (source: EcoPassenger Methodology)
- A 2% per year efficiency improvement of conventional aircraft is considered in order to derive 2040 baseline values (source: ICAO)

Electric propulsion to unlock the regional short-haul market

In addition to the existing air travel market, battery- and fuel-cell-powered aircraft have the potential to further develop regional short-haul air transport.

With current aircraft, airlines struggle to operate short routes economically due to higher fuel burn rates and increasingly tight profit margins.[i] Therefore, short-haul flights are usually operated as connections with large hubs to further serve the more profitable medium- and long-haul markets.[13] Furthermore, in contrast with busy short routes between hubs (such as Amsterdam-London), regional routes to tier-2 and tier-3 airports come with several challenges: lower and seasonal demand, shorter runway length, and limited airport infrastructure.

However, thanks to shorter and quieter take-off and landings, as well as reduced operating and maintenance costs (expected in the long-term), electric aircraft can overcome the current challenges of regional routes and serve smaller airports economically.[14, 15] Additionally, they can contribute to fast, safe, and effective mobility in less populated areas, where the investment in alternative transport solutions is not justified from a traffic density, cost, or environmental and landscape impact point of view.

Reduced noise
Thanks to the absence of a combustion core, slower propeller rotation speed, and significantly fewer moving parts

Shorter take-off distance
Thanks to increased static thrust leading to improved acceleration

Lower operating costs
Thanks to reduced energy costs and to the simplicity and longevity of electricity-powered motors and drivetrains

Lower maintenance costs
Thanks to decreased system complexity and a significantly smaller number of moving parts

Benefits expected in the longer term thanks to future innovation and economies of scale

Note: From a technology and operations perspective, hydrogen combustion-powered airplanes don't differ significantly from kerosene-powered ones, and therefore, the benefits of electric propulsion systems mentioned here do not apply.

Notes: i) Low-cost carriers rely on ancillary services (e.g. extra luggage, in-flight sales and internet services, insurance) to make profit on short-haul flights

Comparing Modes of Transport

Zero-carbon and zero-emissions aircraft will disrupt journeys throughout Europe

Comparing conventional kerosene aircraft with zero-carbon and zero-emissions alternatives

Significant environmental benefits, but slightly increased travel time and costs.

When looking at the different key distance segments, the environmental benefits of zero-carbon and zero-emissions airplanes compared to conventional kerosene airplanes are evident, even considering the potential use of non-renewable energy to produce electricity and hydrogen. Battery-powered flights could lead to the complete elimination of emissions below 500 km, while hydrogen-powered aircraft could reduce the emissions of flights up to 1000 km by 89% and flights up to 2000 km by 68% when using green hydrogen (i.e. produce with renewable energy), a substantial improvement compared to current kerosene aircraft.

Remarkably, the increase in price and total travel time (i.e. considering the inbound and outbound travel between the airport and the city centre, as well as the advised arrival time prior to flight departure) is limited to a maximum of a 23% increase in ticket price for hydrogen combustion flights, while keeping the travel time extension below 11% in all cases. This increase in price and travel time represents a reasonable contribution from customers compared to the significant environmental benefits of zero-carbon and zero-emissions travel on the entire intra-European air travel sector.

See analysis on next page

Air Route Distance

Climate Impact
(in gCO_2-eq/km/PAX)

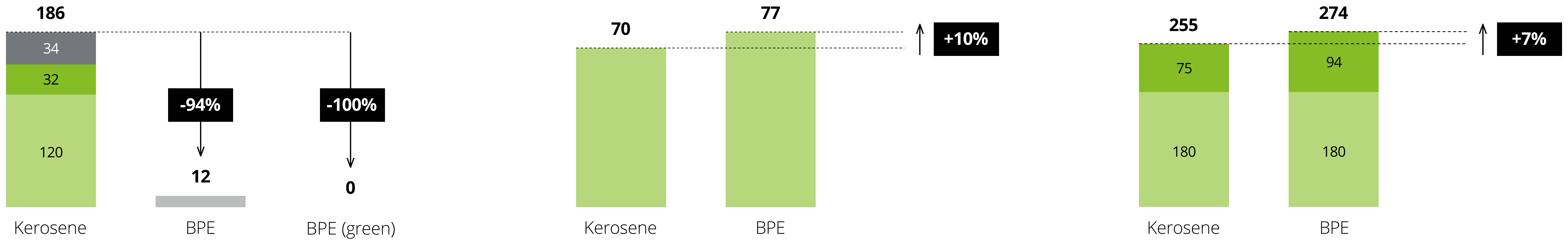
Travel Cost
(in Euros/PAX)

Travel Time
(in minutes)

500km

Annual passenger volume in 2040 for this segment: **298 million**
Example of equivalent route: **Bergen-Oslo**

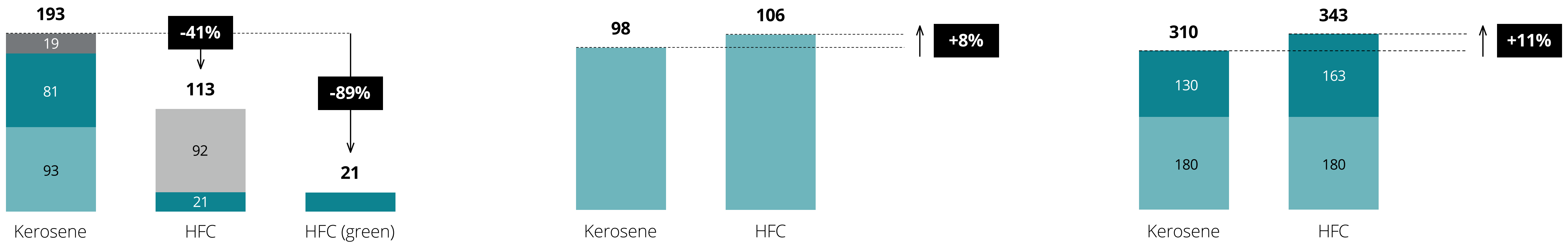
Battery-powered electric (BPE) propulsion



1000km

Annual passenger volume in 2040 for this segment: **380 million**
Example of equivalent route: **Barcelona–Frankfurt**

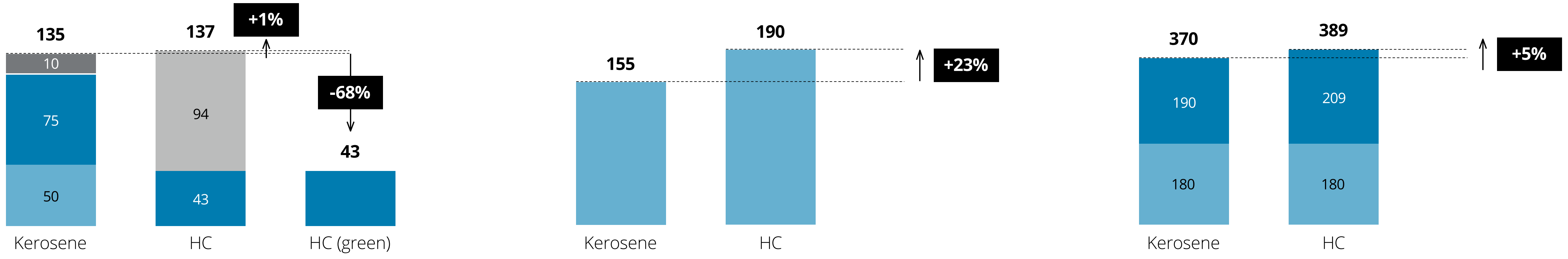
Hydrogen fuel cell (HFC) electric propulsion



2000km

Annual passenger volume in 2040 for this segment: **379 million**
Example of equivalent route: **Paris–Athens**

Hydrogen combustion (HC) propulsion



CO_2 emissions from kerosene consumption during the flight
Non-CO_2 global warming impact (water, contrails, NOx, SOx)
Emissions generated during the production of the required amount of kerosene
Emissions generated if using non-renewable energy to charge the batteries or produce the required amount of hydrogen

Ticket price

Flight time
Pre- and post-travel time: time between final destination and airport or train station, advised arrival time at airport or train station, mandatory breaks during road travel

Note: The travel cost and time are based on the data retrieved from the online travel calculator Rome2Rio.com

Comparing different modes of transport for 500 km journeys

The relevance of battery-powered aircraft on short routes depends on the existing rail network.

Routes of 500 km represent a critical distance segment in which all modes of transport can be considered as viable alternatives. In terms of emissions, electric forms of transport, including battery-powered aircraft, clearly offer the lowest emitting alternatives, whereas kerosene airplanes are by far the most polluting mode of transport.

In terms of cost, the competitiveness of cars depends on the number of passengers splitting the costs. While the travel prices for battery-powered aircraft are the highest of all modes, they remain within the range of those of kerosene airplanes and rail (and two-passenger cars), but above bus prices.

For distances of around 500 km, the differences in travel time between the modes of transport is not considerable. However, air travel remains one of the fastest options and the potential development of regional air routes enabled by electric propulsion might further reduce the pre- and post-travel time necessary for air travel. **The travel time of rail strongly depends on the network in place on selected routes. Journeys between cities connected by an efficient high-speed rail network might be faster by rail than by air, whereas less developed rail services could lead to longer travel times than air alternatives, and sometimes even longer than road travel.**

Notably, on short routes electric vehicles represent one of the best alternatives in terms of emissions and travel costs, and the advent of autonomous driving could mitigate the burden of long driving times and boost the adoption of EVs by travellers.

See analysis on next page

500km Air Route (e.g. Bergen-Oslo)

Mode		Climate Impact (in gCO_2-eq/km/PAX)	Travel Cost (in Euros/PAX)	Travel Time (In minutes)
Battery-Powered Electric Propulsion Airplane		12	77	180 + 63 = **243** (~4h00)
Electric Rail		7	63	Actual time on selected route: 60 + 411 = **471** (~7h45); EU average intercity rail: 60 + 291 = **351** (~5h45)
Electric Car	1 passenger	16	22 + 38 + 48 = **108**	45 + 422 = **467** (~7h45)
	2 passengers	8	11 + 19 + 24 = **54**	
Diesel Tour Bus		59 + 12 = **71**	44	45 + 577 = **622** (~10h30)
Petrol Car	1 passenger	116 + 22 = **138**	32 + 38 + 64 = **134**	45 + 422 = **467** (~7h45)
	2 passengers	58 + 11 = **69**	16 + 19 + 32 = **67**	
Kerosene Airplane		120 + 32 + 34 = **186**	70	180 + 50 = **230** (~3h45)

Notes:
- Travel cost and travel time are derived from EU averaged data (see appendix)
- Travel costs are calculated per passenger, distributing the total costs over the number of passengers (for average occupancy, see appendix)

Climate Impact legend:
- CO_2 emissions from kerosene consumption during the flight
- Non-CO_2 global warming impact (water, contrails, NOx, SOx)
- Emissions generated during the production of the required amount of kerosene
- Emissions generated if using non-renewable energy to charge the batteries or produce the required amount of hydrogen (via electrolysis in this analysis)

Travel Cost legend:
- Fuel or ticket costs
- Road tolls
- Ownership costs (depreciation, maintenance, insurance, tax)

Travel Time legend:
- Flight or drive time
- Pre- and post-travel time: time between final destination and airport or train station, advised arrival time at airport or train station, mandatory breaks during road travel

Comparing different modes of transport for 1000 km journeys

The speed advantage of air travel becomes evident.

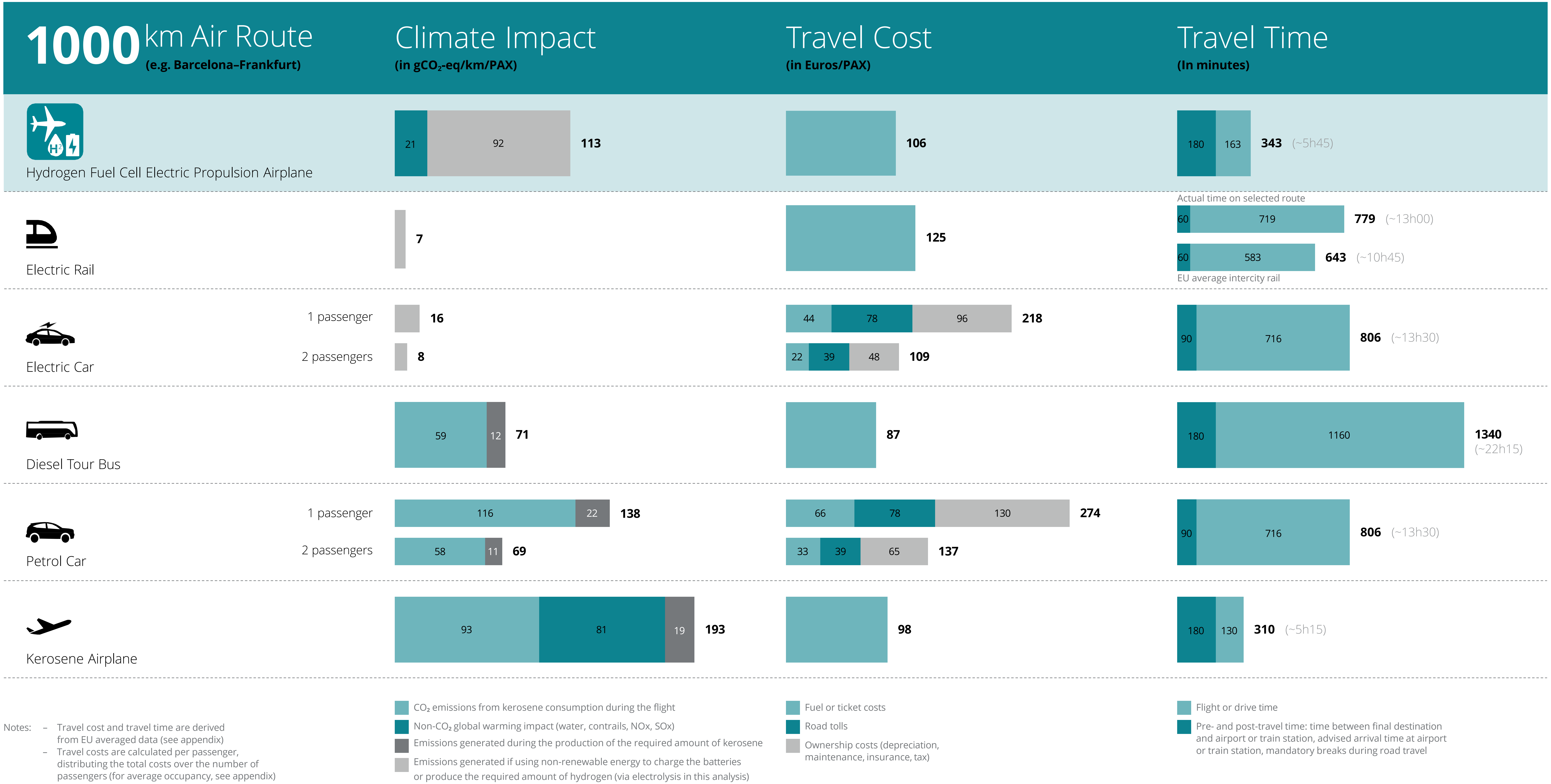
In terms of emissions, the climate impact per kilometer of kerosene airplanes approaches a peak at distances of around 1000 km, with the ratio of CO_2 and non-CO_2 related emissions reaching a maximum. Compared to battery powered airplanes, the climate impact of hydrogen fuel-cell-powered airplanes is slightly more important due to the production of water when reacting hydrogen in fuel cells, leading to an increase in high altitude contrails. Furthermore, the production of hydrogen requires large amounts of energy, which could lead to significant emissions if non-renewable energy is used in the process.

As distances grow, air travel benefits from improved aerodynamics at high altitudes, which lowers the average kerosene consumption over the flight.

Therefore, compared to road and rail transport costs which grow proportionally with the distance travelled, the increase in air travel cost is not as significant, and for a 1000 km travel distance, petrol cars and rail become the most expensive alternatives (for distance of 1000 km and more, it can be assumed that two passengers will usually be present in the cars).

Longer travel routes exacerbate the different in travel time between ground and air transport, and air travel clearly becomes the fastest option for journeys above 1000 km. **Trains and tour buses increasingly suffer from fixed segmented networks which require several stopovers to reach the final destination.**

See analysis on next page



Notes:
- Travel cost and travel time are derived from EU averaged data (see appendix)
- Travel costs are calculated per passenger, distributing the total costs over the number of passengers (for average occupancy, see appendix)

Comparing different modes of transport for 2000 km journeys

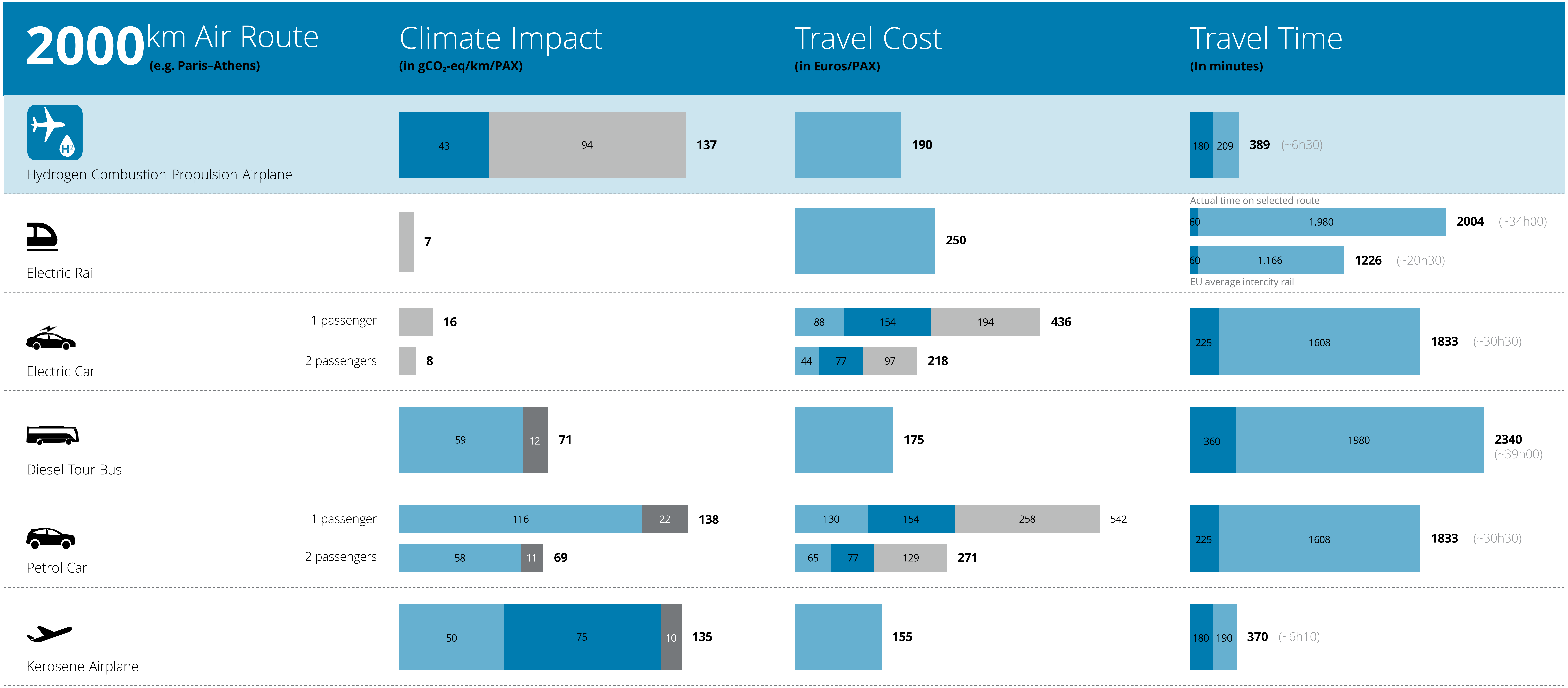
The relevance of ground travel solutions over longer distances is debatable

For distances of 2000 km and above, the use of hydrogen combustion engines increases the need to ensure the production of green hydrogen from renewable energy. As the combustion of hydrogen releases water vapour and nitrogen oxides at high altitude, the non-CO_2 effects of airplanes powered by hydrogen combustion engines become more apparent, nearing the emission level of petrol powered road transport. Furthermore, if hydrogen is produced with non-renewable energy, the combined emissions of a hydrogen combustion-powered airplane could even exceed the ones of conventional kerosene aircraft.

Following the trend observed for routes of 1000 km, the travel costs of ground transport continue to increase for routes of 2000 km, following a steeper curve than air travel. Hydrogen combustion air travel represents one of the cheapest options, even with the expected increase in ticket price for first generation hydrogen combustion aircraft compared to conventional kerosene airplanes.

Reaching a distance of 2000 km, the relevance of ground transport becomes uncertain, with travel times usually well above 24 hours, depending on the available rail network. The fragmentation of the rail and bus network on long distances greatly impacts the overall travel time and car travel becomes faster than train travel on some routes.

See analysis on next page



- CO_2 emissions from kerosene consumption during the flight
- Non-CO_2 global warming impact (water, contrails, NOx, SOx)
- Emissions generated during the production of the required amount of kerosene
- Emissions generated if using non-renewable energy to charge the batteries or produce the required amount of hydrogen (via electrolysis in this analysis)

- Fuel or ticket costs
- Road tolls
- Ownership costs (depreciation, maintenance, insurance, tax)

- Flight or drive time
- Pre- and post-travel time: time between final destination and airport or train station, advised arrival time at airport or train station, mandatory breaks during road travel

Notes:
- Travel cost and travel time are derived from EU averaged data (see appendix)
- Travel costs are calculated per passenger, distributing the total costs over the number of passengers (for average occupancy, see appendix)

Key Takeaways and Drivers for Success

Action is needed now

Zero-carbon and zero-emissions aircraft emerge as the best solutions to seamlessly transport a large number of passengers throughout Europe with a low climate impact

As this report shows, zero-carbon and zero-emissions aircraft have the potential to cover a significant part of the Intra-EU passenger market by 2040, dates at which these technologies will enter into service. Avoiding the large emissions inherent to today's kerosene aircraft while taking advantage of fast air travel at reasonable costs would drive zero-carbon and zero-emissions aircraft away from current public concerns and provide a strong argument in favour of the development of air travel for the future. **Even with decreased flight range compared to conventional kerosene aircraft, these future aircraft have the potential to cover up to 89% of the intra-EU market in 2040, representing a potential climate impact reduction of up to 59%.**

When looking at different distance segments, the attractiveness of air travel on very short routes mainly depends on the rail network available on different routes. In case two cities are connected by an efficient high-speed rail network, travelling by rail can be faster than air. When less developed rail services are available, rail travel will be slower than air alternatives, and sometimes even road travel. Furthermore, the advent of all-electric VTOL and small aircraft[16] in the coming years will also play a role in shifting parts of the ground commuting travel towards the air. On longer routes, the benefits of hydrogen propulsion aircraft are unequivocal, offering low emissions, prices in the range of other modes of transports, and travel times far below the ones of ground travel.

The broad aviation ecosystem needs to start cooperating today to ensure zero-carbon and zero-emissions aircraft will enter into service in time to meet the industry's decarbonization targets

Time is now of the essence to ensure these technologies are ready to enter the large-scale commercial passenger market within short timelines. **With development times between 15 to 20 years and a broad deployment of large fleets usually taking up to 10 years, the aviation sector needs to invest significant resources today to develop the required innovations and technologies allowing the sector to reach the decarbonization objectives for 2050 set by the EU and ATAG.**

Policy makers, industries, and stakeholders from the broader aviation ecosystem need to cooperate to build the long-term regulatory and certification framework supporting the successful development of zero-carbon and zero-emissions technologies. The remaining uncertainties around the extent of non-CO_2 climate impact phenomena need to be clarified to allow clear target setting and development roadmaps that leverage the most efficient solutions. Laying out a long-term vision will strengthen the sector's ability to plan the development of necessary technologies, as well as provide clarity as to where investments are most needed. Clearer perspectives will in turn attract funds more easily into innovation and pioneering R&D activities. On top of this, these new technologies will drive the need to develop supporting infrastructures, such as efficient battery charging/swapping systems at airports and large-scale hydrogen supply chains. Public support will therefore be fundamental in promoting both zero-carbon, zero-emissions technologies and infrastructure with targeted subsidies and economic measures to accelerate the competitiveness of these new sustainable aircraft.

Furthermore, the large-scale deployment of battery and hydrogen-powered aircraft will substantially increase the need for renewable energy production. Relying on non-renewable energy would greatly hinder the overall climate reduction potential of these aircraft and public entities must ensure that the future aviation sector can be supplied with sustainable energy, along with other sustainable modes of transports.

By removing the negative climate impact of air travel on short routes, zero-carbon and zero-emissions aircraft will significantly disrupt future mobility strategies and position aviation at the heart of the sustainable mobility ecosystem

Repositioning aviation on very short-haul travels

Due to the synergies between battery-powered aircraft and other modes of transport on short routes of up to 500 km, targeted actions are required from policy makers to support the aviation industry in fully unlocking the immense potential of zero-emissions propulsion technologies

Whereas the benefits of hydrogen-powered aircraft over other modes of transport for routes of above 500 km is undeniable, distances below 500 km represent the most competitive segment for which both ground and air transport hold compelling benefits and where the existing infrastructure between two travels points has a significant impact on the advantage of a mode over another (i.e., efficient rail and road network, proximity to airports). The present report highlighted the significant benefits brought by electricity and battery-powered modes of transport (rail, EVs, battery-powered aircraft) on short distances in terms of low emissions and climate impact, while offering attractive travel costs and times. These three modes all represent promising solutions for the decarbonization of short-range mobility, but imply certain obstacles to their sole domination:

- Electric autonomous cars could become the most convenient mobility option on short distances, but road capacity challenges would be even more exacerbated than they are today with limited network expansion possibilities.
- A significant portion of travellers could shift to rail, but the same capacity constraints as for road would arise and the potential infrastructure investments could be significant to increase capacities only on targeted routes.
- Battery-powered airplane could represent a true game changer by offering a sustainable and fast travel option at attractive costs (which would further decrease in the future with new innovations and economies of scale). Furthermore, the limited infrastructure requirement needed to support battery swapping and charging systems would boost the development of the promising network of existing regional airports and unlock a seamless air travel over large geographies. Of course, the development of hydrogen aircraft for short routes also needs to be supported in parallel, as they would participate in the overall decarbonization of the 500 km segment by increasing the rate of kerosene aircraft replacement.

Therefore, policy makers need to strongly support the development of battery (and hydrogen) powered airplanes for the commercial passenger market on short routes and bolster the implementation of the required battery charging/swapping and hydrogen refueling infrastructure on large and regional airports. At the same time, the road infrastructure needs to be further optimized for EVs, policies encouraging carpooling have to be developed, and measures increasing the capacity of the rail network need to be taken. A first step would be to investigate the infrastructure requirements to integrate battery- and hydrogen-powered aircraft in the existing air network and compare them with investments required on the rail and road network to support a potential modal shift towards ground transport.

With the advent of zero-emissions aircraft on routes of up to 500 km, policy makers will need to define targeted mobility strategies that leverage the benefits of battery powered aircraft, rail, and electric vehicles based on infrastructure and mobility requirements

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Appendix: List of data sources and assumptions used for the different numerical analysis

Passenger market forecast

- The number of intra-EU passengers in 2018 is taken from Eurostat
- The CAGR of 2.5% to extrapolate 2040 passenger numbers is taken from Eurocontrol (Regulation & Growth Scenario)
- The flight distance distribution based on 2016 flights is taken from ElectricLeap (which uses the DATASET2050 consortium database)

Emissions and climate impact

- Multiple climate impact related data is taken from the Eco Passenger online platform methodology
  - Well to Tank and Tank to Wheel emissions factors for kerosene and diesel
  - Average kerosene consumptions (g kerosene/seat-km) for different flight distances
  - RFI factors to take into account the climate effects of other GHG emissions (per flight distance segment)
  - Average airplane load factors / occupancy (per flight distance segment: 75% for flights of 500 km and 1000 km, 80% for 2000 km)
  - Average petrol car consumption of 5l/100km expected by 2040 (Deloitte's forecast based on the current methodology)
  - Average electricity consumption per passenger for rail travel in the EU
- The expected yearly fuel efficiency improvement factor of the operational fleet of 2% is based on ICAO commitments (and past measurements)
- Battery powered airplane:
  - The EU grid mix CO_2 intensity by 2040 of 80 gCO_2/kWh based on the IEA's forecasts
  - The expected electricity consumption of battery powered airplane is based on the airliner prototype imaging by the Bauhaus Luftfahrt
- Hydrogen power airplanes:
  - The expected climate impact of hydrogen-powered airplanes is taken from the EU-supported Clean Sky 2 JU and FCH 2 JU initiative
  - The expected hydrogen consumption of hydrogen-powered airplanes is extrapolated from a study published by MIT
  - The hydrogen liquefaction energy consumption of 10 kWh/kg is taken from a study published by the US DOE
  - The hydrogen electrolysis energy consumption of 50 kWh/kg is taken from a study done by the US DOE
- Electric cars, petrol cars and diesel tour buses
  - The average diesel consumption of 20l/100km extrapolated for 2040 based on Volvo's buses' average fuel consumption
  - Occupancies of 2 persons per car and 40 passengers per tour bus were used
  - The average electricity consumption of 0.2 kWh/km is taken from data by the IEA
- Rail:
  - The study assumes that rail travel will be done on electric trains and using the average EU grid mix CO_2 intensity based on the IEA's forecasts

Travel prices

- Air travel
  - Kerosene airplane costs are derived from an equation presented by the Rome2Rio online platform averaging multi-million price points for economy class fares on various distances
  - The ticket price increase expected for battery-powered airplane is based on a study done by UCL
  - The ticket price increase expected for hydrogen-powered airplanes is taken from the EU-supported Clean Sky 2 JU and FCH 2 JU initiative
- Electric cars, petrol cars and diesel tour buses
  - An average price of 1.3 €/litre is taken into account to calculate the price of petrol car travel
  - The average price of 0.09 €/km for bus travel is found by averaging the price of routes presented by a study commissioned by the EU
  - The average charging price of 0.22 €/kWh for an electric car is based on a study by ElectricPartner.nl
  - The average toll price of 0.077 €/km is based on a study by Drive Europe News
  - The ownership costs of petrol cars is calculated using an online tool developed by the ECI, and it is assumed that EV ownership costs will fall 25% below the ones of petrol cars (Deloitte analysis, T&E)
- Rail
  - The average rail price of 0.13 €/km is derived by averaging prices on domestic and high-speed routes presented by two EU studies (European Court of Auditors and European Commission)

Travel times

- Air travel
  - The travel time increase for hydrogen-powered aircraft is defined based on expected cruise speed presented by the EU-supported Clean Sky 2 JU and FCH 2 JU initiative
  - For battery-powered aircraft, the same numbers presented for hydrogen-powered are used as they both rely on the same electric motor speed
  - On top of the advised 2 hours of arrival time before flight departure, an additional travel time of 2 x 30 minutes is considered for the commute to the airport and from the airport to the final destination
- Electric cars, petrol cars and diesel tour buses
  - The travel times are taken from the Rome2Rio online platform
  - A driver's rest of 45 minutes for each segment of 4.5 hours of drive is considered as advised by the EU
- Rail
  - The average travel time for rail travel is based on the average travel time for intercity train journeys presented by a study from the European Court of Auditors
  - The actual travel time for routes taken as examples are based on numbers provided by the Rome2Rio online platform
  - The commute to the nearest train station and to the final destination is estimated at 2 x 15 minutes, on top of the advised 30 minutes of arrival time before departure