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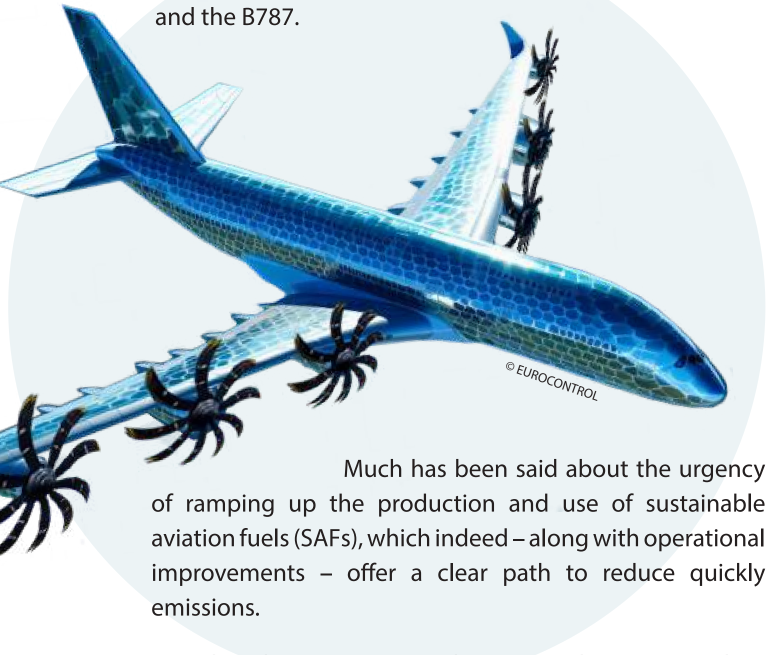
The challenge of long-haul flight decarbonisation: When can cutting-edge energies and technologies make a difference?

Just under 10% of flights from the EU27+UK area are long-haul (i.e. flying more than 3,000 km), but these account for over 50% of all aviation CO_2 emissions – and if no major progress is made, over 60% by 2050. This makes decarbonising long-haul flights both a high priority, as aviation looks to slash its carbon footprint, and a massive challenge where almost 90% of these CO_2 emissions are produced by a few heavy aircraft families, such as the B777, the A380, the B747, the A330, the A340, the A350 and the B787.



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Much has been said about the urgency of ramping up the production and use of sustainable aviation fuels (SAFs), which indeed – along with operational improvements – offer a clear path to reduce quickly emissions.

But what about truly game-changing technologies such as batteries, fuel cells, hydrogen, methane, ammonia or solar energy? This paper takes a hypothetical scenario – a large widebody flying from Paris to Singapore – and assesses how much time, energy and cost it would take to perform that flight, and what that would entail in technical terms, for each new technology.

The answer in each case is that we are, unfortunately, a long way from being able to use any of these technologies before several decades for any large-size aeroplane.

Therefore, to decarbonise long-haul flights, it is imperative to also advance on other technological and operational solutions, in particular massively increasing SAF supply/usage and fleet renewal – which, as we will be exploring in our next Think Paper, poses its own huge challenges.

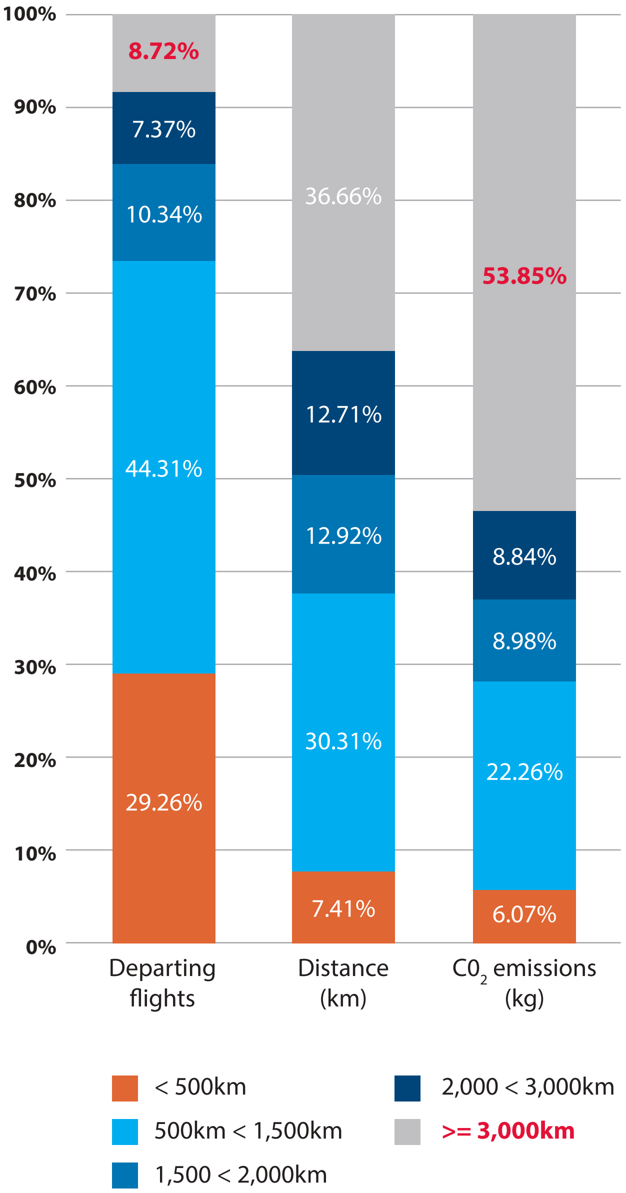
Key findings

- **Electric batteries** in their current form would make a long-haul flight too heavy to take off. Only a massive step-change in battery density, nearly tripling the energy density every decade for the next three decades, could solve this challenge.
- A large aeroplane using **liquid hydrogen combustion** would be able to take off and land, but a large cryogenic tank and supporting infrastructure is lacking. An LH_2 combustion aircraft would also produce significant contrails that would need to be further studied. Using fuel cells would further increase the cost and take-off weight.
- Flying using **liquid methane** would enable a widebody to take off and land. It poses a number of technical challenges and high cost, even if the necessary infrastructure is closer to being ready.
- **Ammonia** produced from green hydrogen is deemed a promising hydrogen carrier. Nonetheless, its use would lead to an excessively heavy long-haul aircraft.
- To have enough **solar panels** to power an A380, you would need to cover the plane – and add at least 7.4km of panels behind, making this the least practical solution of all.
- All of these solutions would require **colossal amounts of electricity** to generate the required power. To decarbonise all EU27+UK long-haul traffic by 2050, aviation would need between a net square of 24 km to 35 km of solar photovoltaic panels at the average EU solar irradiance 3.98kW/m^2/day, or 2,853 to 6,374 offshore 20-MW wind turbines or 10% to 23% of all EU electricity.
- The **level of decarbonisation depends** largely on the **carbon intensity of electricity** used during the entire process **from well to wake**. Wind-generated electricity shows a remarkable CO_2-eq reduction of -79% to -96% compared to conventional jet fuel. Photovoltaic electricity may have a slight decrease in CO_2-eq reduction efficiency, ranging from +7% to -69%. Utilising **coal-sourced electricity** for flying using these solutions could **increase the CO_2-eq emissions by 3 times (for battery aircraft) to 11 times (for liquid hydrogen fuel cell aircraft)**.

Long-haul flight share & our hypothetical typical long-haul journey

In 2019, flights over 3,000 km from the EU27+UK area accounted for only ~9% of departures but were responsible for ~54% of their CO_2 emissions – a stark confirmation, as Figure 1 shows, of the disproportionate impact long-haul travel has on emissions.

Figure 1: **EU27 + UK departures flights, distance flown and CO2 emissions (EUROCONTROL)**



In this paper, we test out the impact of game-changing technologies such as batteries, fuel cells, hydrogen, methane, ammonia or solar energy on a hypothetical journey: a fully laden widebody of similar proportions to an A380 flying from Paris to Singapore with 10,729km/5,793NM (already much below its current maximum range of 15,200km/8,207NM). Our hypothetical widebody would currently consume 119 tonnes of jet fuel and produce 376 tonnes of CO_2 emissions [1,2].

Could this flight be performed using electric batteries?

Even using the most modern Li-ion electric battery cells at 260Wh/kg and 730Wh/l (as used in the Tesla Model 3) poses, as Figure 2 shows, a massive problem. To get our fully-loaded widebody airborne, you would need multiple electrical engines for a total of 131 MW output power[3]. From a purely energy and higher electric engine efficiency-based energy perspective, 2,636 tonnes of batteries would be needed to supply the equivalent total energy of the current aircraft. However, this weight has to be lifted and requires much more energy. Those batteries would occupy a huge amount of space, posing consumption penalties, changing the widebody's aerodynamics and requiring a reinforced fuselage and landing gears to accommodate the volume of the battery. And more bad news: that weight would not diminish, therefore increasing the energy consumption over the course of the flight, causing a further problem as today's jet aircraft are designed and certified with a lower landing weight than take-off weight (394 tonnes in the case of our hypothetical widebody).

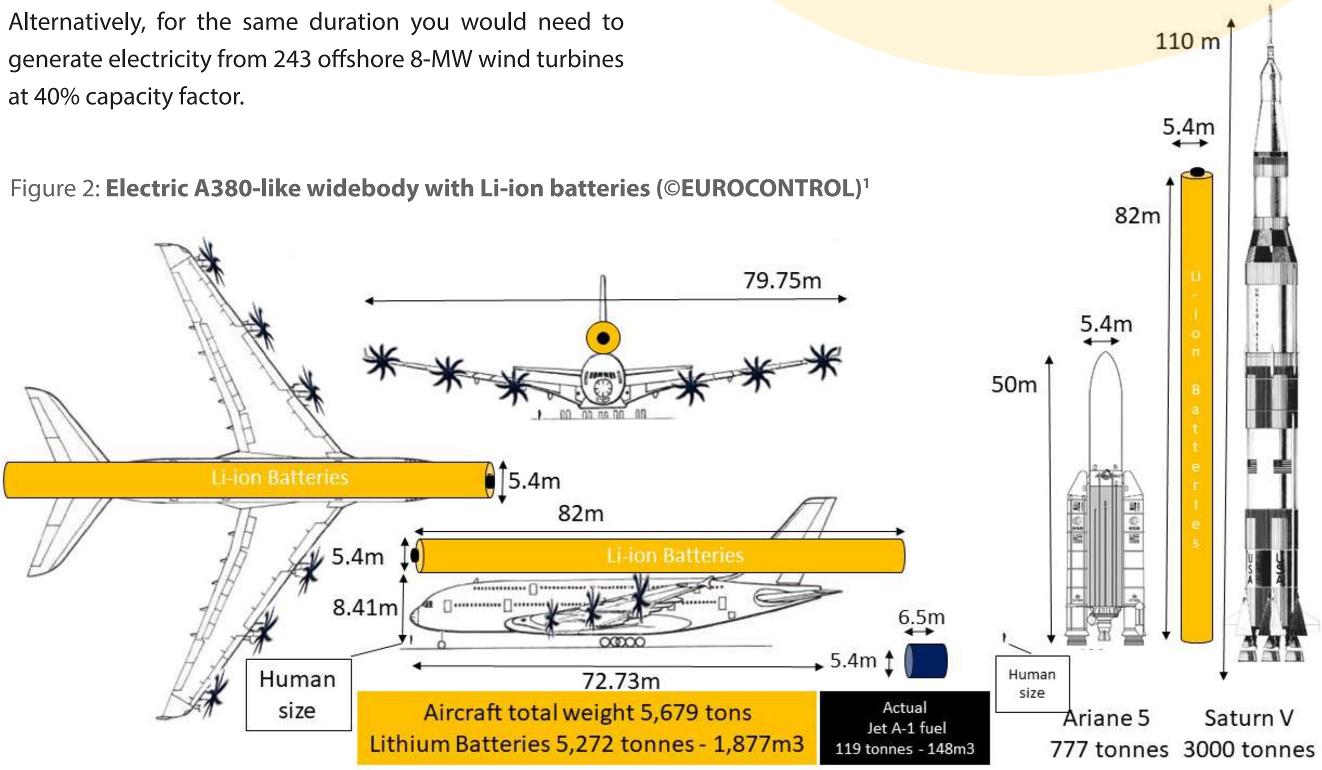
All this would take the maximum take-off weight (MTOW) of our widebody to a staggering 5,679 tonnes with 5,272 tonnes of batteries, 17 tonnes of electric motors including the cooling system, and an additional 8 tonnes of DC-AC converters plus extra fuselage weight, passengers and luggage/cargo. This is more than the Saturn V (3,000 tonnes) rocket or SpaceX Starship (5,000 tonnes)[4], and nearly half of the total weight of the Eiffel Tower.

Electric batteries in their current form would make a long-haul flight too heavy to take off. Only a massive step-change in battery density, nearly tripling the energy density every decade for the next three decades, could solve this challenge.

What would be needed to recharge a battery powered A380-like widebody?

That many batteries would require colossal amounts of electricity. Recharging our Li-ion-powered widebody would require well-to-wake (WTW) 1,554 MWh – equivalent to two hours of solar photovoltaic panels covering an area of 21 square kilometres (4.6kmx4.6km) in Paris or Singapore with an average irradiance of 4.44kWh/m^2/day. This surface area is comparable to that of 2,941 football fields. Alternatively, for the same duration you would need to generate electricity from 243 offshore 8-MW wind turbines at 40% capacity factor.

Figure 2: **Electric A380-like widebody with Li-ion batteries (©EUROCONTROL)**[1]



Technical challenges to surmount:

- Batteries storing this much power have only been used in energy farms for static storage, and never on such a large scale in aviation's stressful operating environment.
- Today's batteries' energy density capacity is far from adequate. Our widebody could only take off and remain below its MTOW if energy density were to increase 19-fold, from today's 260 Wh/kg to 5,000 Wh/kg[1] - and much more to remain below Maximum Landing Weight (MLW), unless the landing gear were massively reinforced to allow the aircraft to bear the same weight as on take-off.
- Today's batteries lack sufficient lifespan. They would need to last for up to 50,000 flight hours, over 6 times the 8,000 hours at present.
- Aviation batteries must withstand full discharge cycles without compromising their durability.
- If it is not possible to extend the lifespan of the batteries, then their cost would need to be significantly reduced and their recycling dramatically improved.
- Safety would be a major showstopper right now, with the electrolyte of current lithium batteries highly flammable.
- Six extremely powerful (20MW) electric engines and lightweight high efficiency 7.5 kW/kg would need to be available.
- An ultra-high-power electricity grid would have to be deployed at airports in all destination countries, requiring as already mentioned significant energy needs to be set aside – as well as being very low-carbon in nature.

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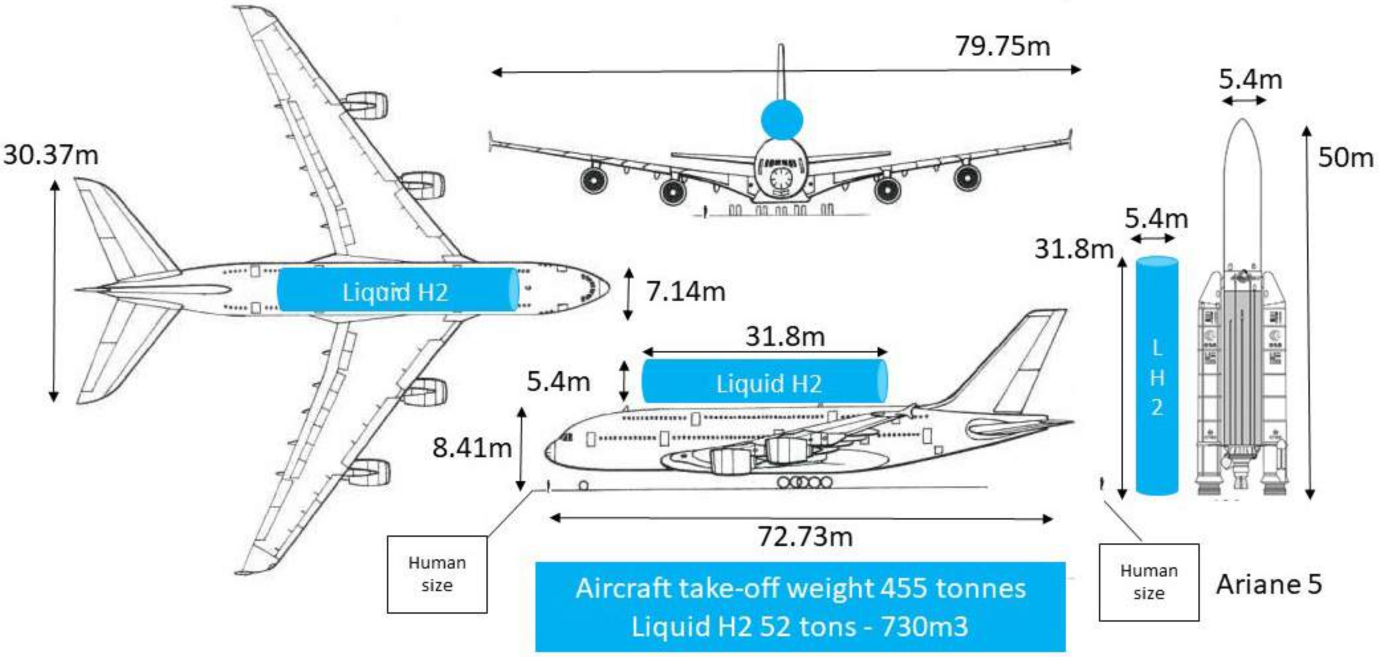
[1] In simulations, we considered the fuselage around the batteries and the aerodynamics. The pictures prioritise displaying only the batteries, omitting the additional fuselage.

Could this flight be performed with liquid hydrogen and turbofan engines?

Figure 2 shows our hypothetical widebody now powered by liquid hydrogen (LH_2), which would require a 52 tonnes tank 31.8 m long to be added to the fuselage, providing a volume of 730 m^3.

Figure 3: **Liquid Hydrogen and Turbofan A380-like widebody (©EUROCONTROL)**[1]



Although hydrogen has a 2.8 higher energy density than jet fuel, its x4 greater volume would require a large cryogenic tank and modification of the fuselage with weight and aerodynamic penalties of 21%, increasing the total energy requirements. This would result in a total take-off weight of 455 tonnes, 52 tonnes of LH_2, 88 tonnes of LH_2 vacuum tank plus valves, pump, pipes at a gravimetric index of 50%, and extra fuselage[5,6,7,8,9], plus 277 tonnes of empty aircraft including turbofan jet engines and 38 tonnes of PAX for 424 passengers at 80% occupancy) – an actual reduction in weight compared to a conventionally fuelled A380 (434 tonnes), and well below the 575 tonnes MTOW. The gravimetric index would lead to rapid deterioration of the weight, and thus aircraft fuel consumption due to additional cryogenic fuel tank weight, as well as causing fuselage and aerodynamic degradation. A gravimetric index from 70% to 50% will increase hydrogen consumption by 9%[1], and a further 18%[1] with a gravimetric index of 35%[10,11]. A gravimetric index of 50% was used in this example. In terms of contribution to global warming, the enormous loss of LH_2 through LH_2 boiling must be avoided.

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1 - In simulations, we considered the fuselage around the cryogenic hydrogen tank and the aerodynamics. The pictures prioritise displaying only the cryogenic tank, omitting the additional fuselage.

Although it is not a pollutant in its own, hydrogen can take part in atmospheric chemical reactions in the lower and upper atmospheres and these chemical reactions may lead to environmental damage [12,13,14].

How long would an LH_2 powered A380-like widebody take to refuel?

The production of such quantities of LH_2 in two hours would require 2,869MWh from solar photovoltaic panels covering an area of 39 square kilometres (6.2kmx6.2km) in Paris or Singapore with an average irradiance of 4.44kWh/m^2/day. This surface area is comparable to that of 5,431 football fields. Alternatively for the same duration, the electricity generated by 448 offshore 8-MW wind turbines at 40% capacity factor would be needed.

> Using **liquid hydrogen combustion** would be able to take off and land, but large cryogenic tank and supporting infrastructure is lacking. An LH_2 combustion aircraft would also produce significant contrails that would need to be further studied.

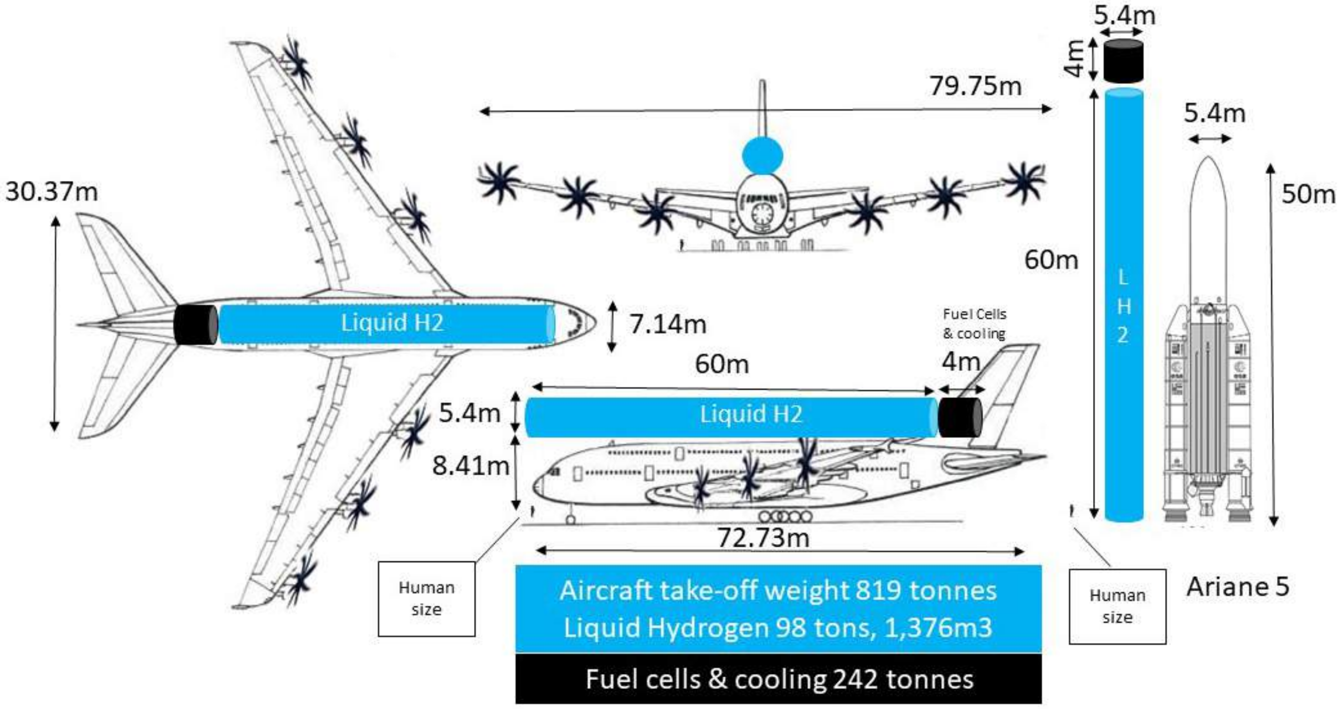
Technical challenges to surmount

- The combustion of LH_2 could produce significant contrails and potentially NOx that would need further studies, both generated during combustion, and both considered to be the most important non-CO_2 contributors to global warming[14] from the current aviation using Conventional Aviation fuel (CAF), in addition to the impact of CO_2 [15].
- Designing a high gravimetric index LH_2 proof tank capable of maintaining a temperature below -253 degrees for 14 hours or more is quite challenging [5,6,7,8,9].
- Current turbofan engines, fuel pump and injectors would need to be adapted.
- Energy losses during electrolysis and liquefaction distribution must be minimised to make LH_2 production cost-effective. Recently, an important step forward has been taken with an increase in the electrolysis efficiency (80% of the Low Heating Value) [16].
- An LH_2 production and distribution infrastructure would need to be set up in all destination and alternate airports – something which is far from the case right now.
- Refuelling would vary according to the cost of the electricity, from kEUR 49 to kEUR 292 depending on the source of electricity [17,18].
- The utilisation of liquid hydrogen presents inherent risks due to its low temperature, low pressure requirements, and flammability. Addressing these concerns will necessitate tailored prevention and protection measures, alongside advancements in regulations and certification methods.
- It may be necessary to utilise multiple smaller aircraft to finish the journey. Although it is feasible to transport a smaller quantity of liquid hydrogen in the aircraft's fuselage, this would result in a decrease in payload capacity. As a result, the range of our widebody would be notably lower, necessitating several stopovers to complete the entire flight.

Would adding fuel cells combined with electric propulsion reduce the electricity cost?

A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidising agent (often oxygen) into electricity through a pair of redox reactions.

Figure 4: **Our widebody powered by liquid hydrogen, electric engines and fuel cells (©EUROCONTROL)**[1]



Combining the efficiency of the fuel cells (50%) with electric propulsion (98%), a propfan open-rotor (80%) and DC-AC conversion (98%) offers 38% efficiency. However, the aerodynamics and weight of the fuselage caused by the liquid hydrogen fuel tank and the weight of the hydrogen and fuel cell weight would increase the total energy needed for the flight. Consequently, 98 tonnes of liquid hydrogen would have to be carried.

Adding fuel cells to our widebody would bring its weight up to 819 tonnes, with 242 tonnes of fuel cells plus 98 tonnes of liquid hydrogen in addition to their associated cooling system, 165 tonnes of LH2 vacuum tank plus valves, pump, pipes at a gravimetric index of 50%[5,6,7,8,9], and extra fuselage plus 250 tonnes of aircraft (empty and without turbofan engines) plus 17 tonnes of electric motors including its cooling system, 9 tonnes of DC-AC converters (15kW/kg)[19] and 38 tonnes of passengers 424 at 80% occupancy). This is about 385 tonnes more than the actual A380 CAF take-off weight of 434 tonnes for Paris to Singapore or 244 more than its MTOW of 575. The only way to solve this would be to reduce the weight carried and the distance flown, reducing its range below our Paris-Singapore route (which, at 10,729km/5793NM, is already much below an A380's current maximum range of 15,200km/8,207NM today).

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[1] - In simulations, we considered fuselage aerodynamics for batteries. The pictures prioritise displaying only the cryogenic tank, omitting the additional fuselage.

How long would it take to refuel an LH2 plus fuel cell powered A380-like widebody?

The production of such quantities of LH2 in two hours would require 5,411MWh to be produced by solar photovoltaic panels which would have to cover an area of 73 square kilometres (8.6kmx8.6km) in Paris or Singapore, with an average irradiance of 4.44 kWh/m^2/day.

This surface area is comparable to that of 10,242 football fields. Alternatively for the same duration, the electricity generated by 846 offshore 8-MW wind turbines at 40% capacity factor would be needed.

> The challenges are very similar to the **liquid hydrogen combustion** engine described previously with additional specificities such as fuel cell cost and heavy weight.

Technical challenges to surmount

The challenges are very similar to the liquid hydrogen combustion engine described previously, with additional specificities.

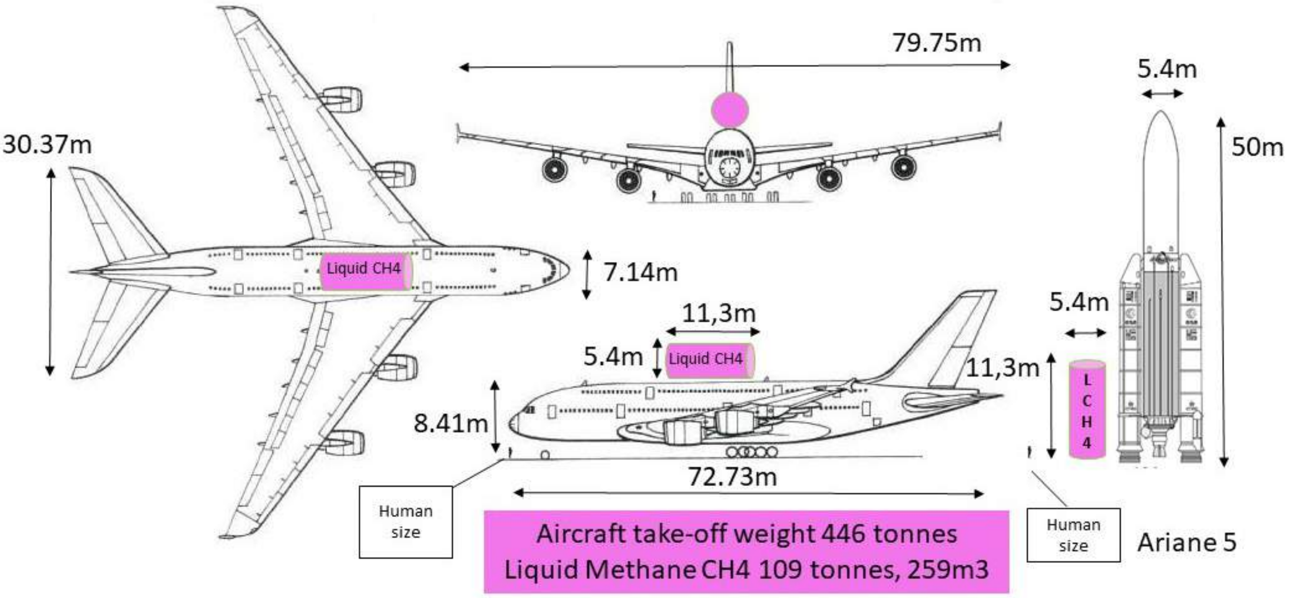
- Much more efficient fuel cells and cooling weight would be required compared to the current power density (including cooling) at 0.6 to 0.75kW/kg[10]. Our modelling and simulations[1] have shown that an improvement by an incredible factor of 2.7 to reach 1.6kW/kg of power density[1] would bring our A380-like widebody down from 819 tonnes to its MTOW of 575 tonnes.
- The landing weight would also be a problem, with MLW of 394 tonnes exceeded by 279 tonnes, despite the 98 tonnes of LH2 being consumed during the flight.
- Fuel cells would need to be created with a capacity of hundreds of MW - a major challenge given that the most powerful ones today only reach 250kW[20].
- Seeking alternative materials to replace platinum is crucial to reduce reliance on geopolitically sensitive sources.
- Electronic DC-AC converters and circuit breakers capable of managing several MWs would need to be designed.
- Six extremely powerful (20MW) electric engines and lightweight high efficiency 7.5 kW/kg would need to be available.
- The lifespan of the fuel cells would need to be extended up to 50,000 hours.
- Fuel cell unit prices would need to be massively reduced for this conversion of liquid hydrogen into electricity to become economically viable. Currently, at a price of between $2,500 (€2,200) for 100 units/year to $1,700 (€1,500) per kW for 50,00 units/year[20], the fuel cells needed to power an A380-like widebody would cost between 218M€ to 319M€.
- The electricity cost for the production of the liquid hydrogen would would vary from kEUR 92 to kEUR 550 depending on the source of electricity[17,18].
- An LH2 production and distribution infrastructure would need to be deployed in all destination countries – something which is far from the case right now.
- The risks inherent in the use of hydrogen will require specific means of prevention and protection accompanied by an evolution of the regulations and means of certification.

Liquid methane and turbofan engines

While the barriers to using batteries or hydrogen fuel cells power for long-haul flying are for now insuperable, there is one power source that is able now to power our hypothetical A380: synthetic or bio methane (CH_4). This could be produced from green hydrogen or from EU27 agricultural, forestry and waste feedstocks included in Annex IX of RED II (part A and B)[21], or from captured CO_2 and renewable H_2. This technology has already been envisaged by NASA[22] and is now used in SpaceX Starship Raptor rocket engines[4,23]. In liquid form, it has a better tolerance at freezing temperatures of -161°C to -182°C compared to -253°C to -259°C for hydrogen. Its larger molecules are less likely to pass through most materials, which would make it easier to handle than liquid hydrogen.

The changed aerodynamics, increased weight of the fuselage thanks to the liquid methane fuel tank, and the liquid methane weight itself, would combined add 7% to the total energy needed for the flight. 109 tonnes of liquid methane (compared to 119 tonnes of kerosene) would be required to perform the same flight using today's turbofan jet engines, compared to kerosene requiring 148 m^3, methane 259 m^3 and liquid hydrogen 730 m^3.

Figure 5: **Liquid methane and Turbofan-powered A380-like widebody (©EUROCONTROL)**[1]



The total take-off weight of an LCH_4 powered A380-like widebody would be 446 tonnes, (109 tonnes of LCH_4 plus 22 tonnes for the LCH_4 tank and extra fuselage[7,22], plus 277 tonnes of empty aircraft weight, and 38 tonnes of passenger (424 at 80% occupancy). This is close to the current CAF A380 weight for a Paris to Singapore flight of 434 tonnes.

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[1] In simulations, we considered the fuselage around the cryogenic methane tank and the aerodynamics. The pictures prioritise displaying only the cryogenic tank, omitting the additional fuselage.

How long would it take to refuel?

Refuelling a similarly sized widebody with 109 tonnes of LCH_4 would require 2,815MWh of electricity WtW, equivalent to two hours of solar photovoltaic panels covering an area of 38 square kilometres (6.2kmx6.2km) in Paris or Singapore, with an average irradiance of 4.44kWh/m^2/day. This surface area is comparable to that of 5,327 football fields. Alternatively, for the same duration the electricity generated by 440 offshore 8-MW wind turbines at 40% capacity factor would be needed.

Any loss of methane through LCH_4 boiling or any leakage must be avoided. Indeed, over a period of a century, CH_4 would contribute more than 30 times to global warming than CO_2, and 82.5 times more over a period of twenty years[25].

Methane aircraft would be able to take off and land.

In case of leakage, the global warming impact can be 30 to 82.5 times higher than CO_2. The main challenges lie in producing it sustainably and preventing any leaks.

Technical challenges to surmount

- The climate-neutrality of LCH_4 must be ensured, along with addressing its non-CO_2 emissions, including contrails and NOx.
- An LCH_4 tank would be required capable of maintaining a temperature below -161°C to -182°C degrees for 14 hours or more, especially when the aircraft is still waiting on the ground – a challenge but certainly easier than maintaining hydrogen at -253°C.
- The engines, fuel pump and injectors on the turbofan would need to be adapted; this however is relatively straightforward.
- Energy losses in electrolysis, carbon capture and liquefaction distribution would need to be reduced.
- The cost of the electricity to produce the liquid methane based on current values would be currently prohibitive, varying between kEUR 48 to kEUR 286, depending on the source of electricity[17,18]. To solve the economics, LCH4 production costs would have to decline massively.
- Airports would only need to have liquefaction units installed and increase the existing distribution infrastructure.

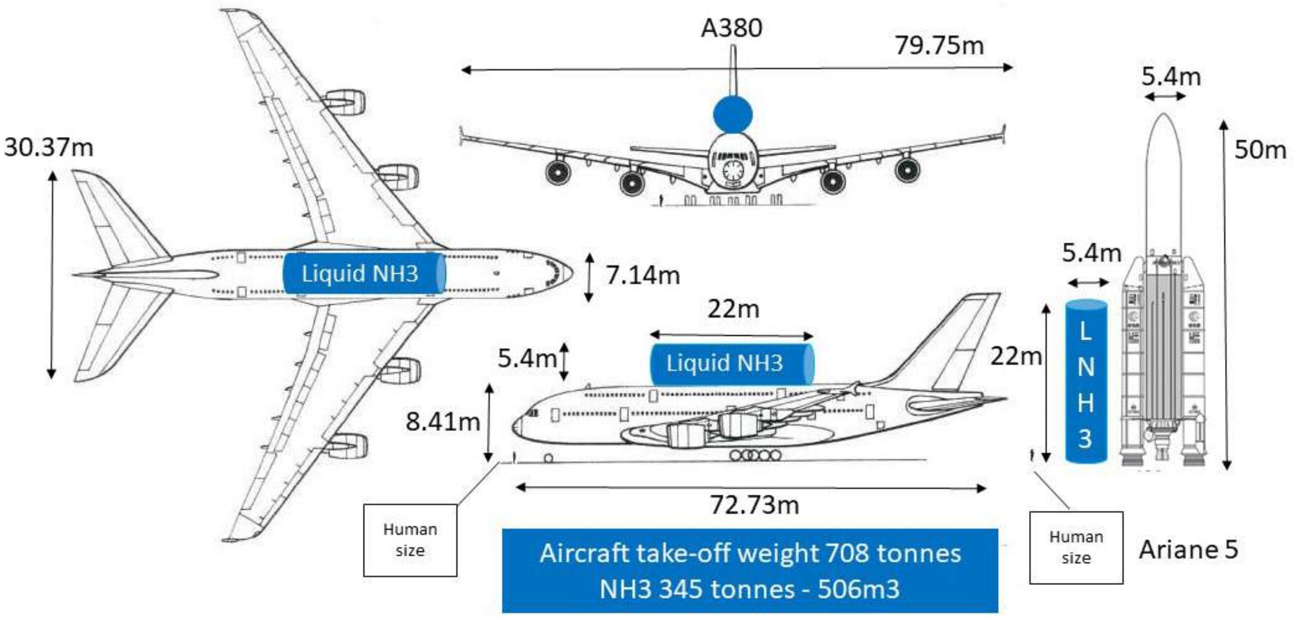
Liquid ammonia and turbofan engines

Liquid ammonia (NH_3) produced from green hydrogen is being considered as an alternative hydrogen carrier, and has recently gained considerable interest [25,26] for use in fuel cells or jet engines with manageable modifications. It emits only water, NOx, and unburned NH_3 during combustion, and does not produce CO_2. It is not explosive or corrosive – but has one major drawback: its vapor is highly toxic. NASA has previously used it on the X-15 rocket engine[27], and Dassault plans to study it for use on the Falcon 50 later in 2023[28]. A group at COP26 led by Reaction Engines has also launched a design for an ammonia cracking unit for aviation use[29].

In liquid form, its volumetric and gravimetric energy content is lower than current kerosene, meaning that more ammonia would need to be used; however, its combustion could potentially be as or more efficient[29,30]. At -33.3°C in liquid form, ammonia is also much easier to manage compared to liquid hydrogen.

A liquid ammonia-powered A380-like widebody would require 345 tonnes of liquid ammonia (compared to 119 tonnes of kerosene) to perform the same flight using today's turbofan jet engines; by comparison, kerosene would require 148 m^3, while liquid ammonia would require 506 m^3. An ammonia-powered aircraft burns all the ammonia during the flight, while our liquid hydrogen fuel cell-powered widebody would consume its liquid hydrogen, but would face weight penalties due to the heavy fuel cell. As a result, an ammonia-fuelled aircraft would demonstrate slightly better tank-to-wake (TtW) efficiency, with the flight requiring approximately 44% more energy compared to a CAF A380. By contrast, our liquid hydrogen fuel cell A380-like widebody would need 137% TtW more energy compared to a CAF-fuelled A380 performing the same flight.

Figure 6: **Liquid ammonia and turbofan A380-like widebody (©EUROCONTROL)**[1]



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[1] In simulations, we considered the fuselage around the cryogenic ammonia tank and the aerodynamics. The pictures prioritise displaying only the cryogenic tank, omitting the additional fuselage.

Aircraft weight?

The total take-off weight of a liquid NH_3 powered widebody would be 708 tonnes (345 tonnes of liquid NH_3 plus 10 tonnes of cracking unit, 38 tonnes for the liquid NH_3 tank, extra fuselage, plus 277 tonnes of empty aircraft weight, and 38 tonnes of PAX (424 at 80% occupancy).

This is nearly the double the current A380 weight for a Paris to Singapore flight at 434 tonnes.

How long would it take to refuel?

Refuelling our widebody with 345 tonnes of liquid NH_3 would require 3,003MWh of electricity WtW from solar photovoltaic panels covering an area of 41 square kilometres (6.4kmx6.4km) in Paris or Singapore, with an average irradiance of 4.44kWh/m^2/day.

This surface area is comparable to that of 5,684 football fields. Alternatively, for the same duration, the electricity generated by 469 offshore 8-MW wind turbines at 40% capacity factor would be needed.

> **Ammonia** produced from green hydrogen is deemed a promising hydrogen carrier. Nonetheless, its use would lead to an excessively heavy long-haul aircraft.

Technical challenges to surmount

- The climate-neutrality of the liquid NH_3 production and combustion and its non-CO_2 emissions such as contrails and NOx would need to be ensured. Indeed, the combustion of liquid NH_3 will still produce contrails and NOx that would need to be further studied.
- A liquid NH_3 tank would be required capable of maintaining a temperature below -33.3°C degrees for 14 hours or more, especially when the aircraft is waiting on the ground.
- The engines, fuel pump and injectors on the turbofan would need to be adapted.
- Efficient and light, powerful cracker units would need to be developed with the ability to decompose 345 tonnes of ammonia into hydrogen in the space of a few hours.
- A reduction in energy losses in electrolysis and liquefaction distribution would need to be achieved.
- The cost of the electricity used to produce the ammonia would vary from kEUR 51 to kEUR 305 depending on the source of electricity[17,18]. There would be a need to reduce the cost of liquid NH_3 production.
- A liquid NH_3 production and distribution infrastructure would furthermore need to be deployed in all countries.

Solar aircraft

Compared to conventional aviation fuels, solar energy is inexhaustible, free and non-polluting, but it has significant variations owing to the Earth's rotation (day-night cycle) and is unpredictable due to clouds. Solar power is not used for commercial air transport for good reasons, as the amount of electricity produced by solar panels is far too low to power a heavy long-haul aircraft.

The best-known solar aeroplanes are Solar Impulse I and II, which represent an incredible technical achievement, proving it possible to transport a single person across long distances in an ultra-light aeroplane with huge wing surfaces covered in photovoltaic cells. These converted the sun's light energy into electrical energy to power the engine, which transforms this electrical energy into mechanical energy through the propeller. In most cases, solar planes use an additional battery to store additional energy to compensate for any lack of sunlight.

Covering the entire surface of an A380-size widebody would yield 1,000 m^2 (covering a wing area of 875 m^2, plus the tail and upper roof area). Taking the performance of Solar Impulse, with a photovoltaic efficiency of 22.1%[31,32] and maximum solar radiation of 1,000W/m^2 at sea level in a vertical orientation, covering our widebody with solar photovoltaic panels would produce just 0.22 MW peak power – falling spectacularly short of the required 131 MW[1,2,3] of peak electrical power, and crucially providing just 0.17% of the electrical power needed to achieve take-off (which could drop as low as 0.02% on a cloudy day). The immensity of the gap is highlighted in Figure 7: a solar powered A380-sized widebody would need to trail after it at least 7,411 metres of photovoltaic solar panels.

Figure 7: **Solar Impulse II**

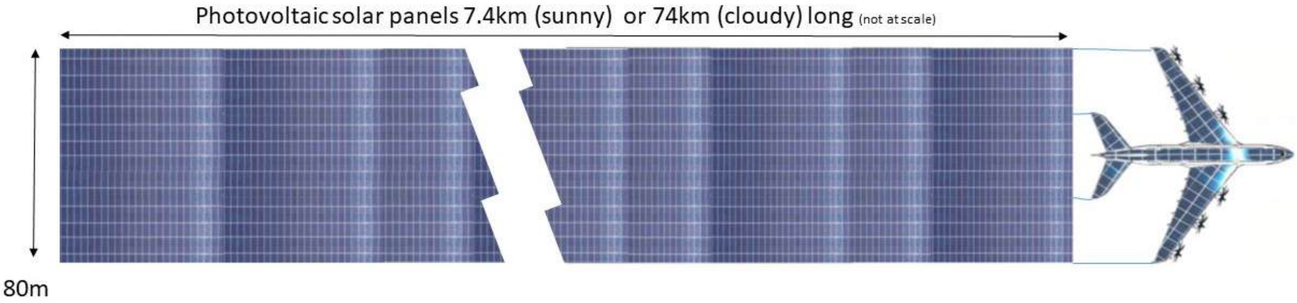

Figure 8: **Our solar-panel equipped widebody and the additional photovoltaic solar panels it would need to transport (©EUROCONTROL)**

What would be the cost and $CO_{2\text{-eq}}$ emission savings comparing electric and other technologies?

The table below summarises the weight of our hypothetical widebody and the energy required for these different technologies. Electric batteries represent the heaviest but most energy efficient solution. Liquid hydrogen combustion and liquid methane follow in terms of efficiency, with liquid hydrogen associated with fuel cells and ammonia being the less efficient. Only a liquid hydrogen and methane A380-sized widebody would be, right now, physically able to take off, while hydrogen fuel cells and ammonia would require a longer runway to achieve lift-off.

Paris-Singapore A380-like widebody required energy	**Electric batteries 260wh/kg**	**Liquid hydrogen with actual turbofan**	**Liquid hydrogen with fuel cells 600w/kg**	**Liquid methane with actual turbofan**	**Liquid ammonia with actual turbofan**	**Actual fossil jet fuel**
Required batteries or fuel cells & cooling (tonnes)	5,272		242			
Required liquid hydrogen, methane or ammonia (tonnes)		52	98	109	345	119
Aircraft total weight (tonnes)	5,679	455	819	446	727	434
(WtW) Required quantities of electricity to recharge or produce, liquefy and transport the hydrogen (MWh)	1,554	2,869	5,411	2,815	3,003	
Average km^2 solar photovoltaic panels (20% efficiency, Paris or Singapore 4.44 kWh/m^2/day avg solar irradiation) to produce WtW electricity in two hours	21	39	73	38	41	
Net PV square of km edge of solar photovoltaic panel (20% efficiency, Paris or Singapore 4.44 kWh/m^2/day avg solar irradiation) to produce WtW electricity in two hours	4.6 x 4.6	6.2 x 6.2	8.6 x 8.6	6.2 x 6.2	6.4 x 6.4	
Nb football fields coverage (105 by 68 metres= 7,140m^2) charging in two hours	2,941	5,431	10,242	5,327	5,684	
Nb time CDG surface (33.38km^2)	0.6	1.2	2.2	1.1	1.2	
Nb hectares	2,100	3,878	7,313	3,804	4,059	
Nb offshore wind turbine 8MW at 40% capacity factor charging two hours	243	448	846	440	469	

Figure 9: **Paris-Singapore A380-like widebody weight and required energy (EUROCONTROL)**

In terms of the cost of powering our hypothetical long-haul aircraft, the table below clearly shows that while the CAF cost is static (depending of course on the price it was purchased at), the same cannot be said of the cost of the electricity required to produce the alternative power sources required to refuel our widebody, which varies enormously depending on the means of production. If best-in-class solar panels are used, the cost of refuelling from all these technologies will be cheaper than current kerosene. However, in most other situations, without a significant reduction in electricity price, the cost of refuelling significantly exceeds the current cost of jet fuel.

A battery-powered electric aircraft is the most cost-effective option due to its superior overall efficiency from "well to wake". The cost of solar and wind electricity has fallen significantly in the past decade, with a tenfold reduction in the price per MWh, making it cheaper than new EPR (European Pressurized Reactor) nuclear power[18].

However, the inconsistent availability of solar and wind power can pose its own challenges, such as increasing fuel factory costs and requiring uninterrupted power. Fortunately, some Proton Exchange Membrane (PEM) electrolyser technologies are capable of producing hydrogen for all types of fuel with frequent interruptions. In addition, the baseload buffer potential of the combination of millions of European electric cars equipped with vehicle-to-grid (V2G) and vehicle-to-home (V2H) systems, whose batteries could be used as a buffer to reduce the intermittency of renewable energy sources, and benefit from similar laws as the one proposed by the Californian legislature, which would require all new electric vehicles sold in the state to be equipped with bidirectional charging as of 2027[33]. For instance, one million electric cars (equivalent to half the predicted 2030 annual sales in France), each with a 100-kWh battery, could store or supply the enormous amount of electricity equivalent to an hour of power from all Europe's 131 nuclear reactors.

2021 electricity cost K€	**Electric batteries 260Wh/kg**	**Liquid hydrogen with actual turbofan**	**Liquid hydrogen with fuel cells 600W/kg**	**Liquid methane with actual turbofan**	**Liquid ammonia with actual turbofan**	**Actual fossil jet fuel (658€/tonne)**
Solar panel best-in-class farms €17 MWh	26	49	92	48	51	n/a
Nuclear electricity at €27.56MWh produced from nuclear long-term operation (LTO) by lifetime extension	43	79	149	78	83	n/a
Wind farm €43MWh	67	123	233	121	129	n/a
Solar panel at €48MWh	75	138	260	135	144	n/a
Cost of electric MWh actual nuclear €59.46MWh	92	171	322	167	179	n/a
Coal power plant €99.97	155	287	541	281	300	n/a
EPR nuclear reactor €101.69MWh	158	292	550	286	305	n/a
Fossil jet fuel at 658€/tonne	n/a	n/a	n/a	n/a	n/a	78

Figure 10: **Paris-Singapore refuelling cost (EUROCONTROL)**

The level of decarbonisation is strongly influenced by the carbon intensity of the sources used to produce the electricity. The table below compares these emissions with the currently used CAF. We use the European Environment Agency's $CO_{2\text{-eq}}$ lifecycle data[34] for our calculations, and compare these data with CAF including its $CO_{2\text{-eq}}$[35].

Sustainable energies such as offshore wind farms, with decarbonisation rates ranging from -79% to -96%, then solar power ranging from +7% to -69% depending on the fuel to be produced, could help power our hypothetical widebodies of the future. However, burning coal to generate any of that electricity required would nearly triple, or multiply by nine, the $CO_{2\text{-eq}}$ emissions generated as a percentage compared to the current use of kerosene[35].

WtW % median decarbonisation depending on the carbon intensity (EEA) from source of electricity and aircraft technology compared to fossil jet fuel		**Electric batteries 260wh/kg**	**Liquid hydrogen & turbofan**	**Liquid hydrogen with fuel cells 600w/kg**	**Liquid methane & turbofan**	**Liquid ammonia & turbofan**	**Current kerosene**
Wind offshore	Median	-94%	-89%	-79%	-89%	-88%	0%
Wind onshore	Median	-96%	-92%	-86%	-93%	-92%	0%
Solar	Median	-69%	-43%	7%	-44%	-41%	0%
Coal	Median	267%	578%	1179%	565%	610%	0%

Figure 11: **Median percentage of decarbonisation for a Paris-Singapore A380-like widebody using different aircraft technologies and energy sources (EUROCONTROL)**

Considering long-haul air traffic demand from 2019 onwards, these technologies would require the use of an equivalent to 9,868 to 34,358 8-MW offshore wind turbines, working 24/7 each year at 40% load factor, to generate the electricity that would be needed. By 2050, assuming progress is made in renewable power generation, battery energy density to from 260Wh to 5,000Wh/kg and fuel cells from 600W/kg to 1.6kW/kg power density, 2,853 to 6,374 20-MW offshore wind turbines operating at 60% load factor would be required to generate just the electricity needed for the aviation sector – making this energy demand extremely unlikely to be met given the various political considerations and competing industries for the same sustainable power sources. These figures illustrate the extreme complexity of decarbonising long-haul flights.

Electricity requirements (in terawatt-hours, TWh) for producing liquid hydrogen or liquid methane for flights over 3,000 km in the EU27 + UK region, considering different technologies and projected traffic for 2019, 2030, and 2050. It also mentions the consideration of improvements in all electricity power generation, batteries energy density and fuel cell power density.	**Electric batteries energy density from 260Wh/kg up to 2030 to 5,000Wh/kg in 2050**	**Liquid hydrogen & turbofan**	**Liquid hydrogen with fuel cells power density from 600W/kg up to 2030 to 1,600W/kg in 2050**	**Liquid methane with actual turbofan**	**Liquid ammonia with actual turbofan**	**Actual fossil jet fuel**
WTW electricity needed for the aviation TWh (2019 traffic)	277	511	963	501	631	n/a
% related to 2019 EU electricity 2,904 TWh	10%	18%	33%	17%	22%	n/a
% related to 2019 France electricity 538 TWh	51%	95%	179%	93%	117%	n/a
A net square shape of X km * X km of solar photovoltaic panels (20% efficiency, EU27+UK 3.98 kWh/m^2/day avg solar irradiation)	31	42	58	42	47	n/a
NB offshore 8-MW wind turbines (load factor 40%)	9,868	18,219	34,358	17,872	22,502	n/a
WTW electricity needed TWh (2030 traffic)	251	464	875	455	573	n/a
% related to 2019 EU electricity 2,904 TWh	9%	16%	30%	16%	20%	n/a
% related to 2019 France electricity 538 TWh	47%	86%	163%	85%	107%	n/a
A net square shape of X km * X km of solar photovoltaic panels (26% efficiency, EU27+UK 3.98 kWh/m^2/day avg solar irradiation)	26	35	48	35	39	n/a
NB offshore 15-MW wind turbines (load factor 50%)	3,825	7,062	13,317	6,927	8,722	n/a
WTW electricity needed TWh (2050 traffic)	300	546	670	535	674	n/a
% related to 2019 EU electricity 2,904 TWh	10%	19%	23%	18%	23%	n/a
% related to 2019 France electricity 538 TWh	56%	101%	125%	99%	125%	n/a
A net square shape of X km * X km of solar photovoltaic panels (37% efficiency, EU27+UK 3.98 kWh/m^2/day avg solar irradiation)	24	32	35	32	35	n/a
NB offshore 20-MW floating wind turbines (load factor 60%)	2,853	5,190	6,374	5,091	6,410	n/a

Figure 12: **Quantities of electricity (TWh) and number of renewable wind turbines, surfaces of solar photovoltaic panels or non-renewable nuclear reactors required to produce the energy to power all long-haul traffic from 2019 to 2050 (EUROCONTROL)**

Conclusion

All activities using fossil-based energy face a huge decarbonisation challenge, and time is running out. Some industries are easier to decarbonise than others. Aviation is in an extremely difficult situation compared to most other sectors because of the very high energy density required to fly an aircraft, especially a widebody. Decarbonising long-haul flights of more than 3,000 km, where almost 90% of these CO_2 emissions are produced by a few heavy aircraft families, such as the B777, the A380, the B747, the A330, the A340, the A350 and the B787, represents a colossal challenge.

As this paper has explained, there are a number of candidate technologies to meet this challenge, but all of these are many decades away from evolving to meet our challenge of decarbonising a typical long-haul flight like our hypothetical A380-like widebody flying from Paris to Singapore.

High energy density is essential for aviation, especially for long-haul flights. Fuel makes up a significant portion of the weight in certain transport modes. For example, in the Saturn V (3,000 tonnes and SpaceX Starship (5,000 tonnes) rockets, fuel accounts for more than 93% of the total weight, compared to around 3% in an average passenger car. A long-haul aircraft sits somewhere in-between, with CAF currently making up as much as 44% of the total weight on any given flight. As a result, while there may be some technologies that are effective at reducing emissions in road transport and short-haul, these are not yet anywhere near suitable for long-haul flying.

An electric battery-powered widebody could work, and would be the most energy efficient, but only if there is a revolution in battery efficiencies, requiring them to nearly triple in energy density, every decade for the next three decades, to reach the required 5,000Wh/kg energy density.

In terms of take-off weight, a liquid hydrogen (LH2) powered combustion aircraft is possible, but for that to happen, a set of huge challenges would need to be met in terms of safety, production, distribution, volume, cryogenic tank and global warming effect. Furthermore this technology poses additional problems due to the unavailability of extremely powerful fuel cells and electric engines, but also their too heavy weight and cost. A factor 2.7 of progress in fuel cell power density to reach 1.6kW/kg, as well as huge quantities of electricity, would be required to succeed.

Liquid methane (LCH_4) aircraft take-off weight makes this technology possible; however both together with ammonia (LH_3) pose additional loss risks.

Finally, a solar-powered widebody is impossible to envisage under any circumstances.

Based on 2019 traffic, the application of these technologies to all flights over 3,000 km from EU27+UK would require a production of electricity equivalent to a net square of 31 km to 58 km of solar photovoltaic panels (average EU27+UK solar irradiance and 20% efficiency), or 9,868 to 34,358 off-shore 8-MW wind turbines (load factor 40%).

By 2050, assuming realistic progress is made in renewable power generation and outstanding battery energy density from nowadays 260Wh to 5,000Wh/kg and fuel cells from 600W/kg to 1.6kW/kg power density, this would be still require a net square of 24 km to 35 km of solar photovoltaic panels (average EU27+UK solar irradiance and 37% efficiency) or 2,853 to 6,374 20-MW offshore wind turbines (load factor 60%) needed to produce the electricity.

In conclusion, a widebody that could be powered by any of these technologies on their own, or in combination, cannot be expected in the foreseeable future. Advances in solving many of the technological challenges outlined in this paper will happen, but significant progress is not expected to take place for decades at the earliest. Each of these solutions is, therefore, highly unlikely to emerge for application to classic widebodies used to fly long-haul routes, especially as such types have a very low renewable rate (with widebodies typically staying in service, either with their original operators, or with secondary carriers, for 23 years on average).

To make significant progress towards decarbonising long-haul flights requires, therefore, a different approach in the short to medium term – which is the subject of our next Think Paper. In it, we will tackle what can be achieved using other, existing or easy-to-envisage technical and operational solutions, including the use of Sustainable Aviation Fuels (SAF), fleet renewal, and operational solutions to deliver on the goal of decarbonisation. It will also examine the challenges faced as aviation competes with other transport industries for the same sustainable energy sources.

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Abbreviations

A380	Airbus A380
CAF	Conventional Aviation Fuel (fossil jet fuel)
DC-AC	Direct current to alternate current
EU27	Europe Union, 27 states
CH_4	Methane
LCH_4	Liquid methane
Kg	Kilogramme
km	Kilometre
kW	Kilowatt
kWh	Kilowatt hours
LH_2	Liquid Hydrogen
m^2	Square metre
m^3	Cubic meter
MLW	Maximum landing weight
MTOW	Maximum take-off weight
MW	Megawatt
MWh	Megawatt hours
NM	Nautical miles (1.852km)
SAF	Sustainable aviation fuel
TtW	Tank to Wheel or wake
TWh	Terawatt hour
V_2G	Vehicle-To-Grid
V_2H	Vehicle-To-Home
W	Watt
Wh	Watt hour
WtT	Well to the Tank
WtW	Well to wheel or wake

Conversion factors

1 NM = 1.852 kilometres
1 kilogramme of jet fuel consumed = 3.16 kilogrammes of carbon dioxide emissions
1 passenger and checked luggage = 90 kilogrammes

Fossil kerosene carbon intensity: 15.77 $CO_{2\text{-eq}}$ gr/MJ (life cycle analysis ec.europa.eu/energy)

LH_2 efficiency production (WtT) efficiency (electrolysis 80% + liquefaction + transport 75% => total 60% efficiency

LCH_4 efficiency production (WtT) Syngas generation by co-electrolysis of steam and carbon dioxide total efficiency 50kWh (LHV)/ 92.85kWh = 54% input Helmeth.eu study 70.3kWh + 17.8kWh carbon capture of 10.7Kg CO_2 at 1777kWh/kg CO_2 (IEA) + 0.35kWh liquefaction 1kg methane + 5% transport and distribution (4.4kWh)= 92.85kWh

Wind Offshore Median carbon intensity: 18 kg $CO_{2\text{-eq}}$ / MWh from EEA
Wind Onshore Median carbon intensity: 12 kg $CO_{2\text{-eq}}$ / MWh from EEA
Solar Median carbon intensity: 90 kg $CO_{2\text{-eq}}$ / MWh from EEA
Coal Median carbon intensity: 1,075 kg $CO_{2\text{-eq}}$ / MWh from EEA

A380-like widebody instant power at take-off has been estimated using the jet fuel flow primary energy content (11.99kWh or 43.15MJ/kg) combined with the thermodynamic and propulsive efficiency of the engines at take-off (18%)

A380-like widebody turbofan thermodynamic and propulsive efficiency 37% in cruise, Maximum Take-Off Weight (MTOW) 575 tonnes, Maximum Landing Weight (MLW) 394 tonnes, PAX: 80% of 530 = 424 passengers

Electric motor efficiency 98%
DC-AC conversion efficiency 98%
Battery charge-discharge efficiency 90%
Open rotor engine propulsive efficiency 80% in cruise, 68% at take-off

Solar Impulse photovoltaic solar pannels efficiency 22.1%

Cryogenic fuel tank gravimetric index 50%
where GI = mass fuel/ (mass fuel tank + structure + mass fuel)

Total EU 2019 electricity production: 2,904TWh
Total France 2019 electricity production : 538TWh
Both Paris and Singapore have an average monthly Global Horizontal Irradiance (GHI) of about 4.43 kilowatt hours per square metre per day (kWh/m^2/day)

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