DECARBONIZING AVIATION

MISSION POSSIBLE

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BY OPENAIRLINES

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Introduction

Hello air travel enthusiast, if you want to learn more about the opportunities and challenges of aviation decarbonization, you've come to the right place!

Global warming represents one of the biggest challenges that humankind has ever faced. In this context, aviation is particularly scrutinized and singled out as one of the most polluting industries. For good reasons? Questionably not considering aviation accounts for 2% to 3% of the global CO_2 emissions (although we will see that it is a little more complex than that). Does this mean nothing is to be done? Certainly not considering the sector is expected to grow an average of 4% yearly for the next 20 years which represents an increase of 200% of aviation emissions by 2050 if no actions are taken!

A collective response is essential to honor the Paris Agreement which aims at reducing CO_2 emissions by 55% by 2030. For the aviation industry, this represents a tremendous challenge that involves transitioning to new-generation technologies and biofuels. However, we're not about to sit tight and wait for these innovations to hit the market. There are immediate and effective actions that can be taken right away to reduce emissions.

In this book, we will explore a mix of short and long-term solutions that aviation can leverage in order to reach its ambitious goal to achieve net-zero carbon emissions by 2050. I strongly believe that decarbonizing aviation is possible providing that all industry players join forces. Let's accept this mission together and act firmly and quickly!

Alexandre Feray, *OpenAirlines CEO and Founder*

CHAPTER 1.

How Much CO_2 Does Aviation Emit?

In this first chapter, you will find facts and some figures on aviation's carbon footprint and its comparison with other sectors.

: SECTION 1

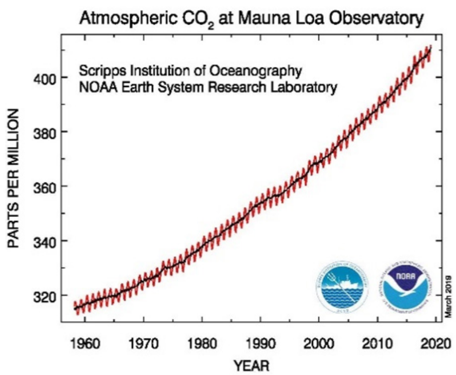
The stakes of global warming

Global warming is the most severe threat that our planet, our civilization, and our industry has ever faced.

In 2019, the concentration of CO_2 in the atmosphere exceeded 410 ppm, the highest level seen in some 3 million years, before humans existed.

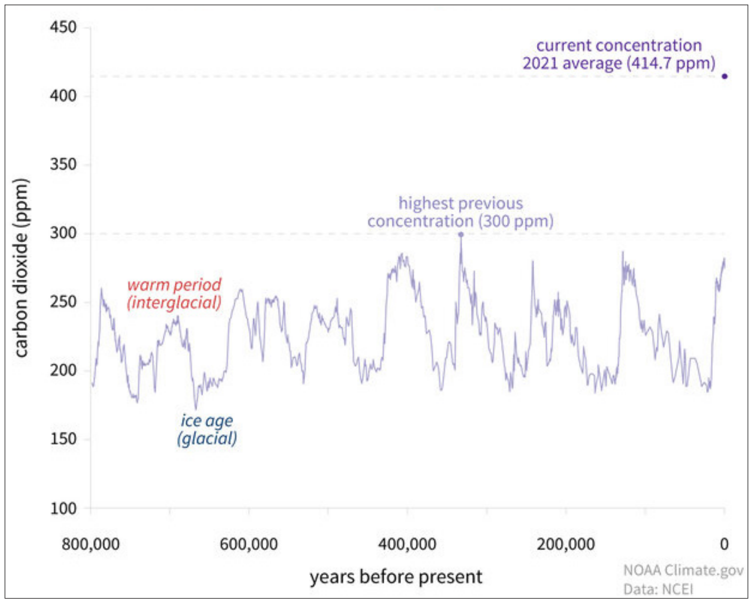
It is growing at an unprecedented speed, and all scientific studies confirm humans cause it.

Figure 1: State of the atmosphere since 1960



Source: climate.nasa.gouv

Figure 2: Carbon dioxyde over 800,000 years



Source: climate.gouv

Glaciers are melting almost worldwide; ocean levels rise, heatwaves and catastrophic meteorological events are more frequent. All our ecosystems are at risk.

Figure 3: The Alps' highest peak, Mont-Blanc, photographed in:

1919 | 2019

Source: Walter Mittelholzer, ETH-Bibliothek Zürich & Dr Kieran Baxter, University of Dundee.

It's time to act, recognize our share and accelerate the world's transition to sustainable aviation.

: SECTION 2

How much fuel does an aircraft burn?

This question is interesting because even though the answer is very factual, there are two ways to look at it. Both perspectives are valid and explain the big divide between environmental and aviation activists.

In short, an aircraft does burn a lot of fuel. A transatlantic flight on a modern A350 from Paris to New York will typically burn ~60,000 liters of fuel (~16,000 gallons). That's quite a number.

But aircraft are also highly fuel-efficient: modern commercial aircraft have an average fuel consumption that can be less than 3 l per passenger per 100 km (or more than 80 mpg). This figure is comparable to the most efficient cars and is remarkable considering that passengers travel at ~800 km/h.

Figure 4: Considering the average car occupancy in Europe (1.2 to 1.6 passenger per vehicle), the vehicle on the right is more fuel-efficient per passenger x 100 km than the one on the left (and travels ~10 times as fast).

Source: Rundvald in Wikipedia https://fr.wikipedia.org/wiki/Fiat_500_(1957)

Source : Boeing 787 (2022, November 19) in Wikipedia https://fr.wikipedia.org/wiki/Boeing_787

: SECTION 3

How much fuel does the industry emit, and how does it compare with other sectors?

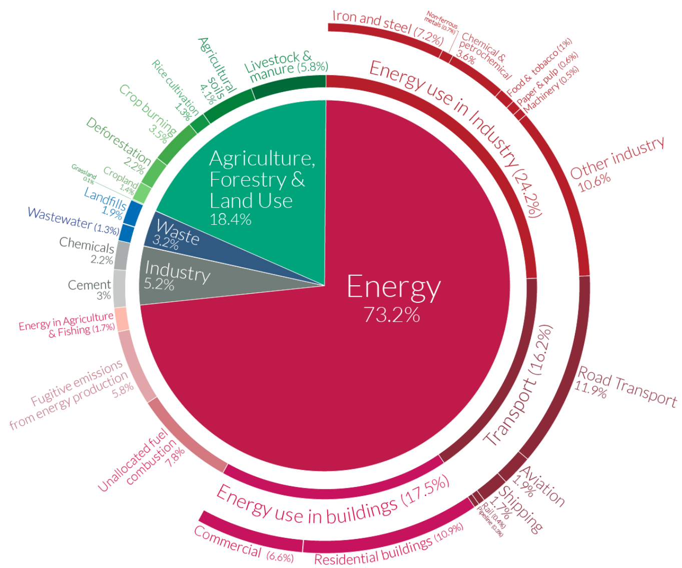
Rather than focusing on a single aircraft, it is much more interesting to look at aviation's total carbon footprint.

Contrary to the general perception, **aviation accounts only for 2% to 3% of the global CO_2 emissions** (more on other warming effects in our next chapter: *Why is aviation scrutinized: aviation growth and other warming effects*).

It is **significant and big enough to care about**, especially when we must collectively reduce our CO_2 emissions by 55% by 2030 to reach the Paris Agreement goal, but it's far from being the major source of CO_2 people think it is.

Even though transportation accounts for a big part of the world's total CO_2 emissions (~16-20%), electricity and heat production, manufacturing, industries, and construction account for more.

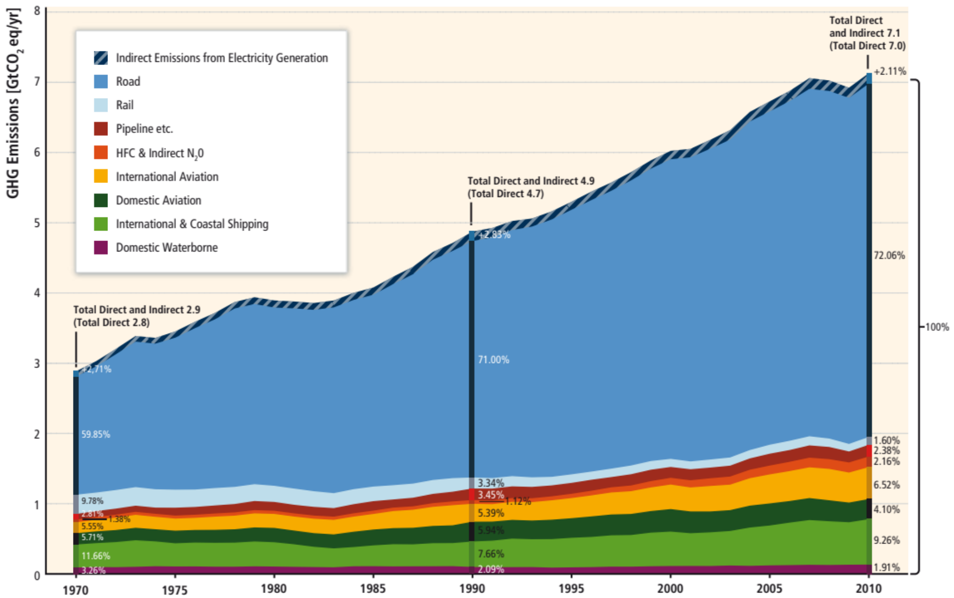
Figure 5: Global greenhouse gas emissions by sector in 2016 (49.4 billion tonnes CO_2eq)



Source: Climate Watch, the World Ressources Institute (2020). ourworldindata.org

Aviation accounts for ~10% of the transportation sector's GHG emissions, and 80% of the sector's increase since 1970 has come from road vehicles.

Figure 6: GHG Emissions since 1970



Source: ipcc.ch

The reason is quite simple: even though an aircraft does burn a lot of fuel, there are not many aircraft in the world. There are roughly 20,000 to 25,000 commercial aircraft in operation. Compare that with the number of cars (~950,000,000), commercial vehicles (~350,000,000), or merchant ships (~54,000), and you'll understand why aviation comes after these means of transportation.

: SECTION 2

Are there substitutes for aviation?

Environmental groups sometimes target aviation because some consider it as non-essential or that it could be substituted by other (cleaner) means of transportation.

Non-essential? That's a very questionable point of view. To quote Guillaume Faury, Airbus CEO, "**Aviation connects and unites people, culture, business**. It makes international trade possible and acts as a vector of development, education, and economic growth." Is fashion that arguably accounts for 8% of CO_2 emissions more essential? Free to everyone to meditate!

Substitution by cleaner means of transportation? Everybody would agree, but only 10% of the 55,000 air routes can be substituted by train.

If we want to continue to enjoy air transport benefits, it's clear that the whole industry must work on decarbonizing aviation as quickly as possible.

Expert Interview

STEPHANE AMANT

Senior Mobility Manager at Carbone 4

My name is Stéphane Amant, I am 47 years old. I have an engineering background in aeronautics, and I graduated from ISAE-SUPAERO.

I worked in the aerodynamic design office and on preliminary projects at Airbus for ten years. In 2008, I joined Carbone 4, a consulting firm specializing in the low-carbon transformation of the economy.

We work with all sectors of activity, particularly the transport sector, including road, rail, air or sea mode, and all its stakeholders. I have been in charge of the center of mobility expertise for five years.

Why is aviation so scrutinized?

CO_2 emissions from the aviation sector represent 2 to 3% of global CO_2 emissions. From this point of view, the air sector is singled out in a somewhat unjustified way because other sectors emit more.
For example, road transport is much more emissive globally, approximately 6 or 7 times more than aviation.

However, keep in mind that most of the world's air traffic is generated by a very small part of the world's population. On top of that, 10% to 15% of air travelers make about 70% of the trips. This figure gives a different perspective on why the sector is a little singled out since there is a question of inequity that is perceived and based on a quantified reality. So as long as we have that, I think there will be some animosity around air travel.

What are the main strategies for decarbonizing aviation?

Collectively at the planetary level, we must all seek to achieve planetary carbon neutrality by the middle of the 21st century. This is the only way to contain global warming below 2 degrees or even below 1.5 degrees. And air transport, like other sectors, must decarbonize rapidly.

To largely decarbonize aviation, the sector is considering breakthrough solutions such as the (low-carbon) hydrogen plane. However, these solutions will hit the market by 2035 at the earliest. The problem is that 2035 is more than ten years away, and even then, we need to decarbonize the entire world's fleet. It will take time before these innovations fully penetrate the market.

The real challenge is to decarbonize very quickly and in significant proportions without waiting for these breakthrough innovations that will play a very important role in the long-term. Until then, we have no choice.

We need to use three other levers: increasing energy efficiency through technology and operations. For instance, eco-piloting solutions will contribute to limiting emissions in the short term. The change of energy vector, so switching from fossil fuels to low carbon energies; and finally, sobriety.

The second lever is to decarbonize the energy carrier, so switching from fossil fuels to low carbon energies. That means replacing fossil fuels with liquid fuels that are low carbon, such as SAF among which electrofuels. Potentially, it could happen tomorrow. But today, the quantities produced are very low, and we can’t scale up the production by snapping our fingers. Nevertheless, we can speed things up, and we should massively invest in developing this lever.

And last but not least, sufficiency. It is a big taboo in our society because we are wired to expand and grow. Today we realize that we are reaching planetary limits on many subjects and must reconsider the place of mankind and the place of the economy to respect these planetary limits. We must consider this new dimension for humanity, which is sufficiency. For aviation, that means questioning air traffic.

What future do you see for aviation?

The future of air travel is not just technological. We must also reflect upon our relationship to aviation, travel, and the utility of travel. For example, does a weekend break to Tenerife have the same social value as an immersive cultural trip for a young person who is spending six months in South America?

It may be taboo today, but it will come to the table in the coming decade. Because once again, if we forget the sufficiency lever, we will not succeed. The sector in a century has made so much progress; it has achieved so many feats. I believe we can invent a new model that will allow aviation's dream to continue by making it accessible to most people. But we need to set limits. I think this debate is very important to have.

CHAPTER 2.

Why Is Aviation So Scrutinized?

Growth and other global warming effects

Why aviation's responsibility exceeds its current CO_2 footprint?

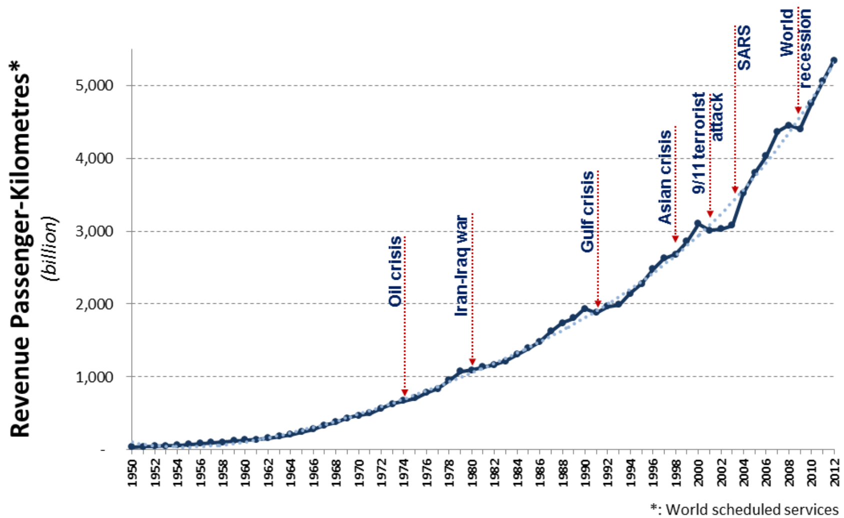
: SECTION 1

Aviation growth

Even though aviation's growth has come to a drastic and dramatic halt with the Covid-19 pandemic, everybody agrees the long-term demand for aviation is unlikely to diminish.

When we look at the past, we can see that aviation's growth has always overcome the various crises this industry has experienced.

Figure 7: The world aviation - 1950 to 2012

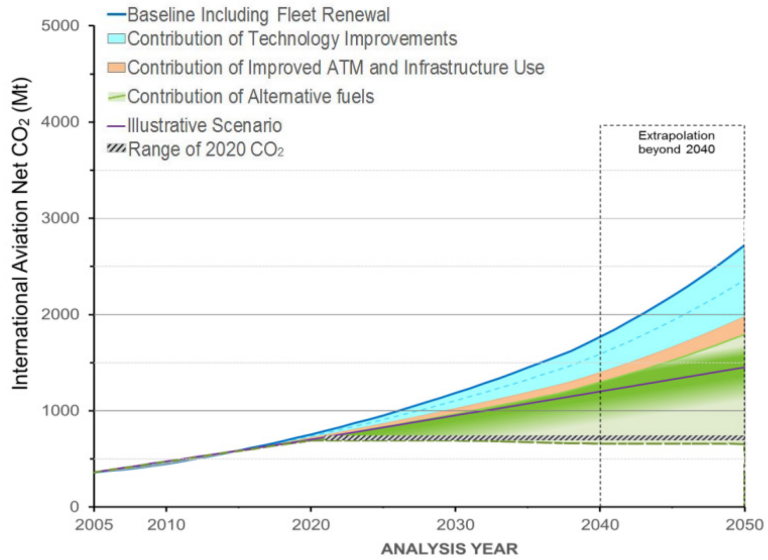


Source: icao.int

The covid crisis is certainly unprecedented, and nobody expects a return to 2019 level before 2024 at best. But if we focus on the longer term, Boeing's most recent market outlook still expects an average 4% yearly growth for the next 20 years.

By projecting this growth, **aviation CO_2 emissions can increase by 200% by 2050**. We are far from the Paris Agreement objectives required to reduce CO_2 emissions by 55% by 2030.

Figure 8: Increase in the level of CO_2 emissions



Source: ICAO Environmental Report 2019

An additional concern with this growth **is that it's hard to find alternate transportation means for aviation.**

We don't have any substitute for airplanes for trans-oceanic traffic. It's hard to imagine what could prevent air travel development in a fast-growing country like Indonesia, which extends over 5000km from West to East and contains 17,000 islands.

Even in a continent like Europe with excellent infrastructures and a dense railway network, it can take days to travel from one country to another by train.

That means that we need to work hard on decarbonizing aviation.

: SECTION 2

Other global warming effects and scientific uncertainty

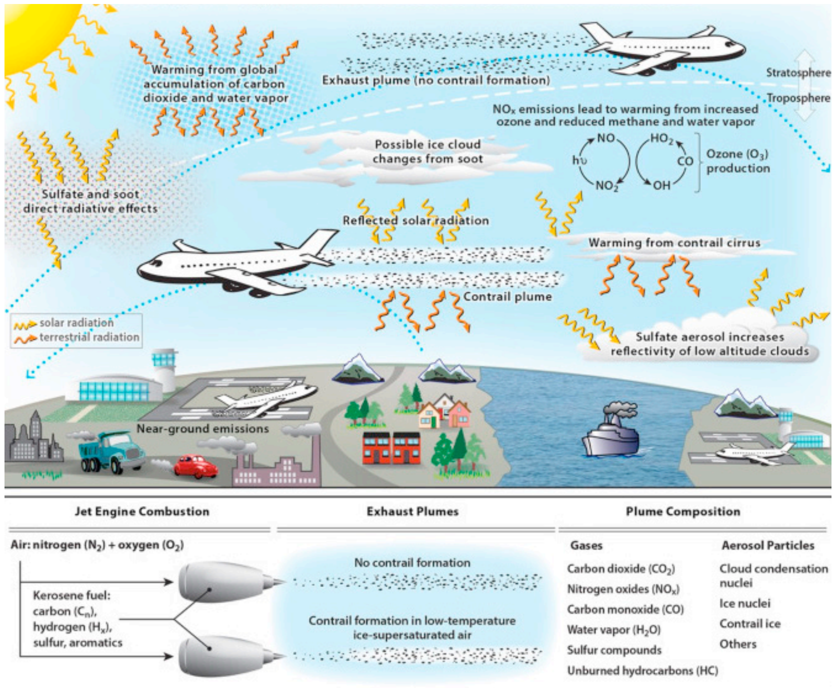
Another issue is that **CO_2 doesn't tell the whole story.** Like all industries, aviation emits other gases that have a warming or cooling effect on our planet.

We rate this effect with effective radiative forcing, which is expressed in watt / m2. The larger the effective radiative forcing, the more the gas contributes to global warming.

Effective radiative forcing can sometimes be hard to estimate because of complex chemical or physical processes that can take place in the atmosphere.

This figure from the recent research paper by D.S. Lee et al. shows some of these aviation-induced emissions processes.

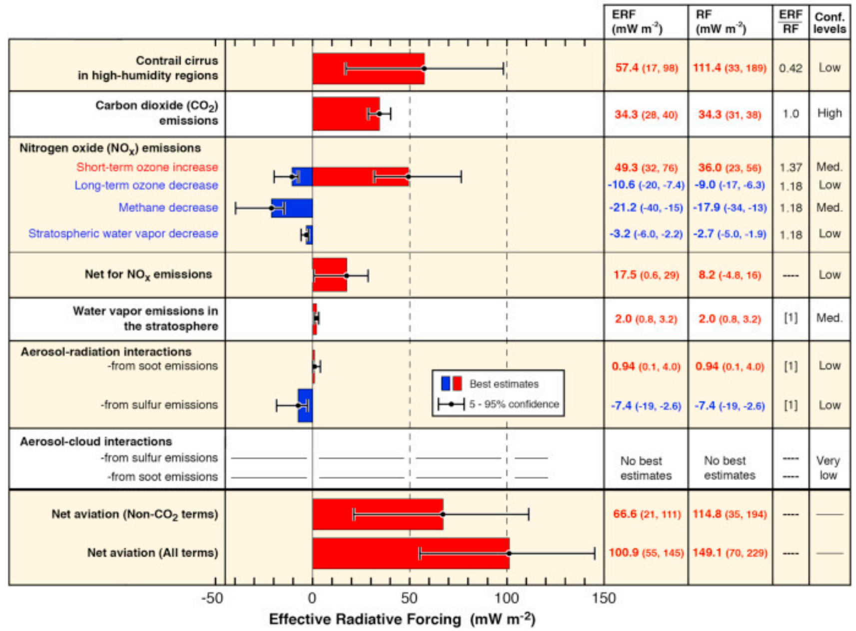
Figure 9: Climate forcings from global aviation and cloudiness



Source: Lee et al, in The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment, Volume 244

The same research paper summarizes the effective radiative forcing from the various aviation emissions and confidence levels.

Figure 10: Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)



Source: Lee et al, in The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment, Volume 244

We can draw several conclusions from this diagram:

- CO_2 is the only aviation-induced greenhouse gas for which we really understand the effective radiative forcing.
- The level of scientific understanding for all others is, at most, medium to low.
- **The non-CO_2 impact of aviation emissions could be twice as strong as the impact of CO_2 emissions**

So, should I triple the tons of CO_2 to get the real impact of aviation? Does that mean that its share of responsibility is closer to 10% rather than 3%?

When computing the share of responsibility, one should compare apples to apples. Either compare aviation CO_2 emissions with all other CO_2 emissions or compare aviation radiative forcing with all other radiative forcings.

And according to this same research paper, **the total effective radiative forcing of aviation (CO_2 and non-CO_2) still accounts for 3.5% of all anthropogenic radiative forcing.**

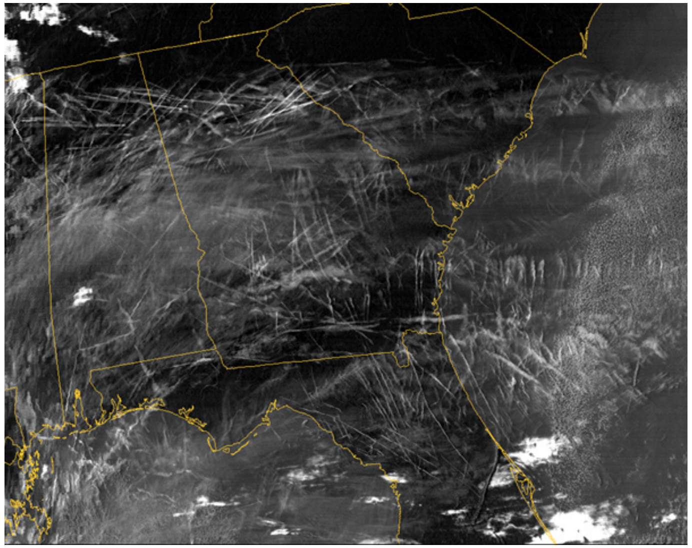
: SECTION 3

A zoom on contrails

Contrails (condensation trails) are the white trails that you can sometimes see in the sky behind an aircraft. In certain conditions of humidity, engine soot and plumes can cause ice particles to nucleate, and this leads to contrail-induced cirrus clouds.

They can be a subject of passionate debates and sometimes myths, one reason being that they are… visible, unlike most greenhouse gases.

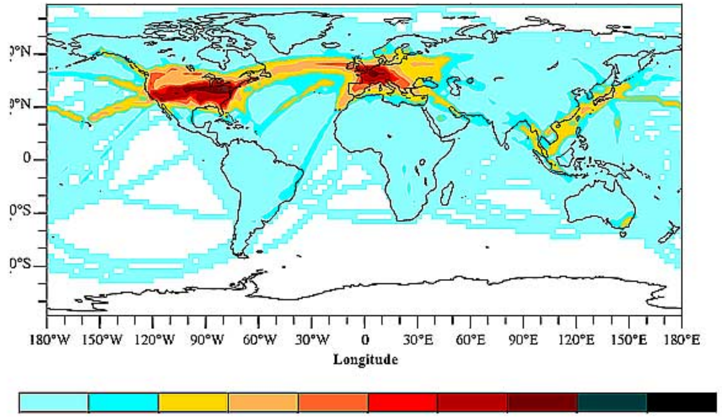
Figure 11: Contrails above the south-east US. by Louis Nguyen, NASA Langley Research Center



Source: earthobservatory.nasa.gov

The Intergovernmental Panel on Climate Change (IPCC) estimates that contrails cover between 0.02% and 0.1% of the Earth's surface with a local maximum of 5% over the eastern USA.

Figure 12: Worldwide contrail coverage



Source: grida.no

Contrails contribute to global warming in two opposite ways: during the day, they cool down the Earth due to the albedo (the reflection of the clouds), but at night they warm it due to the greenhouse effect.

Combining the two effects, it is estimated that **contrails increase global warming, possibly twice as much as aviation CO_2 on a short horizon (20 years), but only half as much as CO_2 on a longer-term (100 years).**

Expert Interview

I am a professor of strategic management at Montpellier Business School and an associate research at Ecole Polytechnique

PAUL CHAMBIARETTO

Professor of strategic management

I am also the director of the «Chaire Pégase», which is the first academic chair in France dedicated to the economics and management of air transport. The main goal of the Chaire Pégase is to connect academia and the air transport industry, so that firms in this industry can build upon the latest research on air transport.

Briefly, what do your past studies tell us?

We investigate how citizens perceive the environmental footprint of air transport and how airlines, airports and manufacturers try to react to this.

In a public report released in February 2020 (and then in a research article published in 2021), we tried to understand the roots of the flygskam (or flight shame) phenomenon.

We show that 90% of French respondents tend to overestimate the contribution of air transport to the global carbon emissions. In the same vein, 95% of respondents underestimate the reduction achieved in terms of carbon emissions per passenger.

In a nutshell, we argue that the air transport industry must pursue its efforts to curb its carbon emissions, but if technology matters, it is not sufficient. The air transport industry must also communicate to citizens, passengers, politicians, associations about its past and current achievements to reduce carbon emissions.

More than 50% of respondents think that the latest generations of aircraft consume more than 10 liters per passenger for 100 kilometers. This is a non sense! So, improving technology is crucial but communicating about these improvements is as important.

Throughout your career, what are significant developments you will remember about global warming?

I don't see any significant moment or development. For me, the improvements made by the air transport industry are gradual and happen every day! As I say to my students, we should not expect that tomorrow a magic technology will solve our problems.

By contrast, it is the sum of all these tiny improvements, each cutting by a few percent's carbon emissions, that in the end allow us to curb carbon emissions significantly.

What future do you see for aviation?

I guess the real challenge for the air transport industry will be its social acceptance. I like KLM former president Pieter Elbers' speech in which he argues that we should not fly more but learn to fly better. This means thinking about when it is relevant to fly or to go by train or use a videoconference.

And in a way, there are many routes (especially short-haul ones) that are not profitable and keeping airplanes on these routes is an ecologic and an economic non-sense. In my opinion, the future of aviation will thus be about learning how to combine different transportation modes and reallocate aircraft to more profitable and relevant routes.

CHAPTER 3.

Aviation Track Record And Roadmap

In this third article, we take a look back at aviation's track-record, its decades-long effort to reduce its footprint, and its roadmap for the future.

: SECTION 1

Aviation track record

The aviation track record of reducing fuel consumption and emissions is remarkable, and this focus on fuel efficiency is nothing but recent.

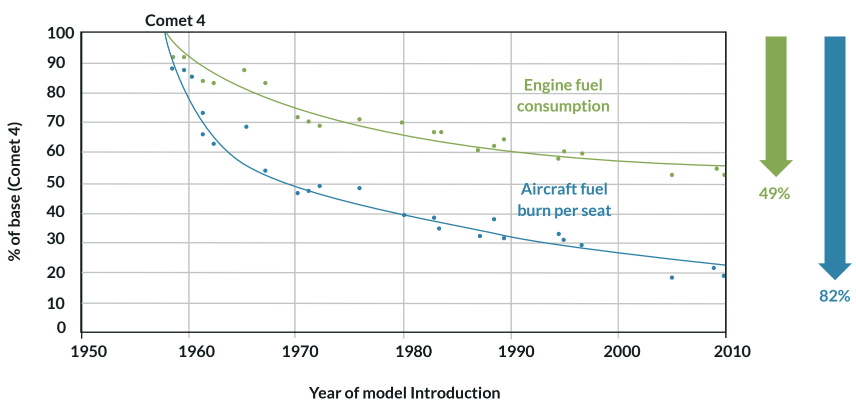
Is it surprising considering that emission reduction is a «relatively new» subject? Well, not really because fuel consumption and emissions are directly related (the combustion of jet fuel being complete, each kg of burnt fuel emits 3.15kg of CO_2).

Fuel has always been on the mind of airplane manufacturers and airlines because:

- **Fuel consumption impacts the range**: the less an aircraft burns, the further it can fly non stop.
- **Fuel is usually the #1 operating cost** in an airline and represents between 20% to 40% of all operational costs, depending on the price of crude oil and the airline's business model.

For these reasons, even when crude oil was cheap, reducing aircraft fuel consumption has always been an obsession. The following figure shows the progress in jet fuel efficiency from 1960 to 2010: **in 50 years, engine fuel consumption has decreased by -49% and aircraft fuel burn per seat by -82%.**

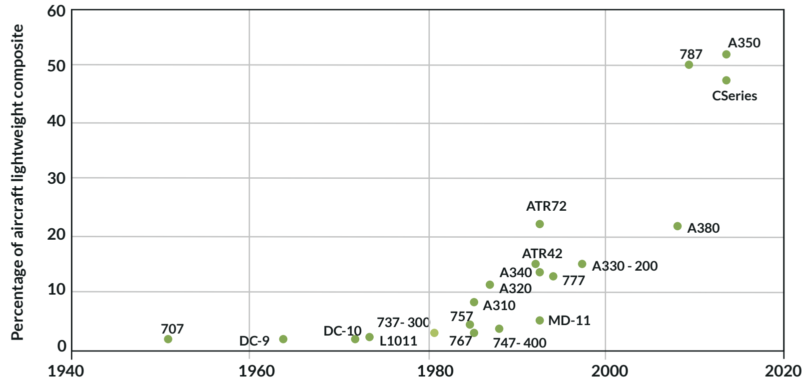
Figure 13: Fuel Efficiency gains since the early jet age



Sources: IPCC Report 1999: Aviation and the Global Atmosphere – ATAG 2050 >> / aviationbenefits.org

And this trend of progress has not stopped. Besides having new engines, the new generation aircraft (A220, A320 Neo, A350, B737Max and B787) are also making progress on weight reduction with more electrical systems and lightweight composites as carbon fiber.

Figure 14: Percentage of aircraft lightweight composite (ATAG 2010)



Source: atag.org

Which industry can claim such progress? Not many probably.

To go back to our Fiat 500 vs. modern aircraft comparison that we used in *Chapter 1: How much CO_2 does aviation emit, and how it compares with other sectors?*, the Fiat 500 from 1957 burned 4.5 liters / 100 km, and the new one from 2007 burns from 3.8 to 6.7 liters / 100 km. No real progress. Besides, individual cars' actual seat occupancy has kept decreasing while aircraft load factors have kept increasing.

Source: Rundvald in Wikipedia https://fr.wikipedia.org/wiki/Fiat_500_(1957)

Source: Alessio Sbarbaro, Fiat 500 (2007). (2022, November 10). In Wikipedia https://fr.wikipedia.org/wiki/Fiat_500_(1957)

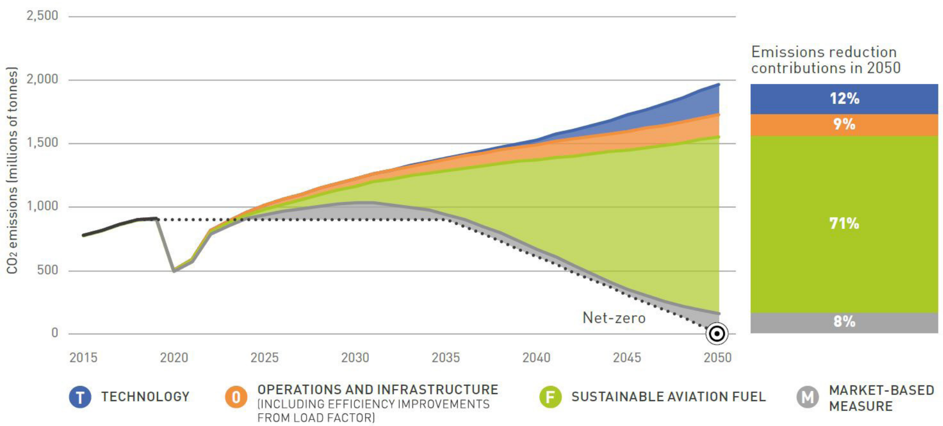
: SECTION 2

Industry roadmap

Now, is this technical progress enough to compensate for air traffic growth? No, because the math of growth is terrible. So what is the industry roadmap to reduce its carbon footprint?

The airline industry has committed to achieving net-zero carbon emissions by 2050.

Figure 15: Schematic CO_2 emissions reduction roadmap



Source: iata.org

: SECTION 3

A mix of solution

The plan to reach this objective is to **leverage a mix of solutions**:

- Improve (known) technology
- Improve operations
- Improve infrastructures
- Use economic measures
- Introduce new-generation technologies and biofuels

The largest potential comes from **new-generation technologies** (such as electricity or hydrogen), which will be the focus of our next four chapters. **But we cannot expect that they are widely available and have an impact before ~2035.**

The same goes for biofuels: even though there are good prospects and existing experiments with **sustainable aviation fuels** (a topic we'll address in *Chapter 8: Sustainable aviation fuels*), **creating an industrial and logistical chain that scales up to the airlines' demand will take years.**

Meanwhile, **continuous improvements** such as the ones we have witnessed in the past (~1.5% fleet improvement per year) are possible with **newer generation aircraft and fleet renewal.**

There is also considerable progress than can be done in **operations and infrastructure** (Air Traffic Management and airports). **The fuel-saving potential is estimated at ~10% for each field or 20% combined** (a topic we'll address in *Chapter 9: Operational and ATM improvements*).

The industry needs one extra lever called **market-based or economic measures** to reach carbon-neutral growth from 2020 on. They consist of schemes such as the European Emission Trading Scheme (EU ETS) or the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

The principle behind these schemes is the following: «If you must reduce your CO_2 emissions by X, but you can't do it by yourself, why can't you pay someone else to reduce theirs by X? This would give the same benefit for the planet».

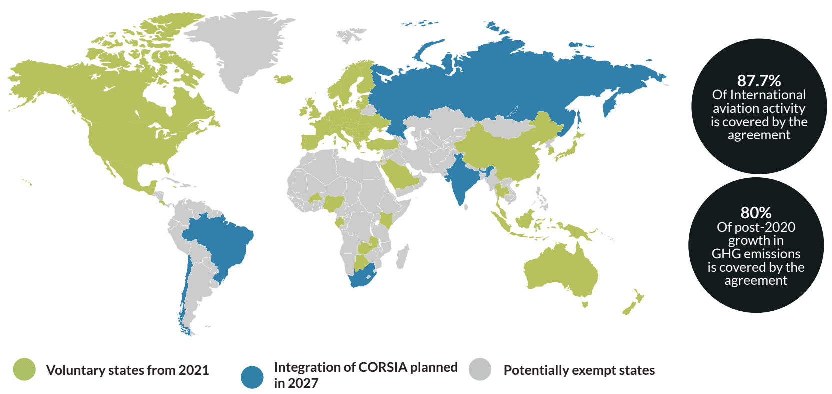
It consists of a market where **organizations that can reduce CO_2 emissions (e.g., by planting trees or by replacing an inefficient carbon-intensive factory with a modern carbon-neutral one) sell carbon offset to other organizations that cannot.**

The European trading scheme was introduced back in 2005 and extended to aviation in 2012. It covers all European routes.

CORSIA is the new international scheme adopted by ICAO (The International Civil Aviation Organization, a United Nations specialized agency) following the Paris agreement. It focuses only on international routes.

In short, CORSIA defines a baseline calculated from the 2019 and 2020 emissions, and all emissions over this baseline will have to be offset when CORSIA's offsetting stage starts (in 2024 for 73 voluntary states and 2027 for all other countries).

Figure 16: Implementation of CORSIA across the states



Source: eco-act.com

: SECTION 4

Can we believe in this industry commitment?

The airline industry has set for itself a very aggressive goal in terms of CO_2 reduction, and we have to acknowledge this.

Now **can it be up to the challenge?**

- Its track record, as we saw before, gives credit to the assumptions for continuous technology improvements.
- The goals set for operational and infrastructure improvement also seem realistic and within reach, as we'll see in *Chapter 9*.
- Market-based measures have been put in place eight years ago for Europe and are being implemented now at the international level.

There remains one challenge: what can we expect from new-generation technologies and biofuels?

Expert Interview

I'm an associate professor at the University of Waterloo.

SUZANNE KEARNS

Professor at the University of Waterloo

At the university, I have a typical professor role meaning I split my time equally between teaching and research. About 20 percent of my time is dedicated to service both the university and the external community.

What has been the focus of my work for the last few years was building connections with other researchers on campus and find out how their work could apply to the aviation sector. I spoke to many professors, sometimes world's leading experts in fields like artificial intelligence or environmentalism. I think what struck me through our discussions is that there's such a need for their research in the aviation sector.

I grew up flying. I started flying when I was 15, airplanes and helicopters, and I was just in love with aviation and still am. But I was trained in a very traditional way. I think many of us in the aviation industry have had a very similar educational path. And I think because of that, we don't necessarily have the tools in our toolbox to address some of the emerging challenges around environmental considerations and sustainability.

So I think the real driving force behind what I've been working on is, instead of starting from the ground up, how do we bring in that cutting edge expertise that is already there and start applying it to support our sector?

Aviation & ecological transition: what are the strengths and weaknesses of the industry?

I think the strength of the industry is our people. I know it comes from both young people who are just getting into the aviation industry all the way up to the leaders. I think all of us have one thing in common: we are very passionate and excited about the field of aviation. That is a true strength because even though we're facing big obstacles, we are motivated to collaborate and innovate. We try to address the issues whilst keeping all the good parts of our sector.

The biggest challenge we're facing in the future of our industry is finding the right balance in sustainability. It's a balance between three pillars: economic, environmental and social sustainability.

I define social sustainability as diversity and inclusion, of course, but I look at it in broader terms to include things like human factors, flight physiology, innovations in training and supporting the workforce and the people in our sector. I think all these aspects form social sustainability.

Social sustainability hasn't always been part of the conversation but I think if you define it in that way, you can start to see how these three elements balance each other. For those like myself who have been in aviation since childhood, I think we were trained in the same way that environmentalism seemed like more work...

However, we can improve our environmental footprints while doing things better to support our people, reduce the negative environmental impacts, and make more revenue.

If you look at the way we train pilots. At the very beginning, they fly in small aircraft, which, of course, burn leaded fuel and create noise. It is also time-consuming because pilots spend a lot of time in briefing or taxi before they actually get to do the training they are set to do.

But look at how innovations are shifting training procedures into either virtual reality or electrically powered simulators on the ground. You can support social sustainability by having a training more targeted to the learners' needs and reducing expenses.

Schools have a higher profit margin on those devices because they are easier to maintain and operate. So, it's an economic benefit for the schools, and you're not burning fuel. You're reducing both carbon and noise emissions. It's an example of a winning strategy where you can pull together and innovate in a way where it's a net benefit to everybody involved.

What is your opinion on the industry roadmap?

I think that I've been excited to see some leading organizations in our sector prioritizing sustainability. In the last 12 months specifically, if you're monitoring as I do, how many times you see the terms aviation sustainability, it's gone to be a priority.

So as far as a roadmap for the future, I think these are the right priorities, the right vision. I guess now it's just about building up that foundation of infrastructure and people and innovation and technologies so that we can achieve those bigger goals.

What future do you see for aviation?

Before the pandemic, we had impending shortages of personnel. We had growing environmental emission issues and a growing flygskam movement. And we also had a rapid evolution of technologies. Our sector was struggling to integrate these safely and efficiently into operations.

When the pandemic hit, I focused on how I could mobilize the research capacity specifically to support some of these big priorities aligned with the three pillars of sustainability so that when the sector would eventually recover, we could help support a more sustainable recovery and a more sustainable future.

I have just recently approved a new research institute called the Water Institute for Sustainable Aeronautics. The institute will have more than 75 different professors from all disciplines across the university. The University of Waterloo is known for its powerful focus on technology, computer science, and engineering. We also have an entire faculty of environment. Its core foundation is to draw together innovations from all of these disciplines. The vision is to mobilize all this research capacity into supporting the sector in its recovery and future.

However the only way it can be effective in doing that is through collaborations with industry, government, policymakers, and other academics. I think the stake for the research field is not to keep behind big walls and closed doors, but to really break those barriers down and form a bridge between the needs of the sector and the academic capacity. And that’s what I hope we can do.

CHAPTER 4.

The Challenges Of Alternative Sources Of Energy

In this fourth chapter, we look at how much energy an aircraft requires, why kerosene has all the right properties, except it’s fossil, and the challenge of alternative sources of energy.

: SECTION 1

How much power does an aircraft require?

A commercial aircraft is a big machine. It weighs a lot, carries a heavy payload (hundreds of passengers with bags and freight), must fight gravity, and moves very fast — all good reasons for requiring a substantial amount of energy.

The following table is from a presentation by Jean Hermetz, in charge of research on new aircraft configuration at ONERA, the French aerospace lab. The numbers are just astonishing.

Figure 17: The amount of energy required by aircraft

	Max Installed Power (MW)	On-board overall energy (MWh)
Leisure aircraft (e.g. DR400)	0.11	1.2
Regional aircraft (e.g. ATR 42)	2.7	55
Single aisle aircraft (e.g. A320)	40	250
Widebody aircraft (e.g. B777)	164	1110

Source: Jean Hermetz – ONERA

It gives the maximum installed power and the on-board energy when the aircraft is loaded at full capacity of its tanks for various types of aircraft.

To make these numbers less abstract, we'll make two comparisons:

- A sub-compact 4-seat conventional car such as a Renault Zoe has a maximum installed power of ~80 kW and will carry an onboard overall energy of ~0.6 MWh.
- A typical civil nuclear reactor produces around 1 GW. This means that **when it flies, a widebody aircraft uses as much power as ~1/10th of a civil nuclear power plant!**

In terms of power, **large commercial aircraft face a double challenge: they require a high level of power, and they need a lot of available energy with a mastered weight.** When you need to fight gravity and move fast, weight is clearly the enemy.

: SECTION 2

Kerosene has all the right properties, except it's fossil

Kerosene has all the right properties to be aviation fuel.

First of all, **it remains liquid and safe at a vast range of temperatures.**

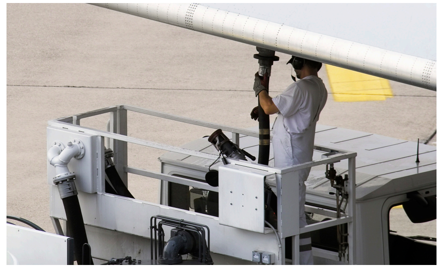
Jet fuel freezes only at -47°C (-53°F), which is compatible with the very low-temperature aircraft meet when they fly high in the atmosphere. And jet fuel's autoignition temperature is 220°C (428°F), making it is safe at very high temperatures.

Secondly, **it is highly energetic: its combustion produces 43.15 Mj/kg**. It means 100 tons of kerosene (the tank capacity of a large aircraft) contain more than 1 GWh of energy. It has **a high density of energy per mass and per volume** (jet fuel's density is ~0.8 kg/liter).

Since weight is the enemy, energy per mass is very important. If the energy per mass is below a certain threshold, it cannot even fight its own gravity.

But, energy per volume is almost equally important. When you look at pictures from commercial jet aircraft since the 1950's, you might have noticed that their shape has very little changed: they are made of a cylinder-shaped fuselage where the passengers sit and of wings that provide the lift.

This is nothing but a coincidence: this shape and the proportion between the fuselage and the wings has reached an aerodynamic optimum for sub-sonic flights. And it so happens that with this optimal aerodynamic configuration, the volume available in the wings is just what it takes to carry the right amount of kerosene for the aircraft's payload and range.



Source: istockphoto.com

This means that kerosene is an excellent energy storage system. Should you substitute kerosene for something else that requires more room because its energy per volume is lower, and you need to reconsider the aircraft's whole shape and aerodynamics, probably for the worse.

And finally, kerosene is cheap. Nature has produced crude oil, and you just need to pay for its extraction, transformation, and handling.

So, kerosene has all the right properties to be aviation's fuel? Yes, except for one big problem: it produces CO_2. Each kg of burnt fuel produces 3.15 kg of CO_2.

As we saw in *Chapter 1: How much CO_2 does aviation emit?*, CO_2 is a powerful greenhouse gas and the main reason why our planet Earth is warming up at unprecedented speed. And unfortunately, when CO_2 is released in the atmosphere, it is there to stay for 300 to 1,000 years.

Because they release quickly large amounts of CO_2 that mother nature took millions of years to capture and transform in its soils, **fossil sources of energy are the enemy of our planet and should be phased out as soon as possible.**

: SECTION 3

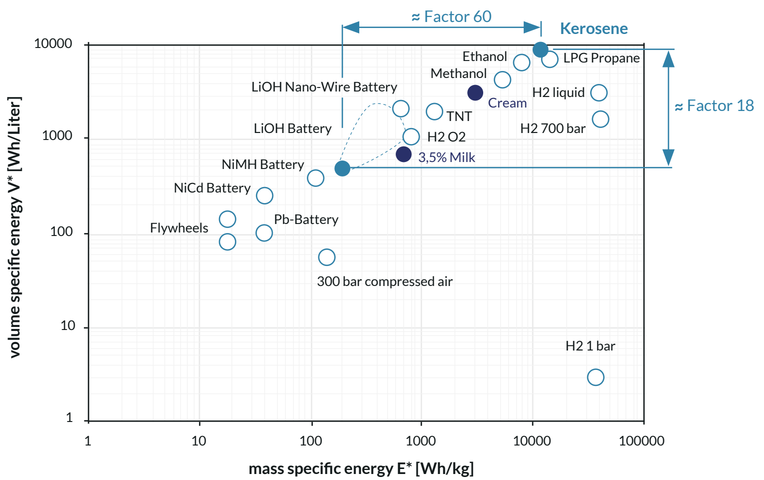
The challenge of mass density and volume density

Why can't we use other decarbonized energy sources, such as green electricity or green hydrogen (produced from renewable sources of energy or nuclear plants)?

We probably will, but we face multiple technical challenges that we'll detail in the next chapters.

One graph from a research paper by Martin Hepperle at the German Aerospace Center shows **the core of the problem: density of energy per mass and volume.**

Figure 18: Volume and mass specific energy characteristics of different energy storage systems.



Source: Martin Hepperle -Electric Flight – Potential and Limitations - German Aerospace Center

This graph positions various energy storage systems on two axes: the x-axis is the energy density per mass: the more to the right, the more energy per kg; the y-axis is the energy density per volume: the higher, the more energy per liter.

One important thing to notice on this graph is that it uses a logarithmic scale: each graduation to the right or the top means an x10 increase.

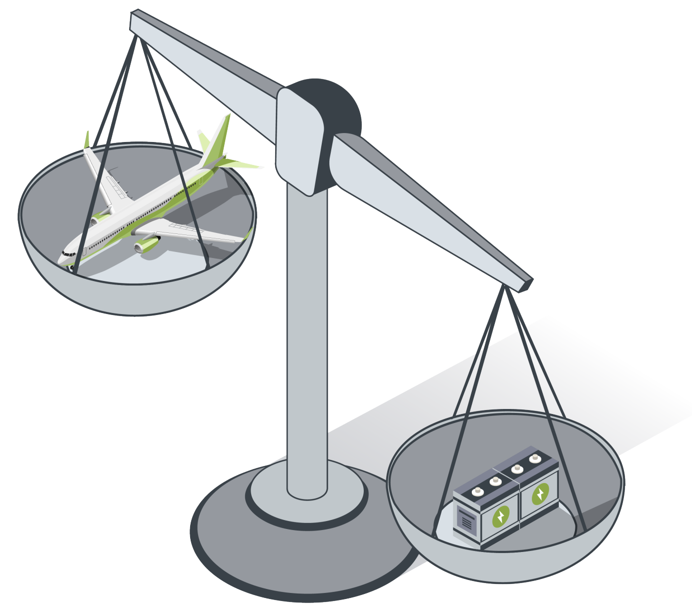
Kerosene is in the top right corner: it **excels in energy per mass and energy per volume.**

Lithium-ion batteries, which are the most modern batteries used for electronic devices or electric cars, **contain 60 times less energy per kg and 18 times less energy per liter!**

If we were to replace jet fuel with batteries on an A320, then the batteries' weight would exceed ten times the maximum take-off weight of the aircraft.

Nevertheless, an electrical aircraft can have interesting properties that we'll detail in our next chapter: *Chapter 5: The electrical aircraft*.

Hydrogen, if it's liquid or under high pressure, stores a lot of energy per kg, making it a good candidate for aviation where weight is the enemy. **But it falls short in terms of energy per volume,** which will inevitably lead to different aerodynamic designs. It also poses other challenges that we'll detail in *Chapter 6: The hydrogen aircraft*.



Source: openairlines.com

Expert Interview

I'm an aerospace sciences professor at ISAE SUPAERO, specifically in the Department of Aerodynamics, Energetics, and Propulsion.

NICOLAS GOURDAIN

Professor at ISAE - Supaero
Dpt. of Aerodynamics,
Energetics and Propulsion
University of Toulouse

My main research topic is the relationship between energy, climate and aviation.

What's the role of education and research on aviation and climate change?

At ESAE SUPAERO, we look at this subject on three different levels. The first one is education. We teach the climate sciences and cover topics such as the basics of biodiversity, the preservation of water resources, and so on.

The second topic is research. There is research from the technological point of view. For example, we look at how to increase the propulsive efficiency of engines used on the aircraft.

We also conduct studies to understand better how aviation contributes to climate change. First, aviation is burning kerosene. So that's the first point. But the second effect, which is a bit less well known, is contrails. Contrails are the artificial clouds generated by the exhaust at the outlet of the engine. Research is still progressing on that topic, and we need to have a better knowledge of these two kinds of effects to understand their impact on climate, especially contrails.

Finally, the last point is about the daily life on the campus at ISAE SUPAERO. For example, how we can heat or cool buildings, but also social aspects like conferences.

Did the pandemic have an impact on the technological transformation underway?

Probably yes. But this is not at the very root of the transformation of the aviation sector. However, we have noticed that the students ask much more questions about the relationship between climate and aviation. That's a question for our students but also us. How can we contribute now to improve the state-of-the-art knowledge on the topic? And can we find the technological levers to reduce the carbon footprint and the environmental footprint of aviation as a whole? This is probably something that has been accelerated clearly by the pandemic.

What future do you see for aviation?

Hard to know! This is not just a question for me, this is a question to ask everyone. What do you want for aviation?

Is it mandatory to still see some aircraft in the sky in the future? I don't know. Maybe. There are indeed plenty of advantages to being able to power aircraft and travel across the sea. Yet, at the same time, there is a price to pay: aviation's carbon and environmental footprint. So, this is a trade-off between these two aspects.

This question should be addressed from a societal point of view, not just from industry, not just from research, not just from students, but we should all have a common debate that is clearly not emerging at the moment.

My personal vision for aviation in the future? Definitely something environmentally friendly.

CHAPTER 5.

The Electrical Aircraft

This fifth chapter looks at what we can expect from battery improvements, different architectures from the more electrical aircraft to the all-electrical aircraft, and exciting designs made possible with electrical engines, in particular distributed electric power.

: SECTION 1

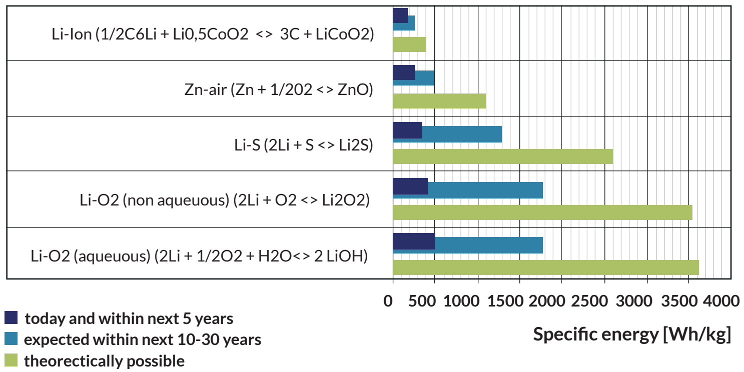
Perspectives in battery improvements

In our last chapter, we saw that current Lithium-Ion batteries were storing 60 times less energy per kg and 18 times less energy per liter than kerosene. This meant that to power an A320, we would need its maxi take-off weight ten times in batteries.

Considering all the efforts put in batteries, driven by the automobile industry, is there hope that the progress curve leads us to viable solutions for aircraft?

Unfortunately, the same research paper from Martin Hepperle at the German Aerospace Center shows that **even though we can expect significant battery technology progress, they will remain insufficient for commercial aviation.**

Figure 19: Current battery technology and expected development.



Source: Martin Hepperle -Electric Flight – Potential and Limitations - German Aerospace Center

This figure shows where we stand today in terms of energy density per mass with the current Li-Ion batteries, the progress we can expect in the next 5 years, the next 10-20 years, and the theoretical limit.

There is a lot of promising research for batteries. Still, even the **technology that has the most potential (Li-02) is not expected to yield more than an x7 improvement compared to current Li-Ion technology in the next 10-20 years.** Beyond this timeframe, its theoretical progress would still be capped at x14.

That is great and very promising for cars or even trucks but falls short of the x60 improvement required for medium-haul commercial aircraft. And we have not even mentioned the time it would take to refill the batteries (even though we could imagine quick battery swaps, for that matter).

: SECTION 2

From the more electrical aircraft to the hybrid aircraft

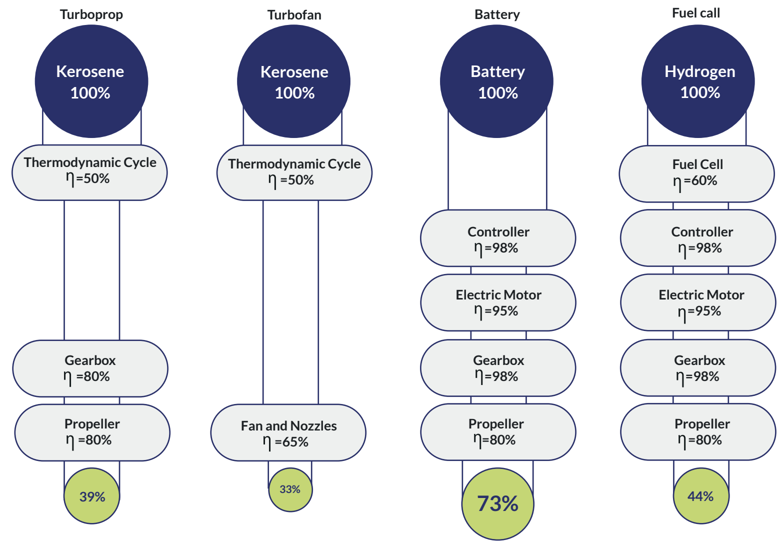
Does that mean that electricity is not part of the future carbon-neutral aircraft? Not at all.

Modern aircraft, starting with the B787, have become what we call "more electrical aircraft." They use batteries to power the onboard systems, which led to significant improvement in weight reductions.

Now, what about the power train?

There certainly is interest there because **electrical engines are much more efficient than combustion ones.** This diagram shows that an electrical power train can be twice as efficient as a conventional aviation power train.

Figure 20: Typical on-board conversion chains with typical component efficiencies and total chain efficiency.



Source: Martin Hepperle -Electric Flight – Potential and Limitations - German Aerospace Center

Hence the idea to introduce hybrid models where aircraft would have combustion engines and electrical engines.

This can be interesting because it's hard to optimize an engine for all phases of flight: the power required at take-off is very different from the power needed during the cruise. The atmosphere (that impacts engine efficiency) is also very different at ground level and very high altitude. In the end, the jet engine's performance is a smart balance between all these constraints.

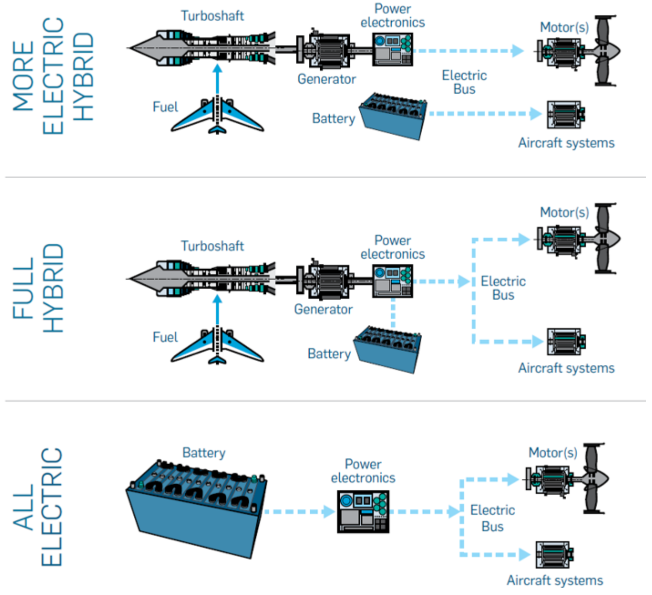
But what if we could use **two types of engines during the flight or complement one engine's power with another one during take-off?**

The increase in efficiency could outweigh the penalty due to the increased weight.

That's the idea behind hybrid aircraft.

This diagram from James Domone, senior engineer at SNC Lavalin's Atkins, shows the architecture of the more electric hybrid aircraft, full hybrid aircraft, and all-electric aircraft.

Figure 21: Potential Propulsion System Architectures



Source: atkinsglobal.com

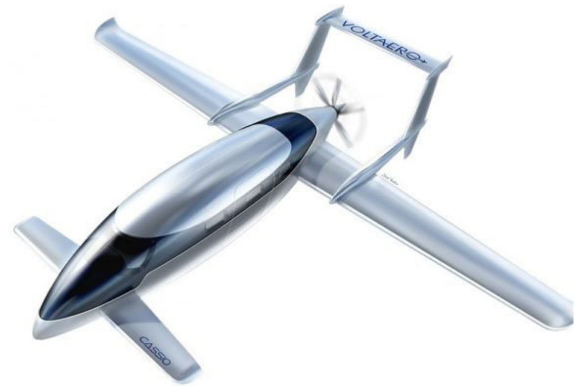
The more electric hybrid aircraft uses a conventional engine that also powers an electrical motor through a generator. In this architecture, batteries are only used to power aircraft systems.

In the full hybrid aircraft, batteries are also used to power the electrical engines. This requires more powerful batteries, but it allows to store extra energy from the main engine when possible and to use this energy at the right time to bring supplemental power to the electrical engine.

Of course, in these hybrid architectures, CO_2 is still emitted because electricity is generated from kerosene combustion, but the power train's overall efficiency can be greatly improved.

VoltAero is a French company developed by former Airbus E-Fan program manager Jean Botti. They flew a demonstrator in October 2020, and their project **aims at developing a hybrid aircraft that could transport 6 to 10 persons on a range of up to 1,200 km.** It will combine a combustion engine with three electrical engines. Short missions could be performed using only the electrical engines, while longer missions would use the combustion engine as range extender. VoltAero argues that the dual power train also adds safety by providing additional redundancy.

Figure 22: The Cassio hybrid airplane from VoltAero



Source: voltaero.aero

: SECTION 3

The all-electrical aircraft

What about the all-electrical aircraft, i.e., an aircraft that would be entirely powered by electricity?

These aircraft already exist and have a commercial future.

André Borschberg, Bertrand Piccard's partner in the Solar Impulse adventure, has founded H55 in Switzerland. They develop fully electric propulsion systems for small (leisure) aircraft.

Figure 23: André Borschberg - H55 Flight Trainer

Source: © H55/ Anna Pizzolante, h.55.ch

In June 2020, EASA certified the first all-electric aircraft: the Pipistrel Velis Electro from Slovenia. Its endurance is sufficient for typical training flights (50 min), and the time to recharge the battery matches the time for debriefing and briefing with the instructor between two flights.

Figure 24 : Pipistrel Velis Electro is the first EASE-certified all-electric aircraft.

Source: pipistrel-aircraft.com

With simplified maintenance and reduced ownership costs, there is no doubt that full electric aircraft will be common for future aviation training.

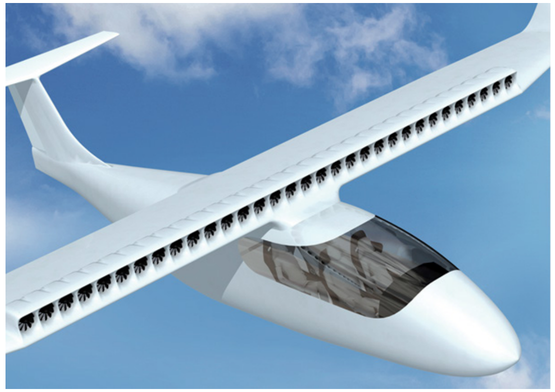
: SECTION 4

Attractive designs made possible with electrical engines

If the all-electrical aircraft seems to be limited to small capacity and short-haul missions, commercial aircraft might see attractive benefits in adding (many) electric engines to their designs.

Onera, the French aerospace lab, developed a virtual "digital aircraft" called Ampere. It is a hybrid aircraft supposed to fly 6 persons on a 500km range. It uses the concept of **distributed electric power.**

Figure 25: The Ampere Project from Onera



Source: onera.fr

By distributing 32 small electrical engines on the wing itself, this design brings many benefits: improved aerodynamics by ingestion of the boundary layer by the engines located on the wing, improved flight control by shifting differential thrust, **improved safety** by pooling functions, and better sizing of the engines (no need to design an engine that must be able to carry a take-off by itself in case of engine failure).

At the Paris Air Show in 2019, Onera presented the Dragon project. It pushes the Ampere concept to the next level and aims at evaluating the benefit of distributed electric propulsion on a jetliner that could fly 150 passengers at Mach 0.8. **They estimate that distributed electric propulsion could reduce CO_2 emissions by 25%.**

Figure 26: The Dragon Project from Onera

Source: onera.fr

: SECTION 5

A tribute to Solar Impulse

Every aviation geek has his/her favorite aircraft. For everybody interested in green aviation, this iconic aircraft is an electric aircraft. Actually, it is much more than an electric aircraft; it is a solar aircraft that can fly perpetually without using any drop of fuel.

This aircraft, **Solar Impulse, the dream made a reality by Bertrand Piccard, managed to fly around the Earth in 2015-2016 using just the energy from the Sun.**

Figure 27: The Solar Impulse Aircraft

Source: aroundtheworld.solarimpulse.com

This wonderful adventure and the message that the **Solar Impulse Foundations carries around the world by promoting the adoption of profitable solutions to protect the environment** is a wonderful inspiration for everybody that is concerned by the future of our planet Earth.

Expert Interview

I am the co-founder/CEO of H55, which is a spinoff of Solar Impulse

ANDRE BORSCHBERG

Swiss entrepreneur, explorer, pilot, and speaker. Co-founder of the Solar Impulse project and H55

At Solar Impulse, I was one of the two co-founders, the CEO and one of the two pilots. I am an entrepreneur by profession and I like to create new projects. I am passionate about aviation. I had the chance to be a pilot in the Swiss Air Force for 20 years. I am married, have three children, and I am passionate about yoga and meditation.

Via Solar Impulse, you have shown that it is possible to fly without a drop of fuel... What do you learn from this achievement? How do you think electric aviation will develop?

Solar Impulse was several things at once. The first goal was to develop an ambassador for clean technologies and for renewable energies.

We wanted to create a new paradigm: to fly an airplane with practically unlimited endurance to show the potential of these technologies.

The endurance is unlimited for two reasons. First, because the plane is electric, it is powered by electric motors fed by batteries, much like electric cars. So, we had excellent energy efficiency and minor energy loss. The second reason is that we collected our energy in flight by solar panels. We were powering it every day so we could make the next 24 hours. The combination of the two made this new paradigm possible. But obviously, that's not what we're looking for in everyday aviation.

However, some of these technologies focused on electric propulsion, i.e., an electric motorization instead of a fossil fuel motorization and powered either by batteries or by a hybrid system. We could produce energy like photovoltaic by combustion engine or a fuel cell with hydrogen. So different ways of bringing energy to something that is electric and very efficient, very simple, very easy to maintain. So, these technologies have a lot of interest.

Does the covid-19 crisis have an impact on the technological transformations underway?

I think so. Aviation and airlines have suffered.

I believe this crisis is precipitating an awareness. On the one hand, governments are asking airlines to make commitments to develop clean aviation. And on the other hand, there is a strong awareness of the problems we create because of the way we live.

The public pressure to develop clean aviation is going to accelerate. People will not stop flying, but they will be more and more sensitive to these issues. They will favor these technologies and then perhaps accept carbon taxes. We are moving towards a «penalization» of polluting technologies.

All this will accelerate and boost the transformation of aviation towards these new technologies.

What future do you see for aviation?

Aviation will be bright. We have many solutions to make the third dimension travels quite acceptable in nuisance, whether it is noise or CO_2.

The technological potential will help us, but it will take time, effort, and financial means.

Carbon taxes will help us to succeed in this transformation. These new technologies allow us to develop new ways of flying. We will gradually move towards autonomous flight, i.e., without a pilot. It will take some time, but it will come. This will allow us to put many more planes in the air, and if they are less polluting and less noisy, they will be more easily accepted.

I am enthusiastic and very confident that the use of the third dimension of our travel will accelerate with these new technologies.

CHAPTER 6.

The Hydrogen Aircraft

This sixth chapter looks at why hydrogen raises such an interest, the different colors of hydrogen (grey, blue and green), possible designs for hydrogen aircraft, and the need for a hydrogen industry.

: SECTION 1

What is hydrogen, and why is it interesting?

Hydrogen (H) is the simplest and most abundant atom in the Universe. It is estimated that hydrogen accounts for 92% of the Universe's atoms and 75% of its mass.

On Earth, hydrogen is mostly present in water (H_2O) but is also present as organic compounds in all living matter and hydrocarbons. It is much rarer as a gas.

The hydrogen gas (H_2) is colorless, odorless, non-toxic, very light, and highly combustible.

What makes it attractive as a carrier of energy is how it can be inflammable with oxygen (O_2) and **produce a large quantity of power with a very simple and clean byproduct: water!**

$$2\,H2 + O2 \rightarrow 2\,H2O + 572\text{ kJ}$$

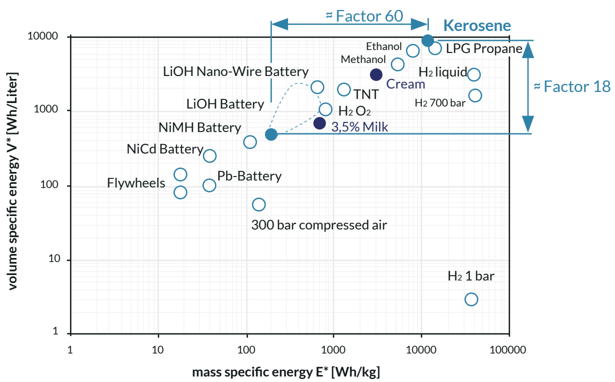
In fact, hydrogen takes its name from this single property (hydro = water; gen = to form).

As a gas, hydrogen is usually not considered a source of energy because it is rare on Earth and challenging to extract. Still, it draws a lot of interest as an energy carrier because:

- Sources of hydrogen (the atom) are abundant and cheap (mostly water)
- Its combustion does not pollute. It produces only water.
- It has a very high density of energy per kg.

This last property makes it especially interesting for aviation, where mass is the enemy. **Its energy density per mass is three times more than kerosene** if you remember this chart from *Chapter 4: The challenges of alternative sources of energy.*

Figure 28: Volume and mass specific energy characteristics of different energy storage systems.



Source: mh-aerotools.de

: SECTION 2

How to produce green hydrogen?

Abundant, cheap, clean, CO_2 neutral? Wonderful! So what's the catch?

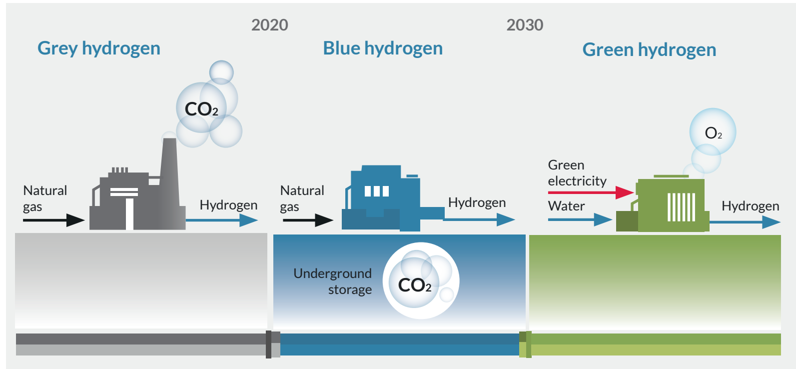
Abundant as an atom, that's true. As a gas, very much less so, which means we need to produce hydrogen (the gas) from other sources. And unfortunately, the most common processes to make it are neither cheap, clean, nor CO_2 neutral...

There are various techniques to make hydrogen: it can be made from natural gas, but it means we continue relying on fossil hydrocarbon, and there is combustion involved that produces CO_2.

The other technique is by electrolysis of water, which requires a lot of electricity. Unless this electricity is produced with renewable energies or carbon-neutral sources (e.g., nuclear), it also means many CO_2 emissions.

Depending on how hydrogen is produced, we speak of grey, blue, or green hydrogen (which is quite funny for a colorless gas).

Figure 29: Depiction of grey, blue and green hydrogen production



Source: gasunie

The hydrogen produced from natural gas is called "grey" hydrogen.

A variant where the generated carbon emissions are captured, stored, and possibly reused is called "blue" hydrogen.

And **the hydrogen that would be produced by electrolysis of water, powered by renewable energy, is called "green."**

Obviously, **it is the green hydrogen that is needed to fight global warming. It is also the most expensive to produce:** when grey hydrogen costs 1,5€/kg to produce, blue hydrogen costs ~2€/kg, and green hydrogen costs 2.5-5.5€/kg.

The challenges of using hydrogen?

Once produced, there are many more challenges to using hydrogen, the first one being hydrogen's low density.

Going back to the figure above, even at very high pressure (700 bars), its energy density per volume is still six times less than kerosene, which means it would require a Beluga as a hydrogen tank on top of an A320. Not sure about the aerodynamics...

An A320 would require a Beluga-size tank to carry high-pressure gaseous hydrogen.

Source: OpenAirlines

Only when it's liquid, hydrogen's density becomes acceptable for aviation, which requires extremely low temperatures (-250°C or 20°K). This is a problem, but solutions exist: Airbus or Boeing, with their spatial activity, have substantial liquid hydrogen experience, even though it's not at the same industrial scale.

Liquid hydrogen still requires three times the volume of kerosene to deliver the same amount of energy. Which necessarily leads to different designs from the ones we are used to.

Figure 30: Photo taken during a visit at NASA KSC chemical processing facility, CC BY-SA 4.0

Source: commons.wikimedia.org - by Raphael.concorde

Possible designs for the hydrogen aircraft

There are many possible designs for hydrogen aircraft, which makes this period open and exciting.

First of all, there are two ways you can use hydrogen: you can either burn it directly in a combustion engine or use a fuel cell which, works a little bit like reverse electrolysis and produces electricity.

With a combustion engine, the design can remain closer to current propulsion designs.

With the fuel cell, you open up attractive new possibilities that we reviewed in *Chapter 5: the electrical aircraft.*

And of course, you can also combine both...

There are also different options to store hydrogen. The safest is to keep the same tube design we are used to with airplanes, but have fewer seats and use the aircraft's rear to store the hydrogen with a safe separation with the passengers. The Airbus concept design below shows how the windows stop just after the wings and leave room for the hydrogen tank.

Figure 31: ZEROe hybrid-hydrogen aircraft concepts

Source: airbus.com

An alternative design is to build a blended-wing body aircraft. Such an aircraft has fascinating aerodynamics properties, can leave a fair amount of room for passengers, and plenty of space in the wings for hydrogen. The challenges are:

- The control of the aircraft which is much more unstable, but there is a lot of experience now acquired from fighters
- The change in infrastructure at the airports to load/unload the passengers

Source: airbus.com

Airbus is investing heavily in hydrogen aircraft with a plan to have a commercial carrier flying by 2035. They are in the early stage and studying many different technologies with three different designs in mind, the two we have seen above and an upper-wing regional turboprop. The latter being "the least ambitious" and the blended wing being the most ambitious.

Source: airbus.com

Carbon neutral or climate neutral?

As we saw in *Chapter 1: How much CO_2 does aviation emit, and how it compares with other sectors?*, CO_2 is the enemy. These aircraft would be entirely carbon-neutral provided green hydrogen powers them.

Would they be fully climate neutral? *Chapter 2: Why is aviation scrutinized: aviation growth and other warming effects?* taught us that other greenhouse gases such as NOx or contrails can affect global warming, even though the scientific certainty is still low. Hydrogen combustion at high temperatures does produce some NOx (Hydrogen fuel cells don't), and the byproduct of hydrogen combustion, water, could cause contrails.

These are impacts that must be better understood and addressed as the industry develops hydrogen aircraft.

: SECTION 5

A hydrogen industry?

Aviation alone wouldn't be able to bring a whole new energy industry behind it.

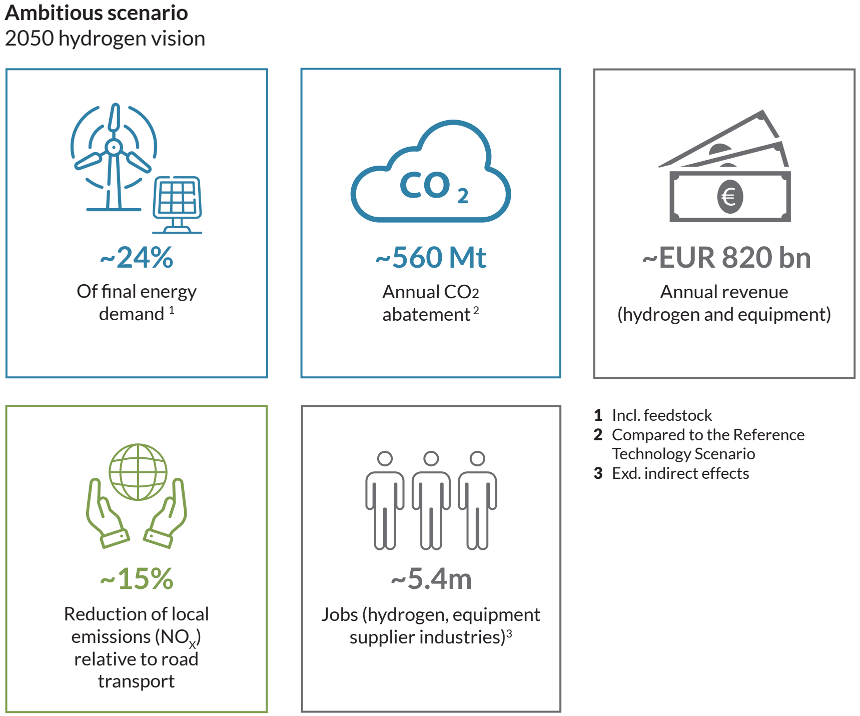
Fortunately, hydrogen gets also a lot of attention for other means of transportation: heavy vehicles like trucks, trains, or ships where the amount of required energy does not seem compatible with batteries, but also cars because it can solve the issue of charging batteries: filling-up a hydrogen car is as fast as filling-up your petrol car, compared to hours of charging for batteries.

Figure 32: A hydrogen charging station for passenger cars.

Source: energies.airliquide.com

That's good news because it means vast prospects can justify the massive investments that will represent the shift from the petrol economy to the hydrogen economy.

Figure 33: Benefits of hydrogen for the EU



Source: fch.europa.eu

In Europe, France and Germany have committed to invest 7 and 9 billion € of public money in the next ten years to bootstrap a hydrogen industry. By 2050, Europe estimates that it would need to invest €180-400 billion for hydrolyzers, solar and wind energy production, transport, and storage. It would then reach 13-14% of its energy mix with hydrogen. The USA and China have similar roadmaps.

These are considerable investments on a 30-year term and substantial changes in the infrastructures: hydrogen pipelines, massive hydrogen storage at the airports, etc.

Expert Interview

I'm James McMicking, ZeroAvia's VP Strategy. ZeroAvia is focused on addressing aviation's climate impacts by developing zero-emission, hydrogen-electric powertrains for aircraft, with growing R&D hubs in the UK and US.

JAMES MCMICKING

ZeroAvia's VP Strategy

In brief, hydrogen fuel cells enable us to electrify aircraft and eliminate the harmful emissions produced by combustion, while hydrogen offers the energy density that aviation needs and that current battery technologies cannot provide. We flew our first prototype aircraft in September 2020, and we will soon begin flight tests using our first commercial model, ZA600 - a 600kW engine which targets aircraft up to 19-seats.

As VP Strategy, I'm responsible for building our growing company's strategic roadmap, bringing together the commercial side of our business with our technical side to plot a pathway to putting a hydrogen-electric engine in every aircraft. Prior to this, I was Chief Strategy Officer for the Aerospace Technology Institute, the UK's flagship organisation for aerospace R&D. I have a background in mechanical engineering, and I have worked with aerospace companies on both the business and technology sides, so it's a privilege to now be shaping the zero-emission future of our sector.

What's exciting about hydrogen aviation right now, what are the latest developments?

The rapid progress that is being made in hydrogen aviation is hugely exciting. Since I began working with the ATI in 2014, I've watched the core technologies of hydrogen-electric powertrains – like electric motors and fuel cells – evolve quickly. Now ZeroAvia is demonstrating those technologies in real-world flight, already with our prototype HyFlyer project and soon with our 19-seat HyFlyer II project. We aim to have passengers taking the first commercial zero-emission flights in 2024. We will be demonstrating our 19-seat powertrain in flight soon, and work is already underway on 2-5MW powertrains required to power aircraft up to 80 seats by 2026.

Your goal is to fly a hydrogen-electric powered aircraft with 200+ seats and 5,000 NM range by 2040. What are your challenges?

Scaling hydrogen-electric propulsion for larger long-haul passenger aircraft requires further investment in fuel-cells, electric motors and the systems that make them work to achieve higher powers and reduce weight. Other companies are looking to use hydrogen in turbine combustion engines, however we see fuel cells achieving superior efficiency, greater impact in tackling climate effects and lower overall running costs. There are no fundamental limits to how much of the existing aviation market can be supported by this technology in time, and we are already investing in the technologies to make this possible.

There is little sense comparing the state of hydrogen-electric and jet engine technology today. One is at the start of the journey, the other has had hundreds of billions spent on it over an 80 year period. Turbofans have become highly complex machines, operating right at the limits of materials, so even small improvements are becoming very costly and difficult to achieve. On the other hand, current fuel cells already outperform turbines for commuter aircraft in terms of efficiency and will be making big strides in a short space of time. The other key aspect is in looking at novel airframe design. Larger aircraft will need to be redesigned to accommodate hydrogen's higher volumetric storage requirements and take full advantage of the new powertrain.

What future do you see for aviation?

If, as a sector, we make rapid tangible progress in developing sustainable solutions, then the future looks encouraging with flight continuing to connect the world and expand in new and exciting ways. By eliminating combustion altogether, hydrogen-electric aviation can fundamentally make better regional connectivity possible. It will be clean, lower cost, lower noise and less polluting, enabling more connections to be made between communities and regions, bringing clean growth and prosperity. Green aviation will drive greater cultural, economic and societal exchange.

CHAPTER 7.

Power-To-Liquid

This seventh chapter looks at synthetic fuel and how power-to-liquid, an emerging technology to produce green synthetic kerosene, could contribute to decarbonized aviation.

: SECTION 1

Synthetic fuel? A new idea? Not really

Synthetic fuels are not unknown to aviation. Actually, they have played a significant role in aviation history, more specifically during WWII by powering up Nazi Germany's Luftwaffe.

Germany realized its dependence on fuel between the two world wars with diesel engines' development replacing steam engines. Very poor in oil reserves but rich in coal mines, it developed the technology to produce synthetic fuel out of coal through various chemical transformation processes.

Nazy Germany invested heavily in this technology and developed a large industrial capacity to produce synthetic fuel.

Source: tracesofwar.com

In 1941, 99% of Germany's aviation gasoline stocks were coming from synthetic fuel.

: SECTION 2

The benefits of synthetic fuel

We saw in *Chapter 4: The challenges of alternative sources of energy* that, **except for being fossil and generating CO_2, kerosene has all the right properties for aviation:** it is stable, supports a wide range of temperature, and has the perfect density of energy per mass or volume.

Source: unsplash.com

What if we could produce green synthetic kerosene?

This would solve many issues we have discovered in the previous chapters on the **electrical** or **hydrogen** aircraft.

There is no need to fully redesign the aircraft nor the engines. It means we don't have to go backward in terms of aircraft capacity, range or speed. It also means we leverage all the existing investment, know-how, and experience that has made aviation the safest means of transportation in the world.

There is no need to modify the airport infrastructure, whether for loading/unloading passengers as we saw for the hydrogen aircraft or storing and distributing energy to the airplane.

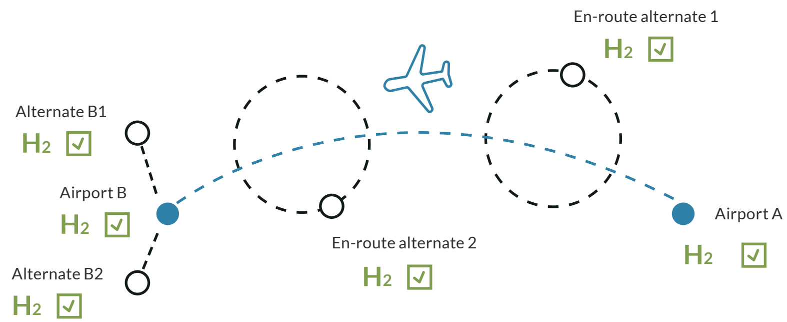
It means airline operations can remain close to what they are today (including short turnaround times, which are crucial for the low-cost carriers' economics). The same goes for maintenance.

Another benefit, and not the least, is a smoother transition path. An electrical or hydrogen aircraft will be restricted to routes where both the departure airport and arrival airports are upgraded to be compatible with these new energy carriers. This will create a daunting chicken-and-egg problem.

When you understand airline flight operations a little more, you realize that to operate a route between two cities, a flight plan must consider many more alternate airports, at destination and en-route, to allow for safe diversion. This means that the origin and destination airports must be compatible with the new technology and many more alternate airports that can be in very remote areas.

New disruptive aircraft will be constrained in operations until the new infrastructures are widely developed, making them hard to operate and unattractive during the early stages of their commercial development.

Figure 34: Flight plan for hydrogen aircraft

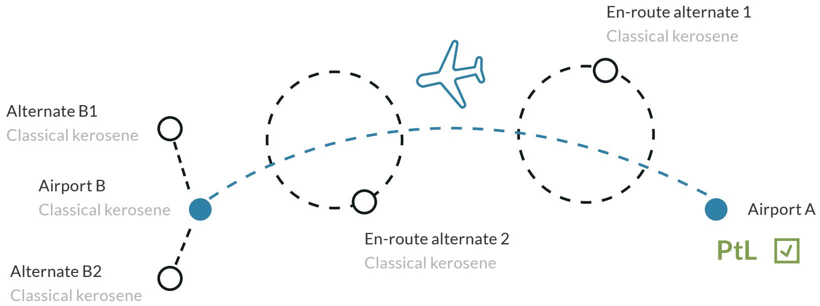


Source: openairlines.com

This simple route from A to B can be flown by a hydrogen aircraft only if airport A and B are H_2-upgraded, as well as all the destination and en-route alternates.

On the contrary, the same aircraft could depart with synthetic kerosene in its tanks from countries where it is available and fly back with traditional kerosene from countries that have not yet converted to this type of green fuel. Its flight plan remains compatible with all existing en-route alternates, which simplifies the operations, especially in ETOPS (Extended-range Twin-engine Operation Performance Standards) flights.

Figure 35: Flight plan for synthetic fuel-powered aircraft



Source: openairlines.com

An airplane that can run on synthetic fuel can fly CO_2-neutral from A to B even if one airport has been upgraded to support the new fuel type.

So, what if we could produce green synthetic kerosene?

: SECTION 3

Power-to-Liquid: the principles

The path to producing green synthetic kerosene is called Power-to-Liquid. It relies on two pillars: do not use hydrocarbons or fossil oil, gas, or coal, and rely on renewable energy for its production.

The principle is quite clever: a synthetic hydrocarbon is produced **mixing hydrogen** (itself extracted from water by electrosynthesis) **with CO_2 captured from the atmosphere.**

Seawater is abundant and cheap, and we all know there is too much CO_2 in the atmosphere.

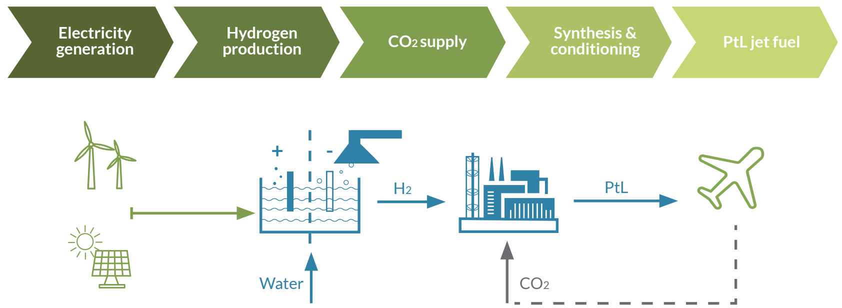
Figure 36: Power-to-Liquid formula

Source: umweltbundesamt.de

The physical and chemical reactions required to produce hydrogen, extract CO² from the atmosphere and combine them to make synthetic fuel require a lot of energy. But if this **energy is produced from renewable sources**, such as solar plants or windmills, or from CO_2-neutral nuclear plants, we then have solutions that are climate neutral.

Of course, the synthetic kerosene combustion will continue releasing CO_2 in the atmosphere, but only as much as what was captured to produce the synthetic fuel, which means we have a **circular carbon-neutral production cycle.**

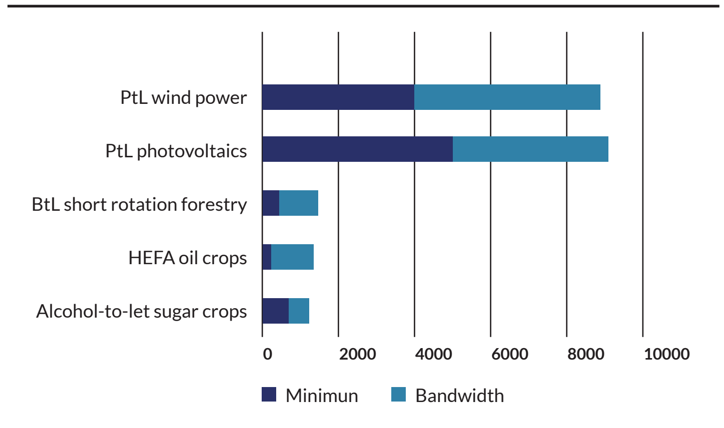
Figure 37: Power-to-liquid relies on a carbon-neutral production cycle.



Source: umweltbundesamt.de

Even when powered by renewable energy sources such as wind power or photovoltaics, power-to-liquid technology's need for the land surface is very much reduced compared to biofuels.

Figure 38: Achievable air mileage for an A320 neo per ha of land (km/(ha-yr))



Source: LBST/BHL, 2016

Power-to-Liquid: where we stand

New jet engines are compatible with biofuels or synthetic fuel blended with traditional kerosene by up to 50%, which means the aviation part of technology is ready.

Concerning the production chain, the technology is estimated to be at TRL 5-8 on the Technology Readiness Level scale.

In 2014, Sunfire, a German PtL technology provider, has inaugurated a demonstration plant in Dresden, Germany, that produces synthetic diesel fuel. It can produce a mere one barrel per day.

In June 2020, a consortium called Norsk e-Fuel (which also integrates Sunfire) was created in Norway to build the first PtL-for-aviation demonstration plant. They plan to produce 10 million liters in 2023 and 100 million liters by 2026.

They would provide a 50% blend to power the five most frequented domestic routes in Norway. The CO_2 savings are estimated to be around 250,000 tons per year.

Source: umweltbundesamt.de

The Norsk e-Fuel demo plant near Oslo will produce enough synthetic fuel to reduce the CO_2 emissions of the top 5 Norwegian domestic routes by 50%.

Expert Interview

I'm the CEO of Nordic Electrofuel

GUNNAR HOLEN

CEO of Nordic Electrofuel

I've been in this organization since early 2016. I've been working for over 30 years in investment banking, and I have built up two companies.

At Nordic Electrofuel, we have evaluated the different technologies for producing power-to-liquid, and we have now started basic engineering. We will finalize that in September 2021 and then plan to start construction.

Power-to-liquid: where we stand and what's next?

I think we had a good development for power-to-liquids. When I started in the company, many people viewed us as a curiosity. People have been aware that it could have been a solution for airlines and other long transportation.

However, at that stage, it was viewed as too expensive. With others in this sector, we work on utilizing the energy better and how we can produce it more efficiently. We have succeeded. Now, our power-to-liquid is one of the leading solutions for long-distance transport and particularly aviation. We can say that because we have an acceptable cost level. There are reasons to believe that we can get down on energy consumption and bring the cost further down.

Power-to-liquid is part of the aviation decarbonization solutions. Hydrogen is also part of the solutions. However, currently, there is no infrastructure for hydrogen. It faces many challenges like explosiveness and pressurization, which makes it a complicated and expensive solution.

The great thing with power-to-liquid is that you can use the current infrastructure. We can work with the airline industry, and it makes perfect sense to continue to use the aircraft we have.

More and more countries want to fly regularly. After the Covid-19 pandemic, aviation will start to increase again. So it's not an option, we both want and need to fly. We need renewable fuels. I have been talking to many experts and one thing is sure: it's limited how much renewable fuel we can get from other sources like cooking oil, for example. So I think power-to-liquid is the technology where we can scale and get a lot of volumes. The cost of producing is coming down.

What role can power-to-liquid play in decarbonizing aviation?

It can play a significant role. It already fits with the existing infrastructures. It has a positive impact on global warming because it completely eliminates the particulate emissions which is more severe than the emissions from the CO_2.

So consequently, the use of power-to-liquid has a triple positive impact for avoiding global warming. I think very strongly that it is the leading solution for making aviation sustainable.

It's limited volumes for the moment, but we will develop it further and make it more efficient and scale it to be potentially the main fuel source for aviation.

What future do you see for aviation?

Aviation will continue to grow. After the Covid-19 pandemic, everybody will want to travel again. However, maybe we will see a reduction of business trips as many meetings can be made virtually.

However, it is different to meet people personally, and I think it is essential to travel to look people in their eyes.

CHAPTER 8.

Sustainable Aviation Fuels

After looking at upcoming solutions such as electrical aircraft, hydrogen aircraft, or power-to-liquid, the next two chapters of our series of articles will look at solutions that can be implemented today.

This eighth chapter looks at sustainable aviation fuels.

: SECTION 1

Biofuel or sustainable aviation fuel?

While biofuel is probably better understood by the general public, the aviation industry prefers to use the term sustainable aviation fuel, or SAF.

There are two reasons for this: not all biofuels are sustainable, and not all sustainable fuels have a biological origin.

To be considered sustainable, an alternate fuel must meet strict criteria: generate no or little greenhouse gas on its lifecycle, prevent depletion of natural resources, and contribute to local social and economic development. Besides, it should not compete with food or water.

Biofuels derived from palm oil, for example, usually do not match these criteria because their production contributes to deforestation and endangers biodiversity. Corn fuel does not qualify either because it competes with lands and crops used to feed human beings or animals.

Figure 39: A picture of Indonesia from space, showing the impact of fires deliberately set to clear land for palm oil.

Source: earthobservatory.nasa.gov

SAF go through a demanding certification program run by independent bodies to make sure they meet these criteria. RSB (Roundtable on Sustainable Biomaterials), one of these certification bodies, has defined 12 criteria presented in the following illustration.

THE 12 CRITERIA USED BY RSB TO CERTIFY SUSTAINABLE AVIATION FUEL.

Principle 1: Legality
Operations follow all applicable laws and regulations.

Principle 2: Planning Monitoring & Continuous improvement.
Sustainable operations are planned, implemented and continuously improved through an open, transparent and consultative impact assessment and management process and an economic viability analysis.

Principle 3: Greenhouse Gas Emission
Alternative fuels contribute to climate change mitigation by significantly reducing lifecycle GHG emissions as compared to fossil fuels.

Principle 4: Human and Labour Rights
Operations do not violate human rights or labour rights, and promote decent work and the well-being of workers.

Principle 5: Rural and Social Development
In regions of poverty, operations contribute to the social and economic development of local, rural, and indigenous people and communities

Principle 6: Local Food Security
Operations ensure the human right to adequate food and improve food security in food insecure regions.

Principle 7: Conservation
Operations avoid negative impacts on biodiversity, ecosystems and conservation values.

Principle 8: Soil
Operations implement practices that seek to reverse soil degradation and/or maintain soil health.

Principle 9: Water
Operations maintain or enhance the quality and quantity of surfae and groundwater resources, and respect prior formal or customary water rights.

Principle 10: Air Quality
Air pollution shall be minimised along the whole supply chain.

Principle 11: Use of Technology, Inputs & Management of Waste
The use of technologies shall seek to maximise production efficiency and social and environmental performance, and minimise the risk of damages to the environment and people.

Principle 12: Land Rights
Operations shall respect land rights and land use rights.

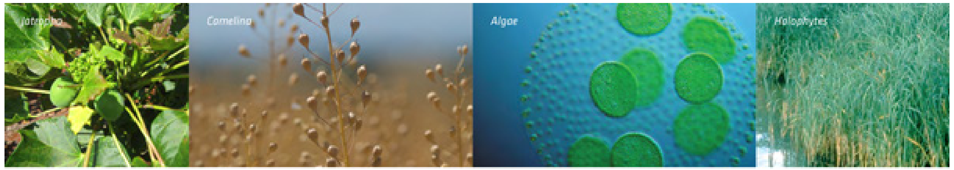
Source: rsb.org

: SECTION 2

Examples of sustainable aviation fuel

Sustainable aviation fuel can have various origins, including non-biological sources, such as municipal waste.

Attractive crops for sustainable aviation fuel include Jatropha, Camelina, Algae, and Halophytes.



Source: aviationbenefits.org

Jatropha seeds are rich in inedible lipid oil that can grow on arid land. As a consequence, they do not compete with food sources nor arable land.

Camelina is a fast-growing crop with high lipid oil content. It can be grown on the same land used to grow wheat, for example, but **will not compete with cereals because it will be planted at periods of the year where the land would be otherwise be left unplanted** as part of the regular crop rotation routine.

Algae are a promising source of feedstock because **they can grow in the desert or areas contaminated with saltwater** that are usually unfit for agriculture. **They grow fast** and can produce 15 times more oil per acre than other crops.

Finally, **Halophytes develop in a saline environment** in areas where other types of plants would not grow.

Waste, whether solid or in the common form of **used cooking oil, is even more interesting because it also contributes to recycling a byproduct of our modern cooking lifestyle, which disposal can otherwise produce harmful environmental effects.** EASA estimates that by recycling used cooking oil from European restaurants and households, it could produce 1 million tonnes per year of SAF. This would represent 2% of the European Union's need for jet fuel.

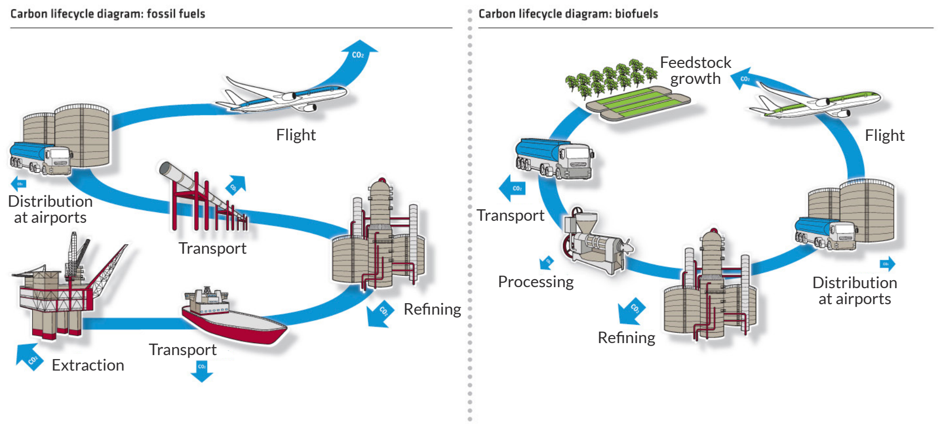
Source: unsplash.com

: SECTION 3

The carbon footprint of sustainable aviation fuel

Like fossil fuels, sustainable aviation fuels release CO_2 in the atmosphere when burnt in a jet engine. But when we look at the global lifecycle, the emitted CO_2 is captured back by the feedstock growth that produces the biofuel. The cycle is thus neutral on a short timeframe and sustainable.

Figure 40: Carbon lifecycle with fossil fuels and biofuels



At each stage in the distribution chain, carbon dioxide is emitted through energy use by extraction, transport, etc...

Carbon dioxide will be reabsorbed as the next generation of feedstock is grown.
Note: *the diagram above does not demonstrate the lifecycle process of SAF derived from municipal waste*

Source: aviationbenefits.org

When considering the whole production-to-use cycle, SAF are not 100% carbon neutral because their harvesting, transformation, and transportation still require fossil energy that generates CO_2. Still, this part is limited compared to the net CO_2 emissions of traditional jet fuel. When all the emissions are accounted for, it is estimated that **sustainable aviation fuel can reduce the carbon footprint by 80%.**

: SECTION 4

Drop-in fuel

If you have been working in an airline, you know that the #1 motto is "Safety first."

Sustainable Aviation Fuel must go through a comprehensive process to be approved as an alternative to traditional jet fuel. Eight pathways to produce SAF have been approved by the ASTM (American Society for Testing and Materials) for drop-in fuel, meaning they can be mixed with conventional jet fuel in a proportion that can go up to 50%.

Figure 41: The Eight approved pathways for drop-in SAF

ASTM APPROVED PROCESS	DATE OF APPROVAL	FEEDSTOCK OPTIONS	BLENDING RATIO BY VOLUME
FT-SPK Fischer-Tropsch hydro-processed synthesised paraffinic kerosene	2009	**Lignocellulosic biomass** Agricultural and forestry residues (e.g.sugar-cane bagasse, sugar cane trash, treetops, corn stover and corn stalks) and municipal waste	Up to 50%
HEFA-SPK Synthesised paraffinic kerosene produced from hydro-processed esters and fatty acids	2011	**Oils and fats** Camelina, jatropha, castor oil, palm oil, animal fats, and used cooking oil	Up to 50%
HFS-SIP Synthesised isoparaffins produced from hydro-processed fermented sugar	2014	**Microbial conversion of sugars to hydrocarbon** Sugarcane, cassava, sorghum, and corn	Up to 10%
FT-SPK/A Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	2015	**Lignocellulosic biomass** Agricultura and forestry residues (e.g. sugar cane bagasse, sugarcane trash, treetops, corn stover and corn stalks) and municipal waste	Up to 50%
ATJ-SPK (isobutanol) Alcohol-to-jet synthetic paraffinic kerosene	2016	**Biomass used for sugar production and ligno-cellulosic biomass** Sugarcane, cassava, sorghum, corn, and ethanol	Up to 50%
ATJ-SPK (ethanol)	2018	**Biomass used for sugar production and ligno-cellulosic biomass** Sugarcane, cassava, sorghum, corn, and ethanol	Up to 50%
CHJ Catalytic hydrothermolysis synthetic jet fuel	2020	**Triglyceride-based feedstocks** Waste oils, algae, soybean, jatropha, camelina, and carinata	Up to 50%
HHC-SPK High hydrogen content synthetic paraffinic kerosene	2020	**Biologically derived hydrocarbons** Algae	Up to 10%

Source: rsb.org

: SECTION 5

Current experiments

Since 2011, ~250,000 commercial flights have used a blend of sustainable aviation fuel.

As of today, a limited number of airports are proposing SAF to airlines: Oslo was first in 2015 and has now been followed by Bergen, Brisbane, Los Angeles, San Francisco, and Stockholm.

World Energy has recently acquired the AltAir refinery in Paramount, Los Angeles. This refinery has been converted to produce SAF out of used cooking oil and produce 170 million liters per annum.

In 2019, United Airlines president, Scott Kirby, has declared: "Investing in sustainable aviation biofuel is one of the most effective measures a commercial airline can take to reduce its impact on the environment." They have secured a contract for ten million gallons supply of SAF with World Energy.

Source: openairlines.com

In late 2019, Air France announced that it would fuel flights from San Francisco airport using a blend of traditional and SAF fuel. San Francisco was selected because the airport's hydrant system allows it, and the carbon footprint of transporting the SAF from the Paramount refinery in California is limited.

Within ICAO, 30 airlines have created the Sustainable Aviation Fuel User Group (SAFUG) to promote the development, certification, and commercial use of sustainable, lower carbon aviation fuels[6]. They include Air China, AeroMexico, Air France, Air New Zealand, Alaska Airlines, ANA, AviancaTaca, British Airways, Cargolux, Cathay Pacific, Etihad, GOL, GulfAir, JAL, Jet Blue, KJM, Lufthansa, Qantas, Qatar Airways, SAS, Singapore Airlines, South African Airways, TAM, TUI Travel PLC, United, Virgin America, Virgin Atlantic, and Virgin Australia.

: SECTION 6

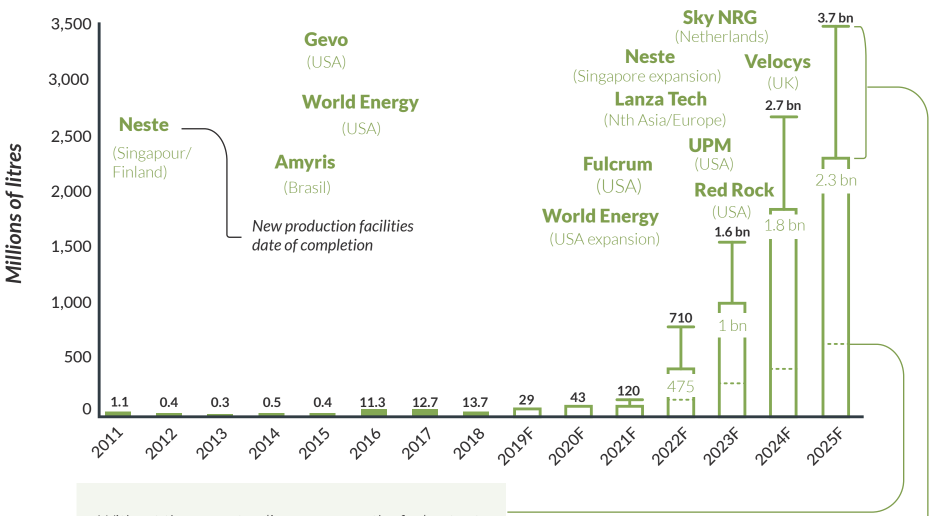
The need for industry and public incentives

Since sustainable aviation fuel seem to be a solution that can be deployed today, what's preventing it's more widespread development? **Today, sustainable aviation fuel only account for 0.1% of global jet fuel use.**

The first hurdle is the lack of infrastructure, but the challenge can be addressed. Compared to road transport (See *Chapter 1: How much CO_2 does aviation emit, and how it compares with other sectors?*), there is a limited number of commercial aircraft operated in the world (~25,000), a limited number of airlines (< 2,000), a limited number of airports and as a consequence a limited number of aviation fuel depots. ATAG estimates that 180 fuel depots account for 90% of the aviation passenger traffic.

The second hurdle is the lack of production capacity, even though there are more and more projects being developed.

Figure 42: Sustainable aviation fuel ramp-up. Estimate of annual global production potential of SAF, as new production facilities come on stream. IATA analysis.



Without the correct policy measures, the fuel output could be optimised go to other forms of transport - the lowest dotted line represents the least uptake of SAF (output goes to road transport.)

This analysis does not include SAF capacity that has not yet been announced, is in concept stage, nor the impact of aggressive policy support which could double the potential by 2025.

Difference between a low take-up of SAF from production facilities (lower number) and a high take-up, driven by policy and airline decision-making. The top number represents the full possible output of SAF production already in operation, under construction or in advance planning and financing.

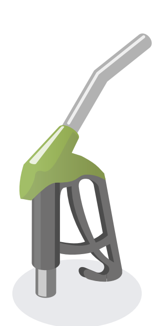
Source: aviationbenefits.org

ATAG estimates that by 2025, 2% of aviation fuel needs could be supplied by SAF.

Figure 43: Global sustainable aviation fuel production ramp-up
Building the facilities needed to produce SAF: 2% of total aviation fuel supply possible by 2025

Source: aviationbenefits.org

These are still small numbers, the reason for that being that sustainable aviation fuels are much more expensive than traditional fossil fuel (2x+). This is a significant hurdle considering that fuel represents 20% to 30% of the airlines' operating costs, that air travel demand is very price-sensitive, and that the market is extremely competitive (and will probably be even more so after the Covid-19 crisis).



Source: openairlines.com

Under the EU ETS or ICAO regulations, an incentive exists for airlines to use biofuels. Airlines must buy carbon allowances to compensate for their CO_2 emissions, but biofuels are exempt or account for less CO_2 emissions, thus reducing their burden. But the ratio between the SAF extra cost and reduction in carbon allowances does not strike a favorable balance.

In an unusual move, the aeronautics, airline industry, and energy providers are all asking for regulations mandating the use of a certain proportion of biofuels. They consider it to be the only way to create a viable supply chain and guarantee a level playing game for all actors. The difficulty being that this incentive or mandate should be as global as possible to prevent competition distortion.

Some countries have taken initiatives, such as Norway, which mandates that the country's aviation fuel incorporate at least 0.5% of advanced biofuels. As part of its "Fit for 55" legislative package, the EU is proposing a mandate expected to start in 2025 with a minimum volume of SAF at 2%, increasing in five-year intervals to ultimately reach a minimum volume of 63% in 2050.

In early September 2021, the U.S. announced a new sustainable aviation fuel goal to increase the production of SAF to at least 3 billion gallons per year by 2030, by proposing tax credits and funding.

Expert Interview

I have been in the aviation industry for over 20 years, specializing in risk analysis, first geopolitical, then economic, and environmental.

MARGAUX THOYER-ROZAT

Sustainable Aviation Fuel Manager at Air France

My name is Margaux Thoyer-Rozat, I am 37 years old. I currently work as a Sustainable Aviation Fuel Manager in the Fuel and SAF Procurement Department at Air France.

I graduated from the Arts et Metiers Institute as an Engineer and got a Specialized Master's degree in International Project Management at ESCP Business School. I have been working at Air France since 2009 in various positions: Engine Maintenance Buyer, Network Planning Analyst and Global Corporate Account Manager. I am passionate about the importance of the ecological transition for the future of the generations to come.

Could you tell us about the sustainable aviation fuel program launched by Air France-KLM?

In January 2021, the Air France-KLM Group launched its "Sustainable Aviation Fuel" program dedicated to corporate customers. It is an innovative program that allows companies to actively participate in tomorrow's sustainable travel. After estimating the CO_2 emissions associated with their travel, Air France-KLM's corporate customers can determine an an nual contribution they wish to devote to the SAF (Sustainable Aviation Fuel) Corporate program.

The Air France-KLM Group invests all these funds to contribute to the supply and use of sustainable aviation fuel. These investments support the creation of a SAF sector that guarantees more eco-responsible air transport.

Air France KLM is committing to use at least 10% of SAF in 2030. This SAF will contribute to our Science Based Targets Objectives to reduce by 30% the CO_2 emissions per passenger km in 2030 compared to 2019.

What are the main challenges of sustainable aviation fuel?

There are mainly three major issues that hinder the use of SAF today.

The first concern is the low production available in the world. This is explained by the significant investment required from the oil industry and by a very profitable road biofuel model production in Europe that does not encourage producers to direct their production and investment toward aviation needs.

At the same time, we observe that the volumes of Used Cooking Oil available (which are the primary biomass used, with the HVO technology of hydro treatment of oil) are becoming scarce in Europe with a more protectionist American market.

The second challenge is SAF's economic viability, which is 3 to 8 times more expensive than fossil kerosene. Kerosene represents, on average, 25 to 30% of airlines' costs. SAF-induced additional costs represent hundreds of millions of Euros. These are immediately and strongly impacting airlines' profitability and creating a real distortion of competition between airlines or areas in the world.

Our collective capacity to address the challenge is critical in developing the SAF pathway. Other countries have managed to find mechanisms that support all actors in the value chain, from the producer to the biomass supplier to the user. They are the same countries where you find production today (Netherlands and US mainly). Encouraging a competitive market is key. So is bringing out new players and supporting research to promote the emergence of complementary SAF technologies such as E-fuels, which have already been certified.

The third challenge is sustainability. It is essential that the various SAF productions can guarantee a significant level of CO_2 emission reduction.

This is closely linked to the sustainability of resources (plants, algae, waste, waste oils, ...) and must be guaranteed by independent certifications such as RSB or ISSC that ensure non-competition food, minimal impact on land use, respect for biodiversity, and the traceability of the product from end to end.

What future do you see for aviation?

Public opinion is putting pressure on aviation for its environmental impact.

As an industry, we have set ambitious targets to reach Net Zero in 2050 and to comply with the Paris Agreement. To do so, all levers will need to be activated.

More efficient aircraft with newer engines and designs, optimization of their usage (more direct routes, less weight on board, ecopiloting...), and of course, the generalization of SAF usage in our Aircraft.

In order to keep this essential means of transport, essential for the people and the economy, it is crucial that the whole industry and our partners (states, oil suppliers, ...) embrace these sustainable objectives.

So, I do see a sustainable future for aviation!

CHAPTER 9.

Operational Improvements

This ninth chapter looks at a sum of initiatives or fuel-saving best practices that can significantly improve the fuel efficiency of an airline's operations, **reduce its carbon footprint, and at the same time improve its bottom line by alleviating its #1 operating cost.**

: SECTION 1

Operational improvements

Operational improvements are measures that airlines can implement to execute their operations more efficiently without modifying their fleet or infrastructures.

Based on benchmarks it has conducted since 2004 on more than 100 airlines, IATA estimates that these operational measures **can reduce the airline's fuel budget by 2-6% for airlines that already have a structured fuel efficiency program in place, and up to 14% for airlines with no such program in place.**

Source: iata.org

These operational measures are described in publications such as IATA Guidance Material and Best Practices for Fuel and Environmental Management, Airbus series of Getting to Grips with Fuel Economy, or Boeing Aero magazine. The most recent publication on the matter is **OpenAirlines' Green Airlines Fuel Book.**

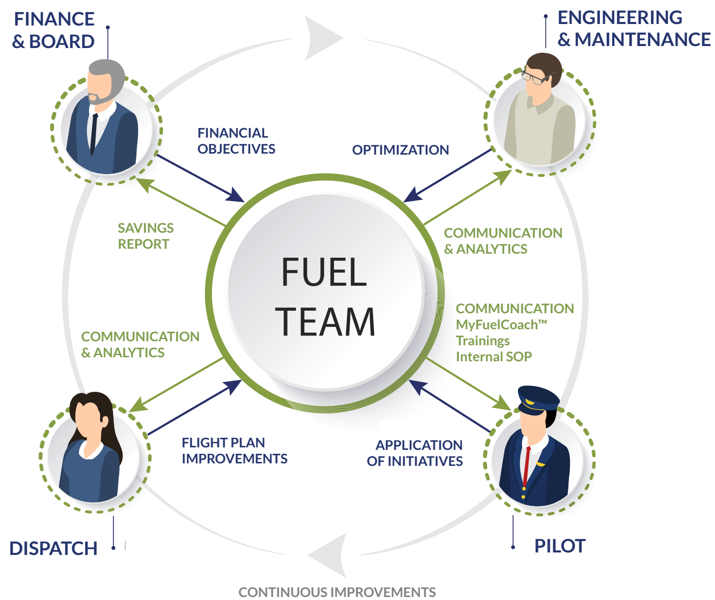
Source: OpenAirlines

: SECTION 2

A company-wide commitment

These operational improvements can be implemented throughout almost all airline departments: flight ops, dispatch, engineering and maintenance, or commercial and ground operations. Representatives from all departments should be integrated into a fuel team that drives the adoption of fuel-saving best practices.

Figure 44: Members of a fuel team



Source: openairlines.com

Figure 45: Industry fuel-saving best practices per department

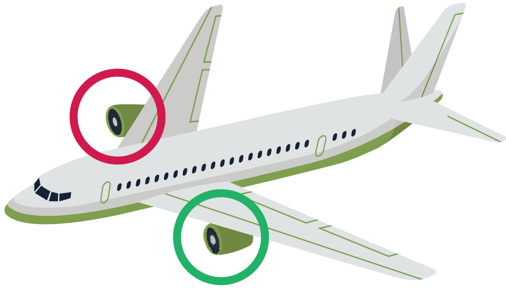
FLIGHT OPS	DISPATCH	ENGINEERING AND MAINTENANCE	COMMERCIAL AND GROUND OPERATIONS
Engine out taxi-out	Pilot extra fuel	Surface controls misrigging	APU at turnaround
APU during taxi-out	Dispatcher extra fuel	Engine wash	Potable water
Reduced flaps at take-off	Best alternate	Aircraft performance monitoring	Reduced zero fuel weight (Magazines, duty free, seats, catering, galley and cabin equipment, etc.)
Derated take-off thrust	Zero fuel weight error		
Reduced acceleration altitude	Over fueling above requested		
Optimal flight level	Over tankering		
Continuous descent approach	Fuel bias		
Reduced flaps at landing	Accurate cost index		
Idle reverse thrust	Optimized flight plan		
Engine out taxi-in	Statistical contingency fuel		
Short approach	Optimized center of gravity		
Direct routes	Optimized taxi fuel		
APU during taxi-in	Fuel reserves usage		
Packs-off take-off			
Holdings			
Go arounds			
Landing gear deployment/retraction			
Speedbrakes usage			

: SECTION 3

Flight Ops

Flight Ops best practices concern all phases of a flight.

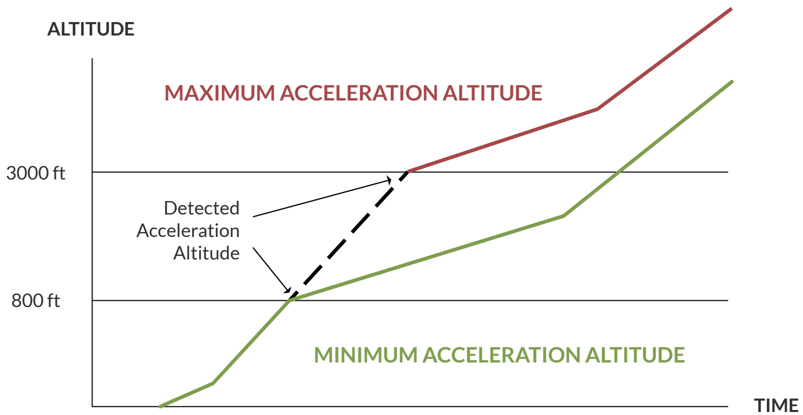
Shutting down one engine during taxi is a safe and widespread best practice to save fuel. **In just 5 minutes of single-engine taxi, a B777 will save 65kg of fuel.**



Source: openairlines.com

When noise abatement procedures allow it, **accelerating earlier during climb can save 200kg on each B777 flight.**

Figure 46: Reduced acceleration altitude application



Source: openairlines.com

If a pilot can perform a CDA (Continuous Descent Approach) during the descent, **he/she will save between 30 to 70kg of fuel on an A320 or B737.**

As Captain Andriy Kostyuk explained it at the Aircraft Commerce Conference in 2017 in London, **Ukraine International Airlines is saving 28kg per landing on the Embraer E190 by applying visual approaches in Kyiv** when VMC conditions allow it.

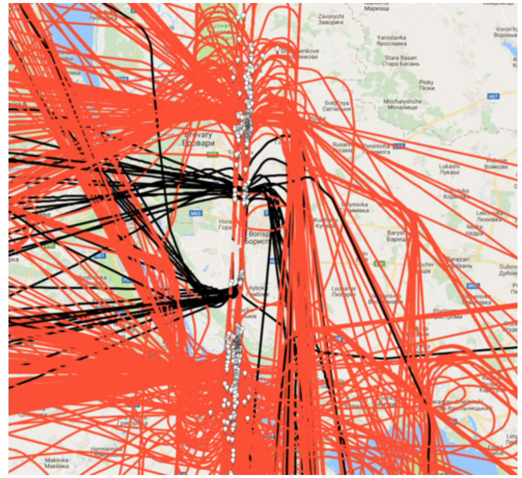


Figure 47: Black lines highlight performed visual approaches that can save 28 kg per landing on the E190.

Source: openairlines.com

And these are just some flight ops fuel-saving best practices among dozens of others.

: SECTION 4

Dispatch

Dispatch best practices look at trajectory analysis, fuel reserves, or flying at optimal speed.

They all contribute to improving the flight plan for 1) safety and comfort, 2) on-time performance, and 3) fuel efficiency.

With advanced data analytics, modern fuel management information systems such as SkyBreathe® create a feedback loop between actual observations recorded daily and flight planning.

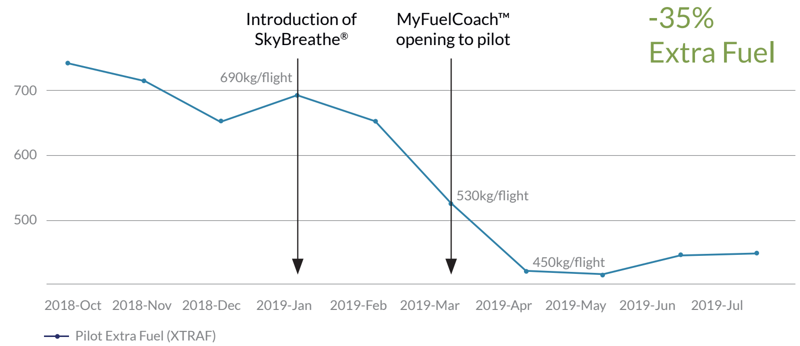
This feedback loop allows dispatchers to select the best SID (Standard Instrument Departure) or STAR (Standard Instrument Arrival) based on weather and expected congestion by the time of day or day of the week. They allow for planning just the right amount of fuel for tax: **if an airline that operates 50 A320 incorrectly plans 20% of extra taxi fuel on each flight (which is not much), it will waste more than 200,000 kg of kerosene in a whole year.**

Building pilot trust

Flight plan accuracy also plays a significant role in pilot trust and reduces pilot extra fuel.

When an airline shares solid data about fuel at arrival or about planned vs. actual fuel consumption with its pilots, trust is created and pilots can confidently and safely reduce their extra fuel where it makes sense.

Figure 48: Just a few months after the introduction of SkyBreathe®, Norwegian could increase its flight planning accuracy and increase pilot trust. This quickly led to a reduction of pilot extra fuel.



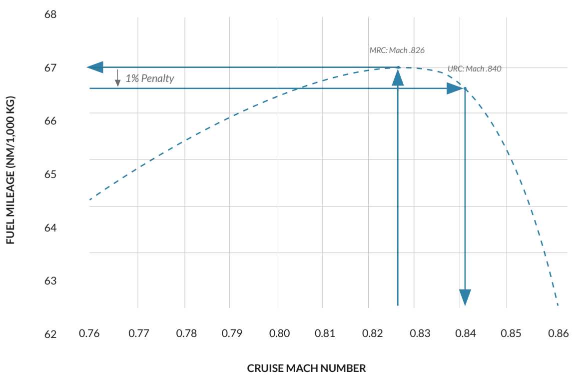
Source: openairlines.com

Pilot Extra Fuel at Norwegian after having equipped all its pilots with MyFuelCoach™ debriefing app.

Fuel vs speed

Selecting the right speed and striking the right balance between the cost of fuel (flying slower burns less fuel) and the cost of time (flying longer increases maintenance and crew costs) is the idea behind the concept of Cost Index. A cost reduction of 1-3% is a realistic expectation with a properly design cost index program.

Figure 49: Cost index



Source: boeing.com

: SECTION 5

Engineering and Maintenance

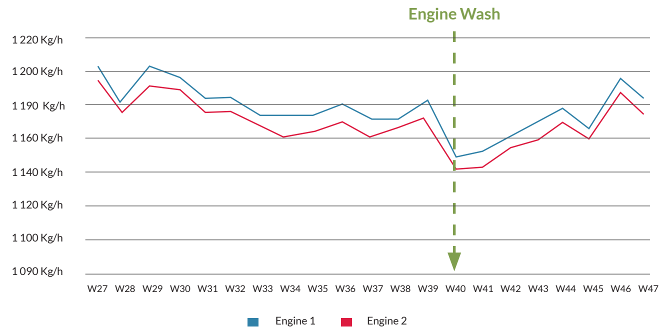
Engineering and Maintenance best practices can focus on weight reduction, engine wash, or aircraft performance monitoring.

Weight is the ennemy

A high-pressure engine wash on a B737 can improve fuel consumption by 80 kg/hour, as shown in this diagram.

Figure 50: Engine performance monitored by SkyBreathe®

By integrating a Fuel Management Information System, modern APM monitoring and maintenance inputs, airlines can measure accurately the cost/benefit of engine washes and compute the most optimal program cycle.



Source: openairlines.com

A good wash saves fuel

Each extra ton carried on a ten-hour flight will require an additional 350 kg of fuel or 1 ton of CO_2. Replacing passenger seats, trolleys, or cargo containers with lighter material can pay off quickly.

Source: elements.envato.com

Expliseat is developing ultra-light seats using carbon fiber and Titanium.

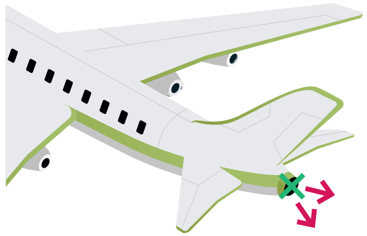
At the Aircraft Commerce Conference in October 2018 in Bangkok, Arief Rachman, Senior Manager, Head of Scheduling Department at Citilink Indonesia, explained how removing one oven from the cabin resulted in saving 20kg of fuel per flight due to weight reduction.

: SECTION 6

Commercial and ground operations

Even commercial and ground operations can have a significant impact on aircraft consumption. According to United Continental, an APU (Auxiliary Power Unit) uses 150 to 400+kg of fuel per hour while Ground Power Units (GPU) provided by the airport use less than 20 kg of fuel per hour.

Citilink reduced potable water quantity on shorter flights and saved 2 tons of fuel per year.



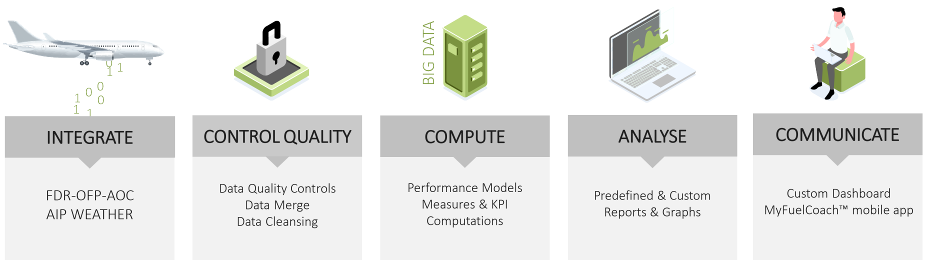
Source: openairlines.com

Digital tools

Forward-looking airlines have embraced the digital revolution and have adopted tools based on Big Data (modern aircraft records gigabytes of information on each flight) and Artificial Intelligence. They leverage the gigabytes of data that modern aircraft generate, ATC (Air Traffic Control) data, and weather data to provide recommendations to airlines specific to their network, fleet, and operations.

Main functions supported by a modern Fuel Management Information System:

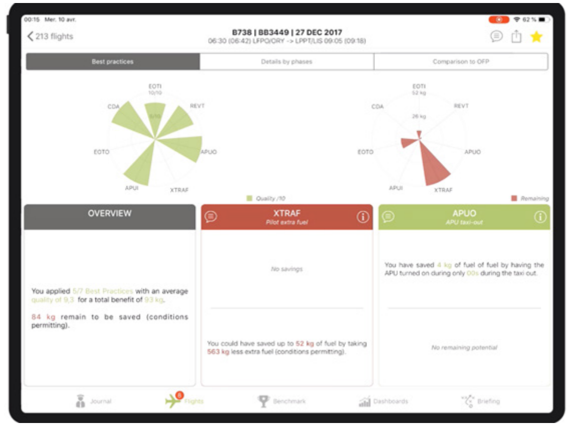
Figure 51: SkyBreathe® integrates all the relevant data from the airlines and provide detailed recommentations to all stakeholders to save fuel



Source: openairlines.com

Pilots are trained to perform Green Operating Procedures; they use dedicated briefing and debriefing apps that act as a virtual coach to help them fly greener.

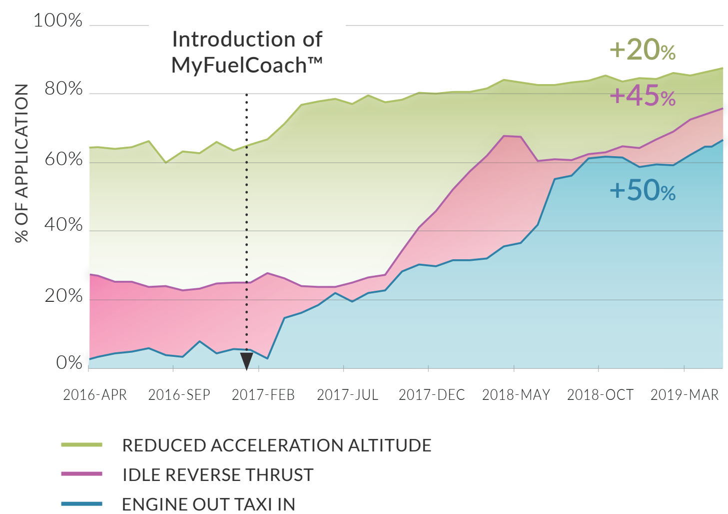
Figure 52 : The MyFuelCoach™ app provides a complete eco-debrief after each flight.



Source: openairlines.com

This diagram from Cebu Pacific shows how introducing such an app to their pilots drastically increased the application rate of various fuel-saving best practices.

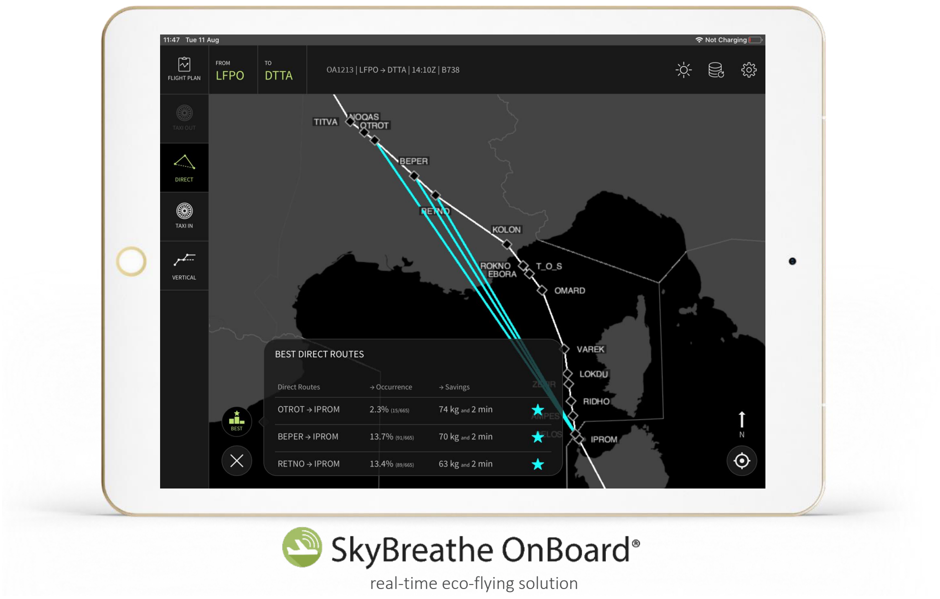
Figure 53: Best Practice application rate since the opening of MyFuelCoach™ to pilots



Source: openairlines.com

Airlines have recently adopted eco-flying apps running on EFBs (Electronic Flight Blag). Leveraging avionics data in real-time through an AID (Aircraft Interface Device), they provide contextualized guidance to the pilots with direct recommendations or taxi assistance.

Figure 54: Direct recommendations by SkyBreathe OnBoard.SkyBreathe OnBoard is an EFB application that provides real-time support for fuel-saving during the flight



Expert Interview

My name is Eric Meyer and I am the Manager of Flight Technical at Porter Airlines.

ERIC MEYER

Manager of Flight Technical at Porter Airlines

As part of my role, I look at technology to help with safety and efficiency. This has some overlap with fuel efficiency as well as operations approach design. We work closely with our partners at NAV Canada and De Havilland, the OEM.

In your opinion, what role do Flight Ops play in decarbonizing aviation?

I think they certainly have a key role to play. At Porter, we implement fuel efficiency best practices in several aspects of our Standard Operating Procedures, such as Engine In Taxi Out and Engine Out Taxi In. Pilots also look to have a fuel-efficient climb profile and constant descent profile if not restricted by air traffic control. They can check how they did on a particular flight and compare it against a typical flight and go from there.
In that way, we optimize fuel efficiency throughout the flight. We also have discussions with dispatch to assess the altitudes, the speeds, and the routings themselves to verify that our routing is as efficient as it can be.

Maybe your question didn't include technology changes, but we switched to RNP AR (Required Navigation Performance - Authorization Required) approaches in the last few years, and we've seen a significant impact with that, with a good uptake from the pilots as well. This would be similar to a visual approach but backed up by instrumentation and flown on autopilot.

Another area of improvement is asking for shortcuts. At Porter, we have a very mature fleet and route structure, which means pilots know when to ask for specific waypoints for a better chance of getting them. However, newer pilots don't have all that experience. So, we've started using SkyBreathe® Onboard, the live assistant app which helps us detect directs leveraging historical data and gives newer pilots the confidence to make those requests.

You mentioned digital technology earlier, do you expect them to be a significant lever for improving fuel efficiency?

I think correctly implemented digital technologies will help with things such as situational awareness. If we take the example of pilots asking for shortcuts again, we're trying to take years of experience on that route and provide a digital option so that pilots can request it earlier. It sorts of condenses those years of experience into a digital interface that can help give new pilots the opportunity to make those requests with air traffic control.

I think that wherever you can make a proactive decision as opposed to a reactive one, it's probably going to be for the better. For example, avoiding a thunderstorm early or recognizing a challenge further ahead in the approach so that you can adjust accordingly. Instead of holding for an arrival gate on the ground, you have the awareness that you can slow down in cruise because there is a certain amount of fuel that the pilots control directly with how fast they're going. I think pilots can make strategic decisions and plan their route or descent a little bit differently if they have a simple way of flagging that instead of having a hold or some obstacle later on.

I suppose in the future, we'll get better equipage in the flight deck. For example, our Dash 8 doesn't have wi-fi or another form of in-flight connectivity so that limits us a little bit. But that'll get cheaper to implement and maintain over time. It will also give us a bit more real-time awareness of what to expect and ways that we can be proactive. I think we'll continue to see it get more sophisticated. And then I think the sweet spot is keeping it relatively succinct and to the point so that the crew can action it and trust the results that it's providing.

What future do you see for aviation?

It is very promising to see the new technologies that are coming out and hear about electric aircraft for example. Some are flying out on the West Coast and I am looking forward to seeing that scale-up. I think the battery storage and weight will be a major consideration but as that continues to get refined, we'll have more and more options and I think we'll see more impressive fuel efficiency and aircraft designs.

There's also NAV Canada and our air traffic control which are really interested in continuing to modernize the air space. There are a few situations where we have our hands tied currently. For example, when we are not able to do constant descents or there are longer arrivals than they typically would be. But with the various performance-based navigation specifications, we will be able to have tunnels in the sky or very defined paths with very consistent results that both controllers and pilots can understand and appreciate. And then we'll be able to use the airspace even more efficiently.

So that's probably the area that I'm most curious about: seeing how we can modernize the airspace and drive the fuel efficiency from there because it's a win-win situation. Pilots are cutting off miles and saving time, passengers get to their destination faster and it is fewer fuel emissions. So I think, reducing some of the barriers to modernizing the airspace, that is a great goal.

CHAPTER 10.

ATM Improvements

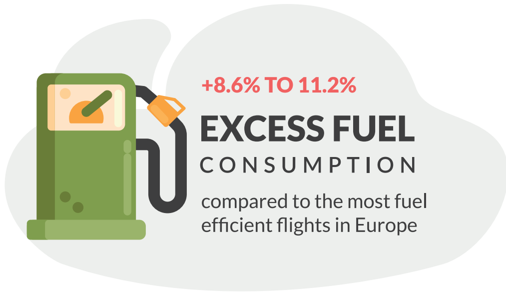
In the previous chapter, we looked at operational improvements in the airlines' hands. We learned that IATA estimated that airlines could reduce their CO_2 emissions by up to 14% by implementing fuel-saving best practices.

In this chapter, we will look at improvements that are in the hands of Air Traffic Management (ATM).

: SECTION 1

ATM inefficiencies

In its study published in December 2020, Eurocontrol estimated that the European air traffic management network's inefficiencies resulted in an average additional fuel burn of 8.6% to 11.2%.

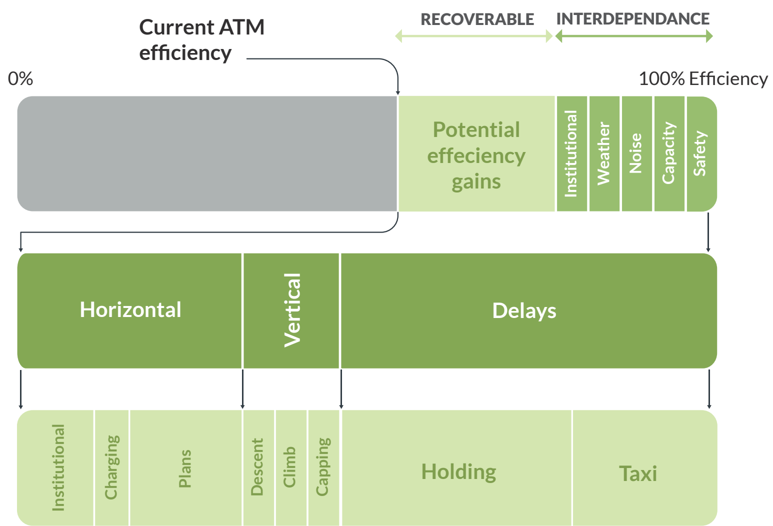


Eamonn Brenna, Director-General Eurocontrol, explains: "This metric for the first time gives us a real picture of the levels of fuel inefficiency in the European air traffic management network. And the fact that it reveals that aircraft are using on average between 8.6% and 11.2% more fuel than the most fuel-efficient flights in the European network should be a wake-up call. However, if the political and operational changes identified in this report are implemented, we could substantially reduce the aviation sector's CO_2 emissions."

Where do these inefficiencies come from, and how much can be recovered?

This diagram from the World Bank's comprehensive report on Air Transport and Energy Efficiency shows that inefficiencies come from various interdependencies.

Figure 55: ATM inefficiencies

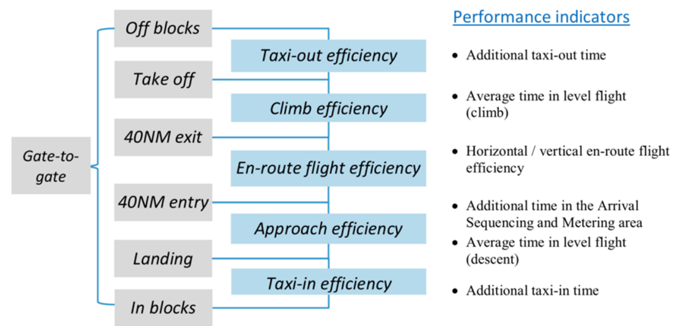


Source: pubdocs.worldbank.org

While improved ATM practices can recover some inefficiencies, 100% efficiency cannot be reached because of arbitration in favor of other critical properties: safety, adverse weather avoidance, noise abatement procedures, constraints imposed by military airspaces...

For each flight phase, the *Environmental Assessment: European ATM Network Fuel Inefficiency Study* looks at performance indicators that account for flight inefficiencies.

Figure 56: Performance indicators for each flight phase

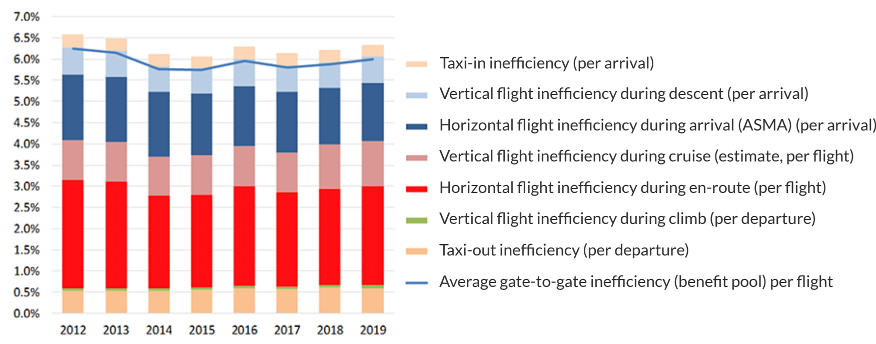


Source: eurocontrol.int

These include **additional taxi time, steps during climb or descent, holdings, and horizontal and vertical inefficiencies during the cruise.**

The following diagram from the same report indicates how each inefficiency contributes to CO_2 emissions.

Figure 57: Inefficiencies contribution to CO_2 emissions.



Source: eurocontrol.int

The report indicates that these are just average numbers and that some routes can exhibit inefficiency figures above 25%!

For simplicity, we have focused on the European ATM inefficiencies, but American airspace deals with similar challenges. Both authorities (Eurocontrol and FAA) regularly publish a transparent joint report that compares their efficiency.

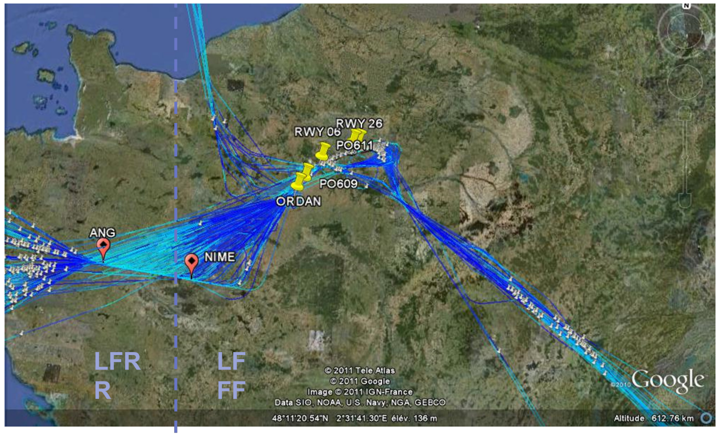
: SECTION 2

Concrete examples

The following figure is from a study that OpenAirlines conducted with SkyBreathe® for its partner airlines Air France, Corsair, and Transavia. It shows the impact of vertical constraints imposed on western arrival in Paris Orly.

These vertical constraints allow segregating traffic to/from Paris Orly from traffic to/from Paris CDG. While this design's benefits for safety and traffic flow are uncontested, this study sheds light on their economic and environmental impact.

Figure 58: Case study – Western arrivals at Paris ORY



Legend: *Light blue: step | Dark blue: descent*

AIRFRANCE CORSAIR transavia fnam

- 100% of Corsair B747 flights were constrained to FL260 at ANGERS leading to 120kg of extra fuel (378kg of CO_2) per flight
- Total cost of vertical constraints during descent: **500kg/flight**

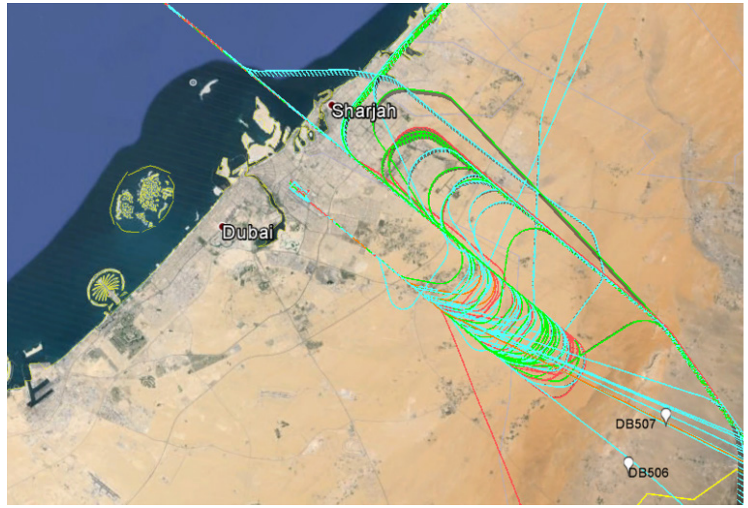
Source: openairlines.com

In this figure, blue curves represent actual aircraft trajectories. Dark blue means the aircraft fuel flow is low (aircraft is descending), while light blue means the aircraft fuel flow is high (aircraft is using thrust to maintain a leveled step).

While we see that controllers are granting many directs, we can also witness that all aircraft descend very early at a waypoint called ANG and maintain this low altitude for a long time before resuming their descent. This is not good because an airplane is more efficient when it flies higher.

This procedure, designed mostly to simplify the aircraft's handover between two controlled zones, is very environmentally unfriendly and is enforced even when there is only one aircraft in the sky.

Figure 59: Case study – Dubai's approach analysis



Source: openairlines.com

The next figure comes from a customer of ours that analyzed Dubai's arrivals using **SkyBreathe®.**

Anticipating a higher traffic flow, Dubai's approach was redesigned, and the trombone (in black) was extended by pushing further the two waypoints (DB501 and DB507) where the last turn occurs. In practice, almost all flights are allowed to shortcut this final approach, which is good, but the consequence of this new design (which seems overkill) is that all aircraft must now plan, carry and burn extra fuel.

Free Route Airspace

Various ATM iniatives can improve flight efficiency. A concept developed both by the European SESAR project, and North American NextGen initiative concerns free route airspace.

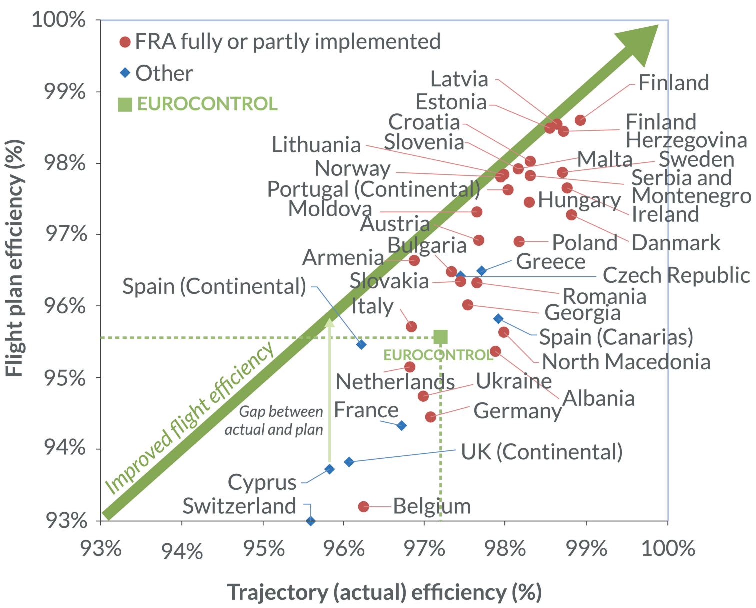
Traditionally, aircraft follow a limited number of pre-defined routes in the sky. These airways are segments between navaids, i.e., beacons or radio transmitters installed on the ground and used by the aircraft to "know its way."

Later, RNAV (Aera Navigation) was introduced and allowed to define waypoints identified by their LAT/LONG and that do not require beacons on the ground. These led to more flexible and more optimal airways, but airways were maintained, and with them, lateral inefficiency compared to the most direct route.

Free route airspace (FRA) allows an airline to create and follow its own routes within a specified airspace volume. Its flight plan still has to be approved by the ANSP for obvious safety reasons.

This clearly improves flight efficiency, as shown in the following diagram. **Airspaces that have implemented free routes** (the red dots) **show, on average, 0.5% higher efficiency compared to traditional airspaces** (in blue).

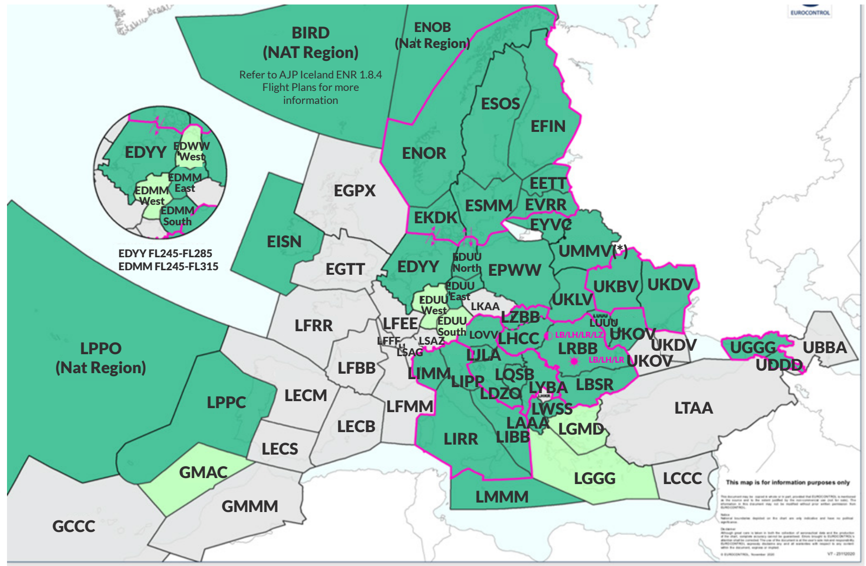
Figure 60: Free route airspace (FRA) benefits on flight efficiency (2019)



Source: eurocontrol.int

This map shows where free route airspace (FRA) was implemented in Europe at the end of 2020. The plan is to have all of Europe covered by the end of 2024.

Figure 61: Implementation of FRA in Europe (2020)



(*) Regional interconnectivity and interoperability of the European route network within the ICAO EUR Region (ERND Function objective)

- FRA Plans to be updated
- FRA (H24/might be level restricted or on seasonal basis)
- FRA (Night/might be level restricted or on seasonal basis)

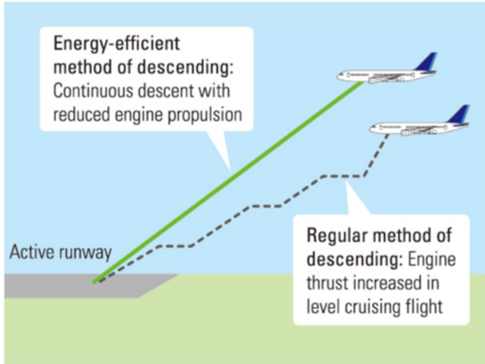
Source: eurocontrol.int

When free route airspace is made available in all of Europe, Eurocontrol estimates it will save 10,000 tons of CO_2 per day.

Continuous Climb/Descent Operations (CCO/CDO)

Because it's easier to ensure safety by imposing aircraft to fly at a set altitude, ATC traditionnaly imposes a step descent to the airport. However, continuous descent is more fuel-efficient (and less noisy) since the aircraft does not need to increase thrust to maintain a step level.

Figure 62: CDA versus non-CDA



Source: eurocontrol.int

Eurocontrol estimates that the potential saving by generalizing CCO/CDO in Europe amounts to 1.1M tons of CO_2 per year.

Unfortunately, current performance, especially at large airports, is far from that, as you can see in the following table:

Figure 63: Application rate of CDO in large airports

	% CDO	Avg Time in level steps	Median CDO Altitude
2019	(Higher = better)	(Lower = better)	(Higher = better)
Amsterdam Schiphol	21%	178 s	3,594 ft
Frankfurt Main	3%	343 s	4,834 ft
London Heathrow	8%	332 s	7,820 ft
Madrid Barajas	20%	174 s	6,882 ft
Paris Charles De Gaulle	3%	341 s	4,433 ft
Rome Fiumucino	33%	106 s	9,704 ft

Source: eurocontrol.int

Performance-Based Navigation

Performance-based navigation and RNP-AR (Required Navigation Performance) are new approaches that optimize aircraft's guidance at arrival using precise GPS navigation.

With proper approach design, aircraft equipment, pilot training, and certification, this new technology can ensure that an aircraft remains within the designed corridor's strict boundaries during the final approach.

This is good for safety, especially at airports where approaches are difficult due to the environment (mountains) or weather, but this is also good for the environment by optimizing the approach and fuel consumption.

Alaska Airlines has pioneered this technology with Boeing and the FAA as part of its NextGen project. It estimates that it can save one ton of CO_2 per landing at Sea-Tac airport.

Source: investor.alaskaair.com, www.faa.gov/nextgen, Nextgen

Expert Interview

I'm Marylin Bastin, Head of Aviation Sustainability at Eurocontrol

MARYLIN BASTIN

Head of Aviation Sustainability at Eurocontrol

My name is Marylin Bastin and I am leading the Aviation Sustainability Team at EUROCONTROL – a civil-military intergovernmental organization that supports European aviation. My team and I provide data-driven models on aviation's environmental impact and contribute to research and innovation programs to reduce aviation's impact of noise, emissions and condensation trails.

We also assist aviation stakeholders in meeting their obligations under Europe's Emission Trading Systems and ICAO's CORSIA. Prior to working at EUROCONTROL I was Head of Environment and Procedure Design at skeyes (Belgian Air Navigation Service Provider, former Belgocontrol).

What is your priority at EUROCONTROL and your roadmap in terms of Air Traffic Management (ATM)?

EUROCONTROL's role is to support European aviation as a whole and not just ATM. Obviously, ATM is our core business and, therefore our priority. However, EUROCONTROL works more broadly. If we want to decarbonize the aviation sector, we can't just look at ATM. Aviation sustainability is cross-cutting. We need to have a complete view of the different solutions.

At the level of the Aviation Sustainability Unit, our scope of activities is very broad. We have an operational pillar that helps airports, airlines, and air navigation service providers and others optimize their operations making them more efficient and sustainable.

We also define new metrics to change the current ones. When we talk about the environment, "horizontal flight efficiency" is the only recognized performance indicator, which indicates the shortest possible routes. However, this is not ideal since the shortest routes are not necessarily the most efficient routes (in case of headwinds, for example).

The "Fuel Inefficiency Study" we recently published shows that flights in Europe are using on average between 8.6% and 11.2% more fuel than the most efficient flights.

Part of EUROCONTROL's role is to bring the different actors involved in these flights together to coordinate and work in a collaborative way to reduce such inefficiency.

The first action for us was to have the right metric and the correct data. With our study's «excess fuel burn» metric, we have a good basis to start discussions. Now that we know how to measure inefficiency, the priority is to know who contributes to which part of the inefficiency to work separately with each stakeholder.

In the Aviation Sustainability Unit, a large part of our work focuses on the EU-Emission Trading System and CORSIA. We help our members with their reporting. We also work in the long term by doing research and development. SESAR 3, for example, is a priority.

Research programs must be launched to optimize procedures and put new technologies such as automation, machine learning, and artificial intelligence at the heart of these research programs to achieve more significant changes.

Are ATM improvements key components to decarbonizing aviation?

They are only one of the four pillars of decarbonization that we regularly refer to. Recent findings in our Objective Skygreen report show that the EU's goal of a 55% reduction in CO_2 emissions by 2030 is achievable, but it is heavily reliant on market-based measures, mainly via the EU Emissions Trading System (ETS), which will make an 83% contribution to the net reduction.

ATM improvements are expected to contribute 10% towards this goal by 2030 with Sustainable Aviation Fuel adding 5% and fleet upgrades 2%. 10% may seem like a small number, but it has enormous potential for reducing aviation's environmental impact when you look at the volume of air traffic.

We are currently experiencing a strong air traffic recovery and the sector is working to integrate new aircraft technologies where possible while coming to terms with new challenges that arise from high traffic levels.

What future do you see for aviation?

The strong recovery of air traffic shows that passengers want to fly but we also know that aviation must transform and reduce its emissions. Like other sectors, aviation is reliant on the energy transition and the need to move away from fossil fuels.

In aviation, technology solutions of the future lie in electric, hybrid or hydrogen-powered aircraft. To produce hydrogen, we need electricity. To produce synthetic fuel - via captured CO_2 and hydrogen - again we need electricity. So just like rail, aviation will be 100% dependent on renewable energies and electricity in a few years.

It is also evident that rail cannot replace air transport – especially when it comes to remote regions, emergency transport, areas that are not easily accessible via land transport etc. In the future, we will need better multimodal solutions that combine air and rail and are highly attractive in terms of optimizing sustainability and improving connectivity.

CHAPTER 11.

Bringing It All Together

This is the final chapter of the series of articles on decarbonizing aviation. It's time to wrap it up and bring it all together, to combine all these solutions, rise to the challenge of global warming and stand responsible in front of future generations.

: SECTION 1

A track record of innovation

In 1903, the Wright brothers completed the first powered flight. It lasted a mere 12 seconds and covered 120 feet (36 m). Its altitude was about 10 feet (3 m) above the ground.

Source: airandspace.si.edu

At that time, who would have guessed that less than 50 years later, commercial passengers could fly at 800 km/h on a jetliner, the Comet De Haviland?

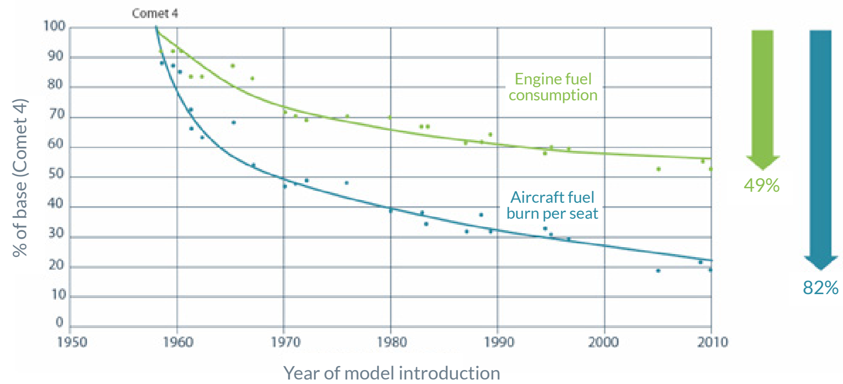
Source: bbc.com

This shows what the human brain is capable of and how quickly the airline industry can develop new technology and make them available to the general public.

Since then, the airline industry has continued innovating relentlessly and has delivered astounding fuel efficiency improvements, as we saw in *Chapter 3: Aviation track record and roadmap.*

Fifty years after the Comet 4, it has reduced its CO_2 emission per seat by 82%.

Figure 64: Fuel efficiency gains since the early jet age



Sources: IPCC Report 1999: Aviation and the Global Atmosphere – ATAG 2050 >> / aviationbenefits.org

: SECTION 2

There is no miracle technology

Pressured by the race against global warming, we have seen how the airline industry was pursuing multiple technological paths to reduce its carbon footprint in the last ten chapters.

Billions are invested in electrical aircraft, hydrogen aircraft, biofuels, operational or ATM improvements.

There are massive hurdles to reach this goal, incredible challenges, but there are also thousands of people who are working their hearts out, night and day, to deliver on this promise. Is the gap as wide as the Wright brothers to the Comet De Haviland? I don't believe so.

Moved by their passion, these engineers and pioneers from the 1st half of the XXth century made cheap and efficient flights available to the general people.

Moved by a superior goal, to preserve our planet, the engineers from the beginning of the XXIst century have all the capabilities to rise to the challenge and make carbon-neutral aviation a reality.

All these ideas, all these technologies do not compete against one another, but it is the combination of them all that will make achieving this goal possible.

As Bertrand Piccard said: "There is no miracle technology, but the miracle is that all these technologies together will make possible the ecological and energetical transition."

As for this transition's economics, he pursues **"It is this efficiency that is profitable."**

: SECTION 3

Shooting for the moon

When John F. Kennedy delivered his infamous speech at Rice University where he set the goal to go to the moon before the end of the sixties decade, it seemed like an impossible challenge.

Source: er.jsc.nasa.gov

Had he not set this objective, would we have achieved it today?

It is precisely when we set such aspirational goals that the human mind can surpass itself and make the impossible possible.

Our feet in the ground

When people look at the hydrogen aircraft's promise, they might complain that it is arriving too late. 2035 is a long time when the Earth is warming up at unprecedented speed, with dramatic consequences to our ecosystems, as we saw in *Chapter 1 How much CO_2 does aviation emit and how it compares with other sectors?*

Source: futura-sciences.com

But more modest **solutions are available TODAY** and can have a considerable impact.

In *Chapter 8, 9, and 10*, we saw how sustainable aviation fuels have already powered 250,000 commercial flights, how new technologies like AI and Big Data are saving millions of tons of CO_2, how ANSPs worldwide are delivering year-on-year improvements.

These technologies impact the existing fleet and traffic without requiring massive airline operations changes. And they deliver substantial cost savings to the airlines.

They are profitable solutions to protect the environment.

Aviation can become the greenest mode of transportation

Guillaume Faury, Airbus CEO, rightfully stresses that "Aviation leaves little physical imprint on the ecosystem - landscapes, flora, fauna and natural river courses remain untouched as aircraft fly over them."

Once it solves its carbon dependency -and it will-, aviation will probably become the most environmental-friendly mode of transportation.

CHAPTER 12.

Solar Impulse Foundation: 1000+ solutions to protect the environment

In this chapter, we will look at the Solar Impulse Foundation, founded to address environmental challenges while enabling economic growth.

: SECTION 1

Solar Impulse Foundation

The Solar Impulse Foundation was created by Bertrand Piccard in 2017. Since Bertrand Piccard and André Borschberg, launched the first flight around the world in a solar airplane, their ambition has been to leverage a pioneering spirit for a useful contribution to the cause of renewable energies and clean technologies. This is why Bertrand Piccard conceived the Solar Impulse project as a platform to raise public awareness and encourage political actions in favor of clean technologies and energy efficiency.

Bertrand has become an influential voice heard among the most distinguished institutions worldwide as a forward-thinking leader for progress and sustainability.

"Protection of the environment would become a reality only if it's perceived as economically viable and requiring no financial or behavioral sacrifices. Today, efficient solutions exist that can boost economic growth, while at the same time reducing our impact on the planet", says Bertrand Piccard.

The Solar Impulse label awards clean and profitable solutions with a positive impact on the environment and quality of life that meet high standards of sustainability and profitability.

In April 2021, Bertrand Piccard and the Solar Impulse Foundation have reached their goal. They have identified 1000+ clean and profitable solutions.

: SECTION 2

Solar Impulse labeled solutions for a clean future of aviation

The Solar Impulse Foundation partner with the French major air transport player, Air France. The partnership objective is to accelerate the adoption of clean and profitable technological solutions in aviation. All technologies that have a positive impact on the following points are selected, promoted, and included in the 1000 Solutions Portfolio:

- Carbon emissions
- Efficiency (fuel, weight, processes)
- Waste management
- Clean ground operations
- Noise reduction
- Aviation and new energies

All relevant solutions for Air France could be part of the airline's sustainability program and implemented.

: SECTION 3

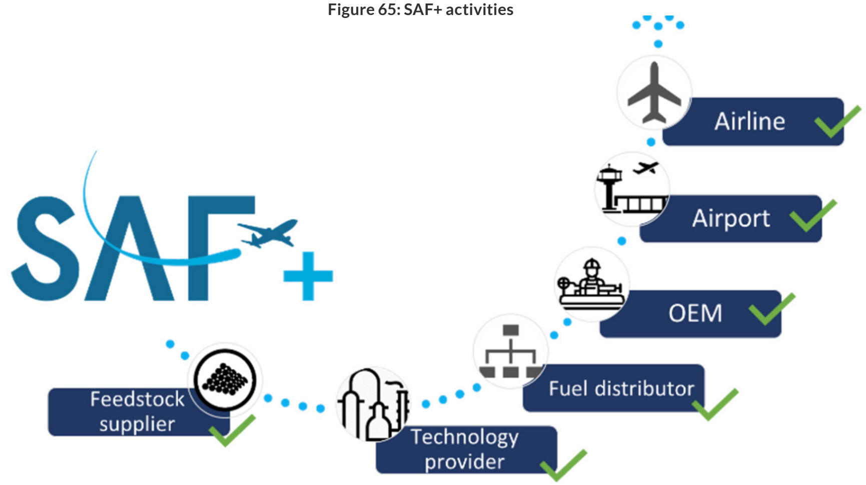
SAF+

SAF+ uses innovative carbon conversion technology to create sustainable fuels for aviation. SAF+ produces a compliant jet fuel by blending carbon with hydrogen. The jet fuel produced reduces lifecycle greenhouse gas emissions by 80% compared to conventional fuel. It helps airlines meet the mandates set by organizations to achieve their GHG reduction goals.

SAF+ key features:

- 1 ton of SAF+ fuel produced = 2.7 tons of CO_2 capture and 100% of the emissions and impacts linked to oil extraction avoided.
- 1 liter of SAF+ fuel produced = 86% reduction of water needed compared with regular jet fuel.
- SAF+ fuel = 80% less CO_2 emissions compared to conventional jet fuel.
- SAF+ fuel = 90% less particulate matter and up to 5% less NOx compared to conventional jet fuel.

Figure 65: SAF+ activities



Source: SAF+ - Solar Impulse Efficient Solution

: SECTION 4

ZeroAvia

ZeroAvia produces the world's practical first zero-emission aviation powertrain. It is powered by a hydrogen fuel cell system and associated with software. It can be installed on both existing and new aircraft.

"Not all the energy is coming from hydrogen," said Val Miftakhov, ZeroAvia's CEO. "There is a combination of the battery and hydrogen. But the way the battery and hydrogen fuel cells combine is such that we are able to fly purely on hydrogen."

ZeroAvia key feature:

Estimates savings up to 115 Mt CO_2 by 2033

Source: Hydrogen electric powertrain for aviation - Solar Impulse Efficient Solution

: SECTION 5

Refuel the Future

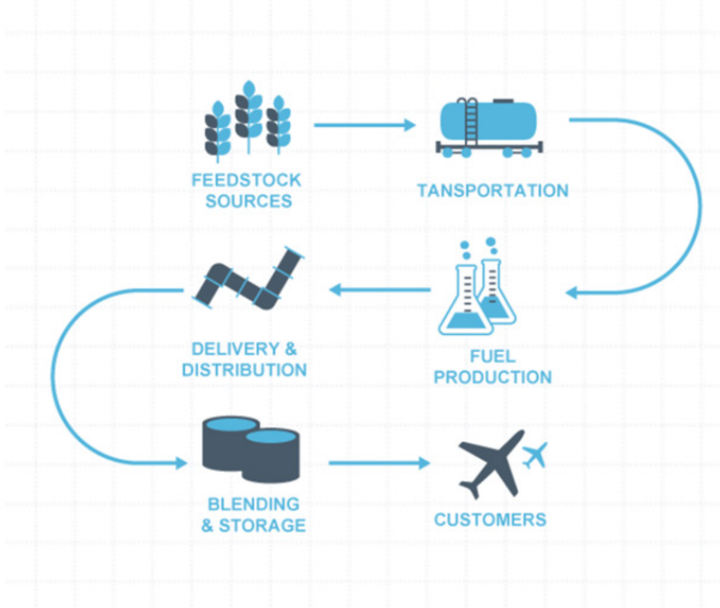
Refuel the Future is working to provide the aviation industry with low-cost, sustainable renewable fuels by 2024. The feedstocks for these fuels are societal waste products. Refuel the Future has a strong track record of developing clean solar, wind, and transmission power. "Our mission is to provide a competitively priced alternative to fossil fuels that reduces emissions, is sustainable across the entire supply chain, and creates economic opportunities for communities," said Zohrab Mawani, co-founder of Refuel the Future.

"Starting with Toronto Pearson International Airport and to be replicated at other global hubs, the use of sustainable fuels by air transport operators will be key to reducing aviation's environmental footprint and to meeting ICAO carbon emissions reduction goals starting in the early 2020s".

Refuel the Future key features:

- Emissions reduction of at least 90% compared to conventional jet fuel or diesel fuel
- Refuel the Future is approved for blends up to 50%, but has been successfully tested at 100%
- By replacing fossil fuels, carbon reduction is expected to reach 244,000 tons per year at one facility
- 90% reduction in CO_2 emissions compared to fossil jet fuel
- 100% waste and off-spec oil feedstock

Figure 66: Refuel the Future production chain



Source: refuelthefuture.com

: SECTION 6

EPS55

EPS55 was founded by André Borschberg. To make aviation quiet, affordable, and clean, EPS55 produces certified (FOCA, EASA, FAR) electric propulsion solution and battery management system. Thus, battery technologies are used in a safe, clean, and cost-effective way.

The EPS55 is designed to maximize and optimize the use of battery technologies for electric-powered airplanes.

With EPS55 solutions, a battery-powered system replaces conventional aircraft engines that are powered by fuel. There are no greenhouse gas emissions, the noise level is less than 55dB, and the savings are real. Indeed, for small aircraft, EPS55 systems are more cost-effective than current propulsion systems.

EPS55 controls the charging and discharging of the battery systems in order to supply the engine drive train.

EPS55 key features:

- Reduction of GHG emissions (250 kg CO_2eq per flight hour)
- Reduction of airplane noise pollution

Source: https://solarimpulse.com/efficient-solutions/eps-55

: SECTION 7

ExpliSeat

ExpliSeat creates a new generation of ultra-light, comfortable and durable aircraft seats. Thanks to a primary structure in composite, TiSeat is the world lightest aircraft seat. Aircraft seats are a mixture of high-performance materials (carbon fiber and titanium). More than 15 airlines (SpiceJet, Air Tahiti, Porter Airlines, Cebu Pacific in the Philippines) are already flying with TiSeat. This green patented technology improves efficiency by reducing aircraft weight.

TiSeat key features:

- Seat 40% lighter compared to other certified aircraft seats in the market.
- Fuel consumption and environmental footprint reduction with more than 400 tons CO_2 saving per year per aircraft on Single Aisle aircraft

Source: https://solarimpulse.com/efficient-solutions/tiseat https://expliseat.com/

Expert Interview

Former Innovators Coordinator at Solar Impulse Foundation

PIERRE MAURY

Entrepreneur, pilot and passionate about innovation

I am Pierre Maury, entrepreneur, pilot and passionate about innovation. I used to work at the Solar Impulse Foundation in the Outreach Team.

My role was to identify innovative solutions (technology, product, service) that have a positive impact on the environment and that are profitable.

One of my focus was the Aviation Sector. I was looking for solutions worldwide on Flight Operations, Ground Operations, Electric Aviation, Hydrogen and more.

How does Solar Impulse Foundation accelerate the ecological transition?

The Solar Impulse Foundation has labelled more than 1000 solutions that are both ecological and profitable. Now, they are connecting Governments, Corporates and Investors with these companies to accelerate their growth and the adoption of Clean Technologies. Their main objective is to prove to the world that ecology is profitable.

What type of solutions are they looking for?

The Solar Impulse Foundation is looking for solutions in all kind of industries (Agriculture, Mobility, Water, Energy, Construction, Smart Cities, Industry, ...). The solution can be a technology, product, service or software; with a TRL (Technology Readiness Level) 6 minimum, ie prototype that has been tested in a real environment. Finally, the company must be able to prove the impact on the environment and the business model with data.

What future do you see for aviation?

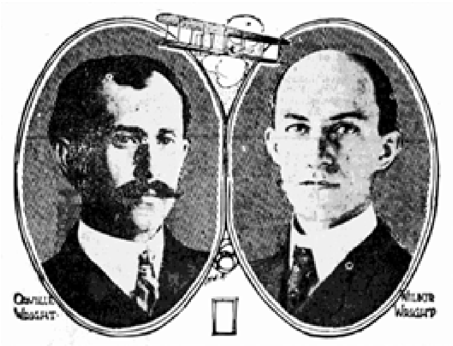
In view of the ecological situation, new regulation and consumer expectations, the new long-term vision is clear: the new era of aviation is clean and carbon-free. This new era coincides with the maturity of many pro-environmental technological innovations and strong political will. SAF is a great example of innovation mixed with political regulations.

In the same time, the aviation industry can rely on industry pioneers to continue breaking down barriers through electric propulsion and fuel cells. I am sure that we will see electric 19-seater aircraft before the end of the decade. This will strongly transform the way we travel on short distances.

Believe

Finally, I would like to pay tribute to a man who makes us believe, a man who has set for himself incredible challenges.

In 1903, the Wright brothers unveiled the uncharted territory of powered flight and inspired generations of pioneers to push the limits of imagination and **make commercial aviation an "irreplaceable force for good in the world."**



Source: pixabay.com

Source: imdb.com

In 2016, Bertrand Piccard, together with Andre Borscherg, became the first human being to fly around the world without using a single drop of fuel.

Bertrand Piccard inspires us to "change altitude" to face our challenges and get another perspective into our lives and planet.

The Solar Impulse historic flight proved that decarbonizing aviation is mission possible.

Source: aroundtheworld.solarimpulse.com

People might look at this incredible achievement as a fool's dream, an adventurer's life-risking venture, a single event that cannot scale... So did Wright's first flight look like, yet 50 years later, the commercial jet age was a reality.

> People of goodwill who are passionate about aviation and care about the planet, may you put all your heart and energy into this adventure, and join the forces that prove that decarbonizing aviation is mission possible.
>
> I would like to pay tribute to an incredible team of talented women and men who give all their passion, talent, genius, soul, and heart into our mission: Accelerate the world's transition to sustainable aviation through digital technology. Despite the adverse winds of Covid-19 that our industry is facing, the good people of OpenAirlines stand united to our cause. They give me faith and strength, and I thank them for that every day.
>
> *Alexandre Feray – OpenAirlines Founder and CEO*

Source: openairlines 2023

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About the Author

ALEXANDRE FERAY

Fonder and CEO, OpenAirlines

Alexandre Feray is a french mountain climber, environmentalist, great traveler, and iconoclastic passionate about developing innovative IT systems that reduce the impact of air travel on the environment. He has 28 years of experience in the Software and Airline Industry, not including his teen years when he invented a programming language awarded and commercialized by Apple.

He holds an MSc in Engineering and IT from École Centrale Paris and started his career at IBM Thomas J. Watson Research Center in New York, USA, working on the first multimedia email system for the Internet. He managed complex IT systems at Air France where he was the head architect of Air France Operations Control Center's reengineering program and head of Air France Crew Management IT Department, leading a team of 50 people.

Starting from the observation that nearly 660 million tons of CO_2 are emitted by airplanes every year, he founded OpenAirlines in 2006 to develop digital solutions to help airlines reduce their costs and environmental impact. Drawing on 8 years of R&D, SkyBreathe® eco-flying software came out on the market in 2013. Using an extensive collection of flight data, Cloud and Artificial Intelligence, the software provides guidance and a series of recommended actions to help pilots lower fuel use. The prize-winning solution is currently helping +51 airlines including Air France, easyJet, DHL, Norwegian, IndiGo, flydubai, Cebu Pacific and Atlas Air, save million dollars and CO_2 emissions every year.

Alexandre has authored and co-authored two essential books on sustainable aviation: "The Green Airlines Fuel Book," a booklet to raise awareness of fuel-saving best practices and help spread the fuel-efficiency culture in airlines. And "Decarbonizing aviation: mission possible", a series of educational blog articles.

In 2021, he initiated Green Pilot, a collective movement of like-minded airline professionals and aviation lovers concerned about climate change, and committed to promoting green actions to reduce aviation impact.

About OpenAirlines

DIGITAL LEADER IN FUEL EFFICIENCY

Air transport industry emits almost 660 million tons of C02 every year, and this represents more than 20,000kg of C02 per second. Fuel represents 30% of airlines' costs, and the pressure of the competitive dynamics of the airline industry is ever-present. **That's why OpenAirlines decided to act by developing an innovative solution to help airlines reduce their fuel consumption and environmental impact.**

SkyBreathe® eco-flying software was introduced to the market in 2013 after 4 years of R&D and testing under the Clean Sky Joint Undertaking (CSJU) project.

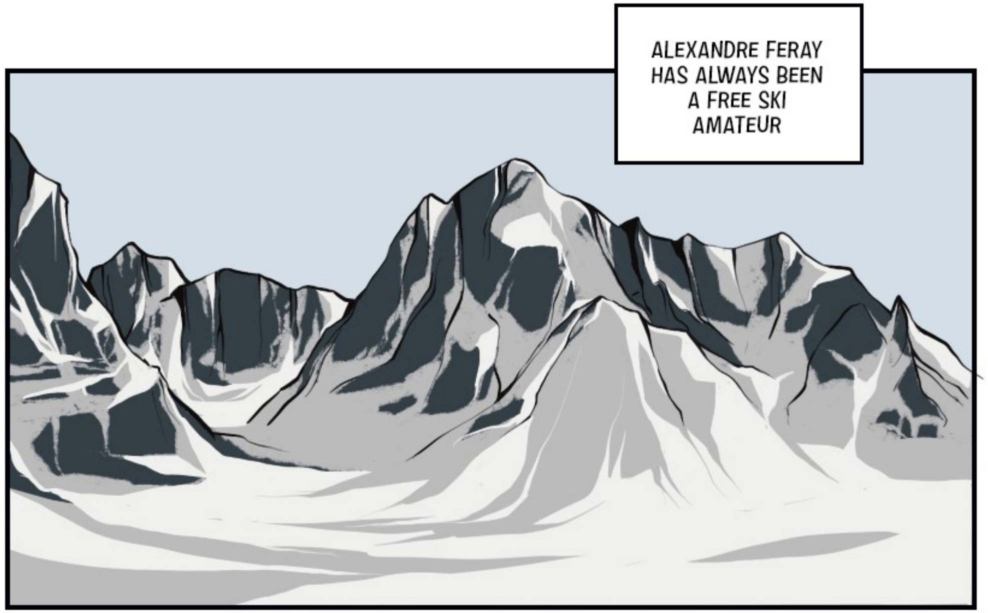
Based on Big Data algorithms, Artificial Intelligence (AI) and Machine Learning, the digital solution reduces an airline's fuel cost by 2 to 5% without any modification to their fleet. More importantly, it enables them to be part of the "greenest" airlines in the world.

OpenAirlines has received many international rewards for its innovation and environmental work. The cleantech company is today a world leader in the market with a very active community of airlines customers from around the world including Air France, easyJet, DHL, Norwegian, IndiGo, flydubai, Cebu Pacific and Atlas Air to name a few.

OpenAirlines

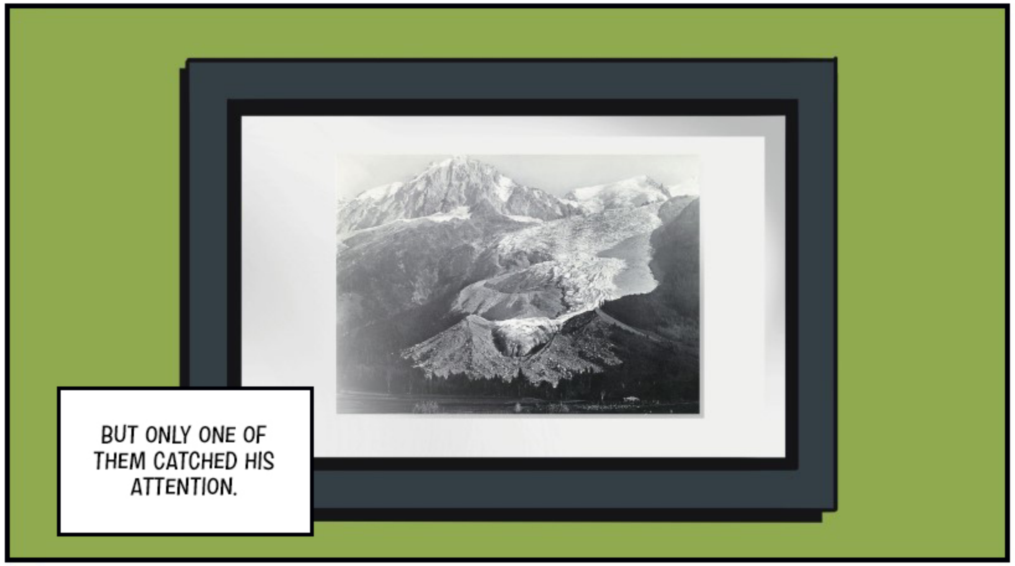
info@openairlines.com - www.openairlines.com

How it started

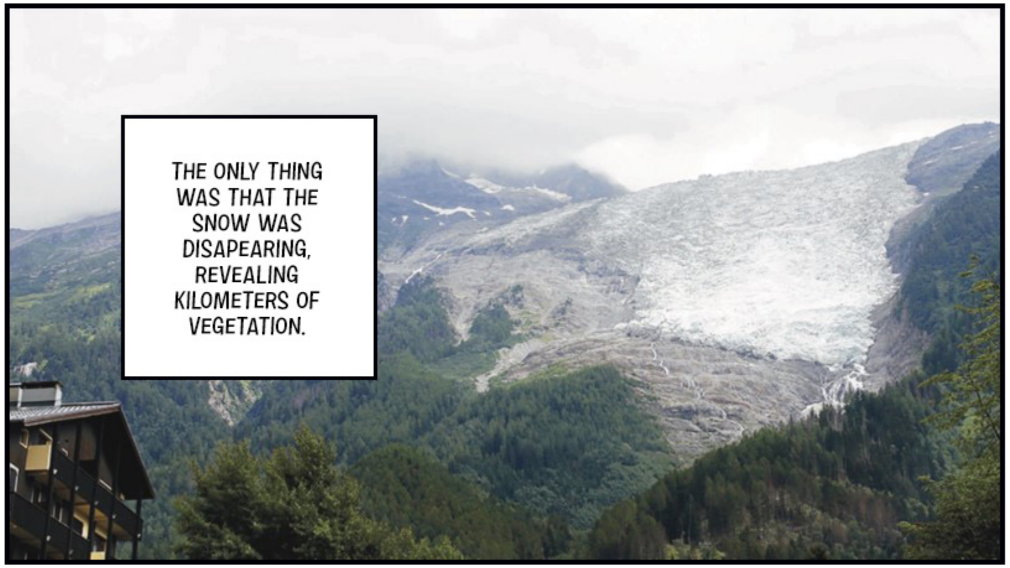



AFTER A LONG DAY IN THE MOUNTAINS, HE DECIDED TO REST IN A GUEST HOUSE.
THAT DAY, HE DISCOVERED THE "CRÈMERIE DU GLACIER"


MANY PICTURES DECORATED THE WALL OF THE HALLWAY...

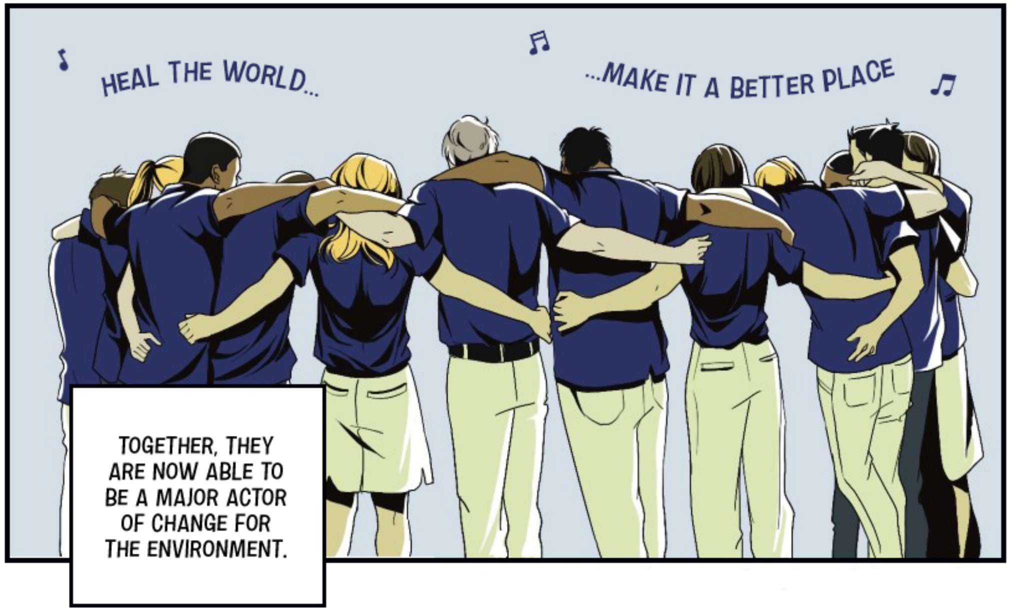

BUT ONLY ONE OF THEM CATCHED HIS ATTENTION.


HE CAST A GLANCE OUTSIDE AND NOTICED THE MOUNTAINS IN FRONT OF HIM WERE THE ONES OF THE PICTURE...


THE ONLY THING WAS THAT THE SNOW WAS DISAPEARING, REVEALING KILOMETERS OF VEGETATION.


ONLY THEN, HE UNDERSTOOD GLOBAL WARMING WAS REAL ...


AND EVERYONE'S RESPONSABILITY.
IN 2006, HE FOUNDED OPENAIRLINES TO LIMIT THE IMPACT OF AIRCRAFTS ON THE ENVIRONMENT


HEAL THE WORLD...
...MAKE IT A BETTER PLACE
TOGETHER, THEY ARE NOW ABLE TO BE A MAJOR ACTOR OF CHANGE FOR THE ENVIRONMENT.

The opportunities and challenges of aviation decarbonization

MISSION POSSIBLE

What if decarbonizing aviation isn't at best a utopian dream for a greener future, at worst yet another marketing buzzword aiming to sway public opinion? What if we truly have in our hands the power to reduce aviation's carbon footprint down to making it the most environmentally-friendly mode of transportation?

In this book, the author and industry experts deliver an in-depth analysis of the many challenges and opportunities that arise from aviation's carbon dependency. They offer a pragmatic and comprehensive overview of the solutions that are effective today to cut CO_2 emissions. They also explore the innovations that will shape the aviation of tomorrow.

"People of goodwill who are passionate about aviation and care about the planet, may you put all your heart and energy into this adventure, and join the forces that prove that decarbonizing aviation is mission possible."
Alexandre Feray – OpenAirlines Founder and CEO

OpenAirlines

Green Pilot