Dieter Scholz, 2021

Environmental Protection in Aviation

Background and Arguments for the Current Discussion

We hope to slowly emerge from the corona pandemic. This means that air traffic could continue where it came to an abrupt end in 2020. But wasn't there something to do with climate change? Flight shame? Can we really fly again like we used to with a clear conscience in times of proven global warming? In any case, after Corona we have gained one new insight. The unthinkable is possible. Planes can actually sit on the ground in rows. Organizations like Stay Grounded (https://stay-grounded.org) had already propagated this before Corona, but their demands were hardly taken seriously. After Corona, the basis for discussion has shifted. The EU has fleshed out the "Green Deal" with the "Fit for 55" package of measures. In Germany, policies with an environmental focus are given a chance of gaining a majority. Heavy rain events show that climate change has reached us. Aviation questions have become part of the news. Should short-haul flights be replaced by train journeys? Many citizens have the feeling that their own lifestyle also needs to be questioned. Spaceship Earth is finite in its dimensions. At some point the atmosphere will be full of CO2 and other greenhouse gases. One climate-relevant process then triggers the next and the climate tips over like a row of dominoes.

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Question 1: Are aviation emissions relevant?

Global aviation had emitted 32.6 billion tons of CO2 by 2018 (Lee 2021). This corresponds to the global annual total emissions of CO2 in 2018 (Wikipedia 2021). Air traffic has grown at a fairly stable rate of 5% per year for decades (ICAO 2012). This corresponds to a doubling every 15 years ($1.05^{15} = 2.1$). Fuel consumption per capita and kilometer was reduced by 1.5% every year. However, this still left growth of 3.5% per year, which corresponds to a doubling of CO2 emissions every 20 years ($1.035^{20} = 1.99$) (Lee 2021). See Figure 1.

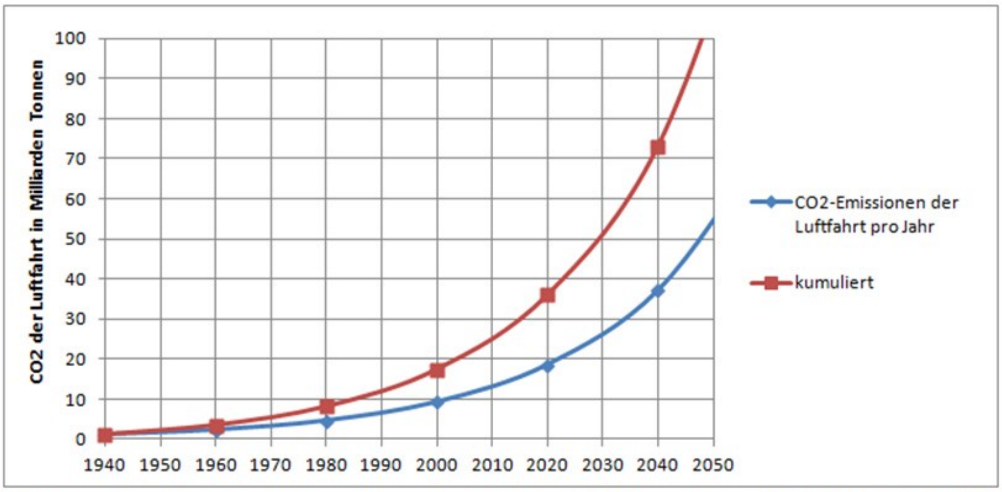

Bild 1: Einfache Darstellung des exponentiellen CO2-Wachstums der Luftfahrt bis 2019 fortgeschrieben bis 2050 unter der Annahme von einem weiteren Wachstum des Luftverkehrs von 5 % pro Jahr und Einsparungen im Kraftstoffverbrauch pro Kopf und Kilometer von 1,5 % pro Jahr. Dies führt zu einer Verdoppelung der CO2-Emissionen alle 20 Jahre. Luftfahrtkrisen haben sich in der Vergangenheit im Kurvenverlauf kaum bemerkbar gemacht (ICAO 2012). Es wird aber prognostiziert, dass eine Rückkehr zum bekannten Luftverkehrswachstum von 5 % nach Corona länger dauern könnte. Gezeigt ist vereinfacht der kontinuierliche Verlauf.

Looking at air traffic figures from the beginning of civil aviation (before the Second World War) to 2020 shows that this is exponential growth. How threatening **exponential growth** is was explained to us using the example of SARS-CoV-2. Within certain times a doubling occurs (time to double). 2 becomes 4, then 8, 16, 32. What gets doubled? In the case of air transport, the volume of traffic and therefore CO2 emissions have doubled. However, the CO2 accumulates in the atmosphere and remains there for several hundred years. If 2 in the first year become 4 in the second year, then at the end of the second year there are already 6 units of CO2 in the atmosphere followed by 14 (6+8), 30 (14+16), 62 (30+32). Exponential growth can also be expressed as a percentage per year. The compound interest formula can then be used to calculate how many years it will take, for example. B. a doubling occurs (see above). Interest can cause “debts to grow over your head”. The same applies to the exponential growth of aviation emissions. In addition, there are positive feedback mechanisms in the climate system, in which an initial impulse is strengthened. There are tipping points. If these are reached, a chain reaction is triggered and the climate tips over like a row of dominoes (Federal Environment Agency 2008).

But maybe it's not all that bad because aviation's CO2 emissions only account for 2.4% of all man-made CO2 emissions (Lee 2021)? As is well known, you can always use statistics in whatever way seems advantageous and 2.4% doesn't sound like much at first. However, it is estimated that 80% of people on earth have never flown (OurWorldinData 2020). On average, every person on earth makes half a flight per year. In Europe there are 1.3 flights per year (calculated according to CityPopulation 2020). According to the general Pareto principle (80/20 rule), 20% of the world's population should be responsible for 80% of emissions. In aviation, however, the distribution appears to be more unequal than usual, as 20% of the world's population would be responsible for 100% of the emissions. Seen this way, the 2.4% now reads differently. **Aviation is “only” responsible for 2.4% of man-made CO2 emissions because most people on earth are so poor that they have never been able to fly in an airplane.**

According to a presentation on the “Green Deal” (EU 2019a), 25% of greenhouse gas emissions in the EU come from the transport sector. **The share of civil aviation in emissions from the transport sector is 13.9%** (Figure 2). That would then be 3.5% (0.25% to 13.9%) of man-made greenhouse gas emissions in the EU. Science (Lee 2021) also confirms that civil **aviation contributes 3.5% to man-made global warming** if non-CO2 effects are taken into account in addition to the CO2 effects. **The aviation share of emissions rose steadily** because the growth of aviation was stronger than the growth of other areas.

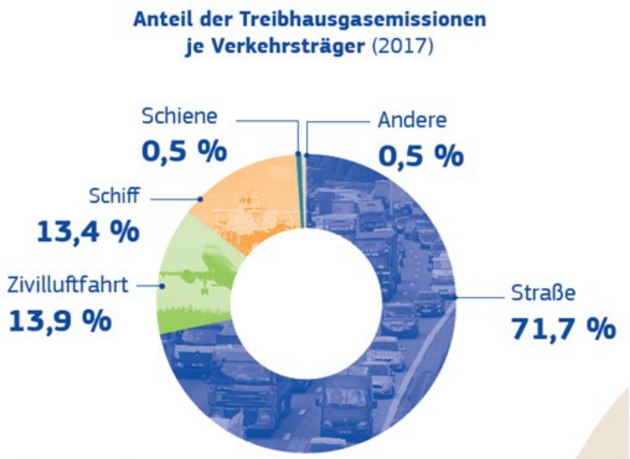

Bild 2: Der Anteil der Zivilluftfahrt an den Emissionen des Verkehrssektors beträgt 13,9 % (EU 2019a).

In addition to aviation's 13.9%, rail accounts for the smallest individual share at just 0.5%, while road traffic accounts for the largest share of emissions from the transport sector in the EU at 71.7%. Given these numbers, one might ask why aviation has come under so much criticism. Without going into technical details at this point, it should first be noted that road traffic is simply part of everyday transportation, while flights, in comparison, are still special, individual events in life (see above). The **share of aviation is therefore "significant"**. This is also due to the high flight speeds, which enable long flights in a limited amount of time. **No other means of transport can generate as much emissions per person in one hour as a plane.** Consumption primarily depends on the route. Long flights therefore require a lot of energy and generate a lot of CO2. A return flight Frankfurt – New York (12,400 km) can be equivalent to the entire annual mileage of a car.

Question 2: What is it about – fuel consumption or emissions?

Fuel consumption and CO2 emissions are linked by the composition of the fuel, which consists of carbon and hydrogen in a certain mixing ratio. Carbon burns to form CO2 and hydrogen burns to form water. The mass of one kg of kerosene produces 3.15 kg of CO2. When hydrogen is burned, no CO2 can be produced because hydrogen does not contain carbon.

It's about resource consumption and global warming. When we complain about fossil fuel consumption, we are saying that we are leaving future generations with no energy left that can be relatively easily taken from the earth and used. When we complain about CO2 emissions, we are expressing concern that we could overload the atmosphere, which will eventually reach its limits. I imagine two barrels (picture 3). One barrel with the energy will eventually be empty and the other barrel with the CO2 will eventually overflow. We pump from one barrel into the other barrel. That can't work well in the long run, especially if the tap is turned on twice as much every 20 years.

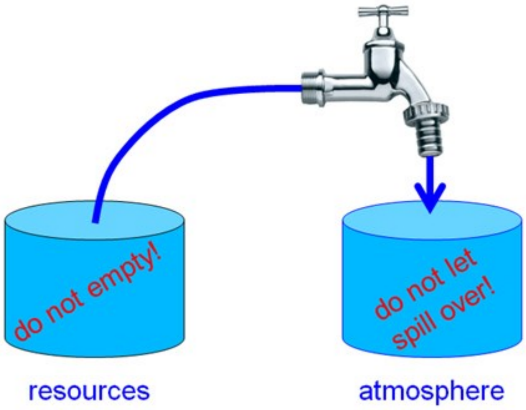

Bild 3: Zwei Fässer symbolisieren die endlichen fossilen Energievorräte und die endliche Aufnahmemöglichkeit der Atmosphäre.

The **atmosphere** is a comparatively thin layer of air. 80% of the air mass is below an altitude of around 11 km (Helmholtz 2021). That's only 0.17% of the Earth's radius.

In addition to the local effects, global **warming** involves an increase in the global mean temperature of the air at a height of 2 m compared to the pre-industrial value. In 2020, the global temperature was 1.25 °C higher than the pre-industrial value (Copernicus 2020).

Global warming is linked to the **CO2 concentration in the air**. There is an approximately linear relationship between the cumulative total amount of greenhouse gases emitted and the resulting increase in temperature - as long as the climate system does not reach a tipping point and the processes accelerate by themselves. Based on volume, the air contains around 0.04% CO2. This 0.04 parts per 100 parts can also be expressed as 400 parts per million parts. This is expressed as 400 ppm (parts per million). **In pre-industrial times the CO2 concentration was 280 ppm**, in 2021 it was 420 ppm. At current CO2 emissions, **the CO2 concentration is increasing by about 3 ppm every year** (1 ppm is equivalent to about 10 billion tons of CO2). Doubling from 280 ppm to 560 ppm will increase the average temperature by approximately 3 degrees. According to the Paris Agreement of 2015, the temperature increase should ideally be limited to 1.5 °C compared to pre-industrial levels. That would then be at 420 ppm – already in 2021! (This almost corresponds to the information from Copernicus 2020). We would have to reduce CO2 emissions to zero today. **At the 2 degree limit we could get to 467 ppm** and there would still be 15 years left at today's CO2 emissions. In practical terms, emissions could be reduced linearly from 100% today to 0% in 30 years (i.e. around 2050). However, if we were to use up all fossil energy reserves (coal will last for several hundred years), then the CO2 content of the atmosphere would rise to around 1600 ppm, which, based on simple calculations, would mean a temperature increase of 14 °C. This consideration makes it clear that an overflow of the right barrel (Figure 3) will occur first and is therefore more critical. **The climate disaster comes before the end of fossil fuels**. The remaining fossil energies must remain unused in the ground and therefore become worthless. (With data from Wikipedia 2021 and references listed there.)

Question 3: What climate goals does aviation have?

The aviation industry had determined that growth in aviation could no longer be communicated without further explanations and propagated " **climate-neutral growth from 2020** " (Carbon-Neutral Growth, CNG) (IATA 2009, ATAG 2012). Aviation should be allowed to continue to grow, and CO2 emissions should continue to occur as before, but should no longer increase. The tap (in picture 3) should no longer be turned on from 2020. The z. B. 3.5% of annual growth remaining after fuel savings should be offset with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) of the International Civil Aviation Organization (ICAO, a specialized agency of the UN). However, several problems arose here:

1. **CORSIA only compensates for growth**. If the tap is not turned on any further, then one barrel will eventually be empty or the other will overflow.
2. The start of CORSIA is voluntary from 2021. **The actual start of CORSIA is in 2027** and the end is already agreed for 2035.
3. The effectiveness of CORSIA is questioned for various reasons (Transport&Environment 2021, EU 2021a).
4. Forestry projects that are allowed to release the bound CO2 again from 2037 should be viewed critically (Fern 2017) (ÖkoInstitut 2020).
5. In 2020, the rules for CORSIA were weakened due to the pandemic (ICAO 2020). This means that payments through CORSIA will only occur if emissions are above 2019 levels. **Airlines will therefore not be offsetting any emissions via CORSIA in the next few years**.

Under increasing pressure from environmental activists, the concept of "climate-neutral growth" appeared to be unconvincing and was replaced by **the new concept "Zero Emission"** (Airbus 2020a, NLR 2021, ...). Aviation should be powered by renewable energies. “Zero emission” is not further defined and often just stands for “CO2-free”. What is certain is that the goal should be achieved by 2050. That currently leaves enough time for an unacknowledged “keep it up”. The new target, together with the collapse in passenger numbers in air traffic due to the pandemic, has also pushed aside the question of whether compensation will at least be made as promised from 2020 in the sense of “climate-neutral growth” (CNG). The first months of 2020 before the lock down showed that nothing was happening. CORSIA was referenced, but CORSIA had not yet launched. Goals and years come and go, but aviation's CO2 emissions continue to grow. An analysis of the goals and promises of aviation in Scholz 2020a.

The chemistry of the atmosphere is complicated. It's actually not about the emissions into the atmosphere, but about how the atmosphere reacts to the emissions. So, it's about whether something is **climate neutral**. But zero **emissions** are better than **CO2-free** because, in addition to CO2, there are also other climate-damaging gases that are evaluated based on their CO2 equivalents. If an activity emits CO2, then CO2 can be bound elsewhere. In this way, CO2 emissions can be compensated. This makes the activity **CO2-neutral**.

Terms must be precisely defined and differentiated. In the end, it's always about how an initially good idea like "Zero Emission" is incorporated into the argument. It is good if pollutant emissions are reduced every year on the way to “zero emissions”. An allocated **emissions budget must be adhered to**. But if air traffic continues to grow with reference to "zero emissions" in 2050 and emissions continue to rise every year despite technical successes and fill the barrel more and more quickly, then that will be of little help. The approach is also not justified by reference to the year 2050, in which any number of emission-free flights will no longer cause any emissions, because by then the aviation emissions budget will have already been exceeded.

"Zero emissions" is being promoted by the aviation industry, but it seems to be just a diversionary tactic. This was uncovered by InfluenceMap (https://www.InfluenceMap.org). The organization reports on systematic blockages to climate progress based on data-driven scientific methods. The current study (InfluenceMap 2021) identifies a dual strategy to avoid regulations on climate emissions. The industry has communicated high-level support at the European level for EU aviation's net-zero emissions by 2050 (https://www.destination2050.eu), while engaging directly with policymakers against specific national and EU climate regulations pronounced. At a global level, the International Civil Aviation Organization (ICAO) aims to ensure that CORSIA takes precedence over measures to reduce aviation emissions in absolute terms. The aim is to undermine the ambitions of the EU Emissions Trading System (EU ETS) for aviation (Figure 4).

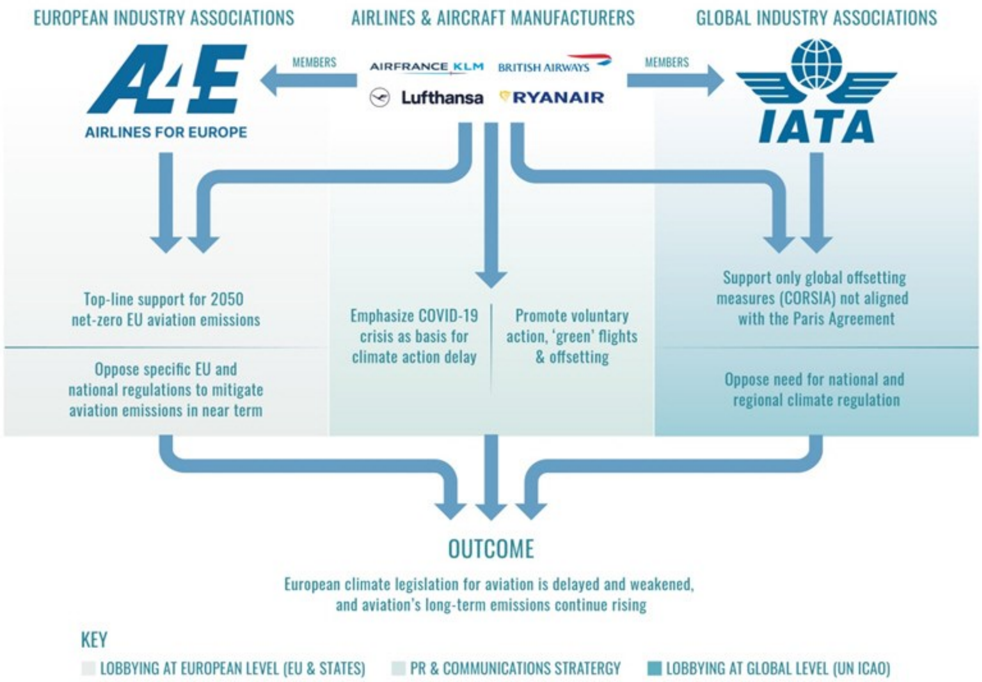

Bild 4: Die klimapolitische Strategie der Luftfahrtbranche (InfluenceMap 2021)

The statement by **John S. Slattery**, President of the engine manufacturer General Electric, could also be understood to mean that "zero emissions" is not a real goal. In Flight 2021a he is quoted with his statement about the "nirvana of zero-carbon flight"."Zero emissions" would then be more of a statement of faith. Exactly how “Nirvana” will be applied to aviation remains unclear.

Question 4: What climate goals does the EU have for aviation?

According to the EU's 2019 **"Green Deal", "no net greenhouse gas emissions should be released in 2050"**. "To achieve climate neutrality, transport-related emissions must be reduced by 90% by 2050." This means that the remaining 10% of emissions can be offset. "All modes of transport (road, rail, air and shipping) will have to contribute to this reduction." Aviation companies are to be allocated fewer certificates free of charge as part of the EU emissions trading system (EU ETS). This should be coordinated with the ICAO measures through CORSIA. The aim is to " improve **air quality near airports** by combating pollutant emissions from aircraft and airport operations." (EU 2019b)

In 2020, Europe's climate target for 2030 was defined. **As an interim goal for the Green Deal, greenhouse gas emissions are to be reduced by 55% compared to 1990** - i.e. only 45% of the 1990 value. This value should be achieved by 2030 (EU 2020a). The EU Commission has also submitted its proposals for aviation under the motto **"Fit for 55" (EU 2021b):**

1. The **free emission certificates** for aviation in the EU emissions trading system (EU ETS) **will be gradually abolished** (EU 2021c). For intra-European flights, the certificates are reduced by 4.2% every year. CORSIA (EU 2021d) applies to flights outside the EU. All European countries will participate voluntarily from 2021 (EU 2021e).
2. A **tax on kerosene** will be gradually introduced from January 1, 2023, before the final minimum rate of EUR 10.75/GJ is reached after a transition period of ten years (EU 2021f, EU 2021g).
3. **Fuel providers must gradually add sustainable aviation fuel** (SAF) to the turbine fuel offered in the EU (Figure 5), including so-called e-fuels (EU 2021h). Details on e-fuels see below. The European Aviation Safety Agency (EASA) is supposed to monitor and report (EASA 2021).
4. Airplanes must have access to clean electricity at airports (EU 2021b).

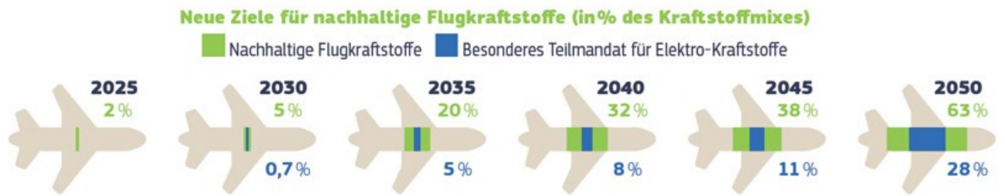

Bild 5: Nachhaltige Flugkraftstoffe (Sustainable Aviation Fuels, SAF) sollen dem konventionellen Kerosin schrittweise in höheren Anteilen beigemischt werden (EU2021d).

Total emissions in the EU are already falling by around 1% per year. Of the 55%, an average of 30% points have already been achieved. But things are different in the aviation sector, where emissions have grown since 1990 due to the increase in air traffic (Figure 6). The 55% reduction compared to 1990 now means a reduction of more than 80% for aviation by 2030, i.e. around 9% per year. Fuel consumption has so far been reduced by 1.5% annually through operational measures and technology. **Air traffic would** therefore **now have to permanently shrink by 7.5% per year** (regardless of the short-term impact of the pandemic). Given the social and political environment, this will probably not happen.

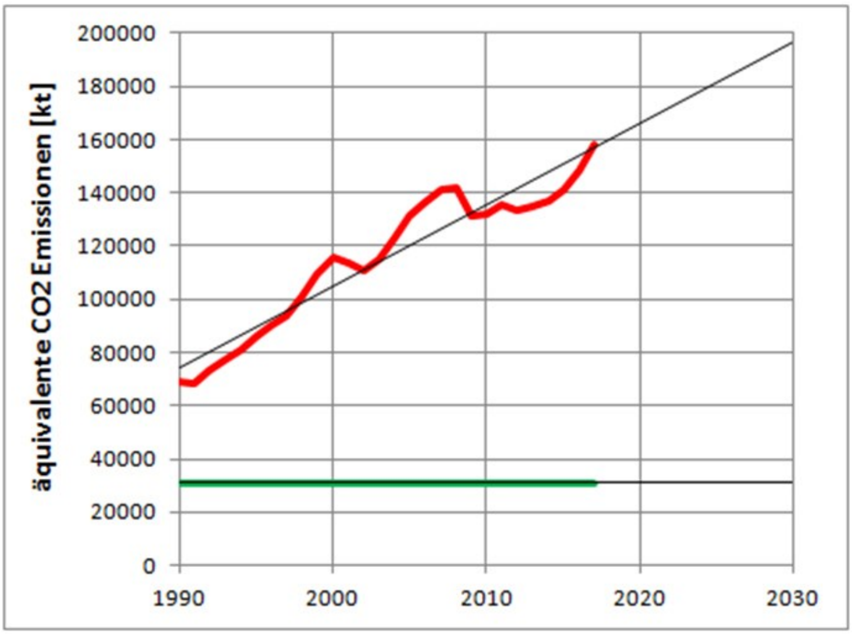

Bild 6: Die äquivalenten CO2 Emissionen (in 1000 Tonnen oder kt) der internationalen Luftfahrt in der EU steigen kontinuierlich (rote Linie), dabei sollen die Emissionen eigentlich nach dem "Green Deal" der EU gesenkt werden (bis 2030) auf 45 % des Wertes von 1990 (grüne Linie). Diagramm erstellt mit Daten von EEA 2019 (Scholz 2021b).

The EU Commission 's **"Fit for 55"** proposals now have to be concretely implemented in directives. Figure 7 shows the entire package of measures. The **ReFuelEU Aviation Initiative** (EU 2020b, EU 2021g) addresses aviation directly. This is about the use of sustainable fuels (Sustainable Aviation Fuel, SAF). Also of importance are the **Energy Taxation Directive** (**ETD**) (EU 2021f) and the **Renewable Energy Directive** (**RED II**) (EU 2019c). The rules are complicated.

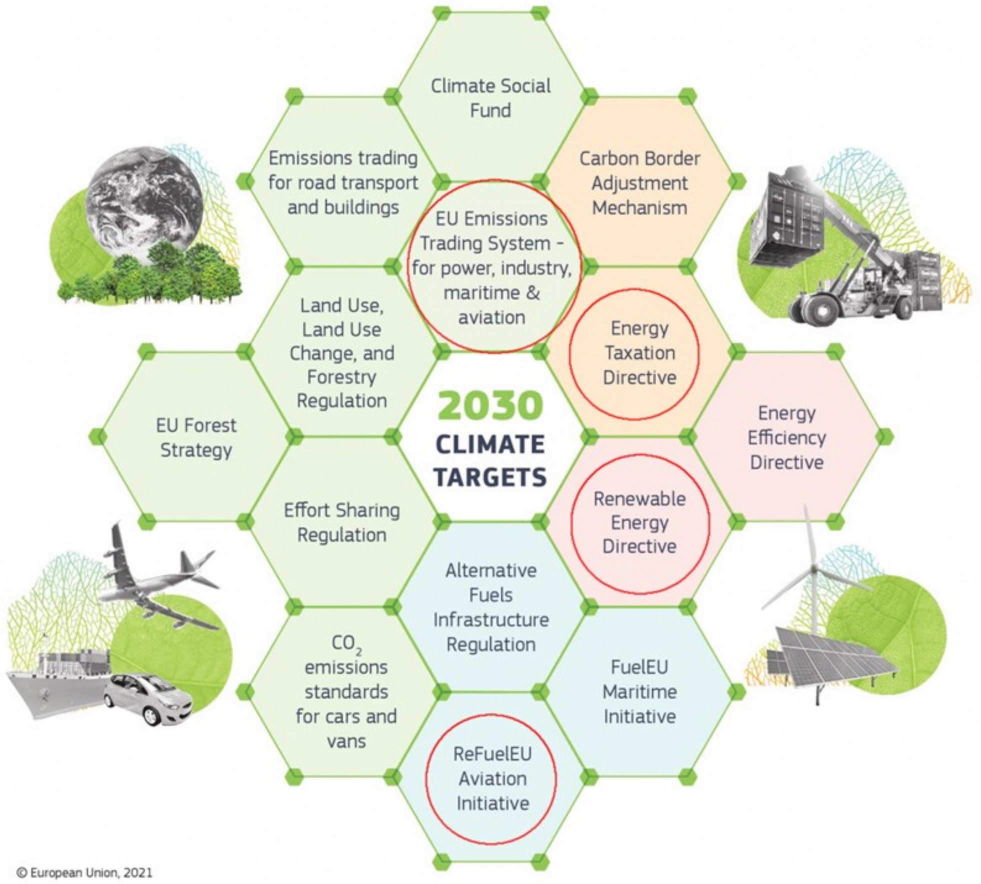

Bild 7: Das Paket für die Klimaziele bis 2030 ("Fit for 55"). Rot gekennzeichnet sind die Direktiven die besondere Bedeutung für die Luftfahrt haben (EU 2021i, CC BY).

Question 5: How do we get from oil to new aviation energy sources?

Fossil energy (petroleum) is so practical because it is taken from the earth and, after comparatively easy processing in the refinery, can be used as **kerosene in passenger aircraft.** Kerosene has a mass of one kg that stores a lot of energy (43 MJ) and requires little volume because of its high density (800 kg/m³). They say: "Kerosene is so good for flying - if nature hadn't given it to us, it would have had to be invented."

If aircraft are to or must operate without fossil fuels, then energy must be provided in another way and brought on board in an appropriate form. There is now a broad consensus in Germany that only renewable energies can be considered as **energy suppliers for aviation**. So it's about electricity from wind, biomass, sun and hydropower. In Germany, nuclear energy is no longer an energy supplier for aviation. The substance in which the green electricity is stored on board is the **energy carrier for aviation**. Batteries could absorb green electricity directly. Hydrogen or synthetic kerosene would first have to be produced using green electricity (see below).

Over the years there have been many suggestions as to how aviation could get by without fossil fuels and become more climate-friendly. It is not uncommon for such suggestions to be in the media for some time. But then it becomes quiet and you can't hear anything anymore. So e.g. with algae. Aviation **should run on fuel made from algae** (Reddy 2015). Algae fuel is a variant of biofuels. Since, in addition to agricultural land, fresh water supplies are limited in the world, the algae should grow in the ocean and then be processed into kerosene (NASA 2012). The issue has been resolved (Wesoff 2017). The process requires too much energy.

Renewable electricity should be stored in batteries. **Passenger aircraft should** be **battery-electrically operated**. Airbus wanted to experimentally convert an engine of a four-engine BAe 146 passenger aircraft to electric drive (Airbus 2018). The project was abandoned in 2020 (Airbus 2020a). Batteries are too heavy for flight operations and sufficiently light batteries are not in sight (Scholz 2018). **Hybrid-electric passenger aircraft** are being discussed. They use one of many possible combinations between conventional and electrical technology, but do not offer any advantages. The complicated drive technology increases costs and weight. Ultimately, there are hardly any advantages in terms of fuel consumption or emissions. However, word of this finding has not yet spread, so research continues with public money.

Two proposals for energy sources are currently being discussed:

1.) Water should be broken down into hydrogen and oxygen using green electricity and electrolysis. The **hydrogen** should then be transported as liquid hydrogen (LH2) in special tanks on the plane at around -250 °C. LH2 can then be used in only slightly modified jet engines. The principle was successfully demonstrated in the USSR in 1988 with a TU-155. Nevertheless, new aircraft would first have to be built and the infrastructure at the airports made available. Airbus initially wanted to offer an aircraft powered by LH2 on the market by 2035 (Airbus 2020b, Flight 2021b). **However, Airbus has confidentially declared to the EU that an LH2 medium-haul aircraft (100 to 250 seats) will not be used before 2050** (Airbus 2021, page 14). Even after that, it will not be possible to penetrate the market immediately because aircraft are usually in use for 30 years. Furthermore, **the impact on the climate of hydrogen aircraft is similar to that of kerosene-powered aircraft due to the non-CO2 effects** (Scholz 2020b). Due to conversion losses during electrolysis and hydrogen liquefaction, the amount of green electricity required is 1.7 times as high as the energy in the hydrogen produced (EU 2020c). **Taking the electricity mix into account** (see below), **the climate impact of hydrogen aircraft is higher** than that of kerosene aircraft.

2.) In order to offer a solution for existing aircraft, synthetic kerosene (**e-fuel**) should be produced from electricity, water and CO2. In addition to biofuels (e.g. from algae, see above), e-fuels are a variant of Sustainable Aviation Fuels (SAF) (EPRS 2020). Hydrogen is first obtained from water using electrolysis. CO2 is extracted from the air using Direct Air Capture (DAC). The components are connected to the fuel using the Fischer-Tropsch process, which was developed in Germany in 1925. A carbon cycle results because the CO2 is removed from the air with DAC. The details are shown in Figure 8. Because the synthetic kerosene largely corresponds to conventional kerosene, **aircraft that fly with e-fuels still have around 2/3 of the climate impact due to the non-CO2 effects**. When fuel production and DAC losses are taken into account, emissions are higher (see below).

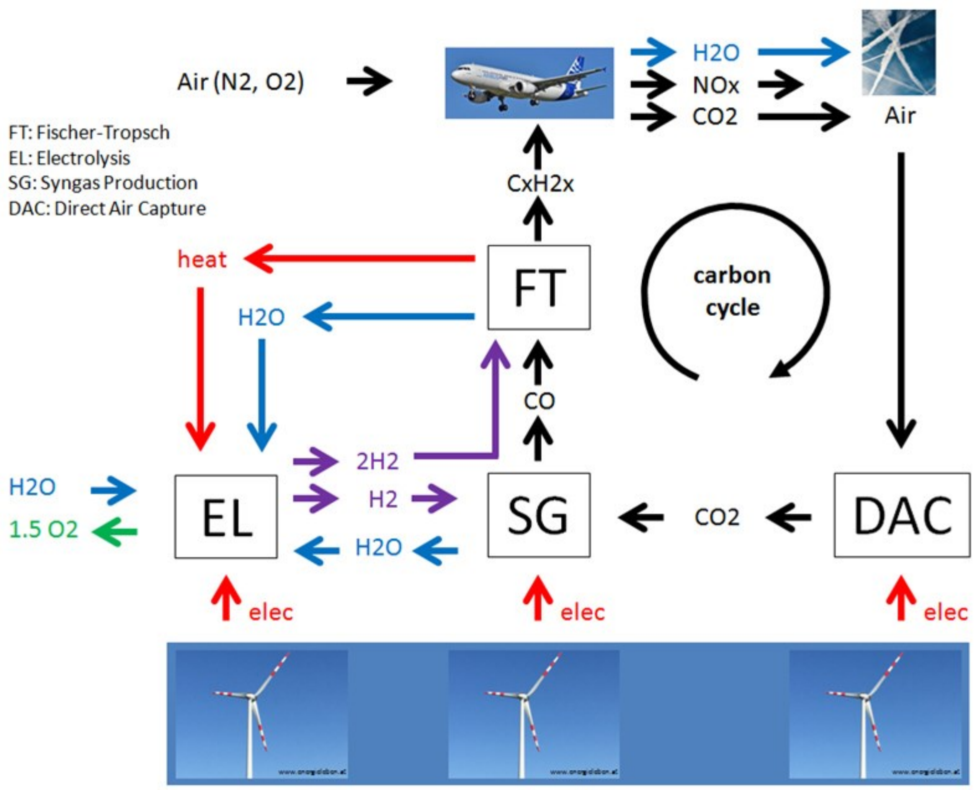

Bild 8: Herstellung von synthetischem Kerosin (E-Fuel) mit Power-to-Liquid (PtL). Durch die Entnahme von CO2 aus der Luft (Direct Air Capture, DAC) wird ein Kohlenstoffkreislauf (Carbon Cycle) ermöglicht. Gleichungen siehe Verdegaal 2015.

Very different information is given about the **conversion losses when creating e-fuels.** According to most data, the amount of green electricity required is 2 to 4.5 times as high as the energy in the synthetic kerosene produced (EU 2020c, ÖkoInstitut 2013, König 2016, Ueckerdt 2021). The company Sunfire (https://www.sunfire.de) wants to achieve an efficiency of 84% and thus only use 1.2 times the amount of green electricity. If there is no green electricity to produce the e-fuel, but only an electricity mix, then the CO2 from the electricity mix (see below) would also have to be taken out of the air using DAC and stored using CO2 capture and storage (carbon dioxide capture and storage). Storage, CSS).

The **effort required to capture CO2 from the air** (Direct Air Capture, DAC) is considerable because the air only consists of 0.04% CO2. At least 1.8 MJ of energy is required for capture per kg CO2 (Smith 2015). In practice, however, this is more like 7.2 MJ/kg (Brandani 2012). The Climeworks plant (https://www.climeworks.com) in Switzerland requires 12 MJ/kg (CarbonBrief 2017). 3.15 kg of CO2 are produced when 1 kg of kerosene is burned. With the energy content of kerosene of 43 MJ, DAC requires at least 4% of the energy of synthetic kerosene, more likely another 17% or even 28% in addition.

For the production of LH2 or e-fuels, you cannot select clean electricity from the grid and leave the dirty electricity to others. **The electricity mix must be considered**. The electricity mix in Germany currently has a share of 44.5% fossil energy (Figure 9). If more than 2.2 times the amount of green electricity is required for the entire e-fuel production process including DAC (Figure 8), then there will be no CO2 savings. According to the figures in the last two paragraphs, it is clear: **today no CO2 can be saved with e-fuels. This means that the climate impact of aircraft using e-fuels is no better than before - but possibly worse**. A linear extrapolation suggests that the share of fossil energy could have fallen to 20% in 2050 (Scholz

2021c). If e-fuels are produced in 2050, it might be possible to save CO2 emissions. However, "zero emissions" would not be achievable even in 2050.

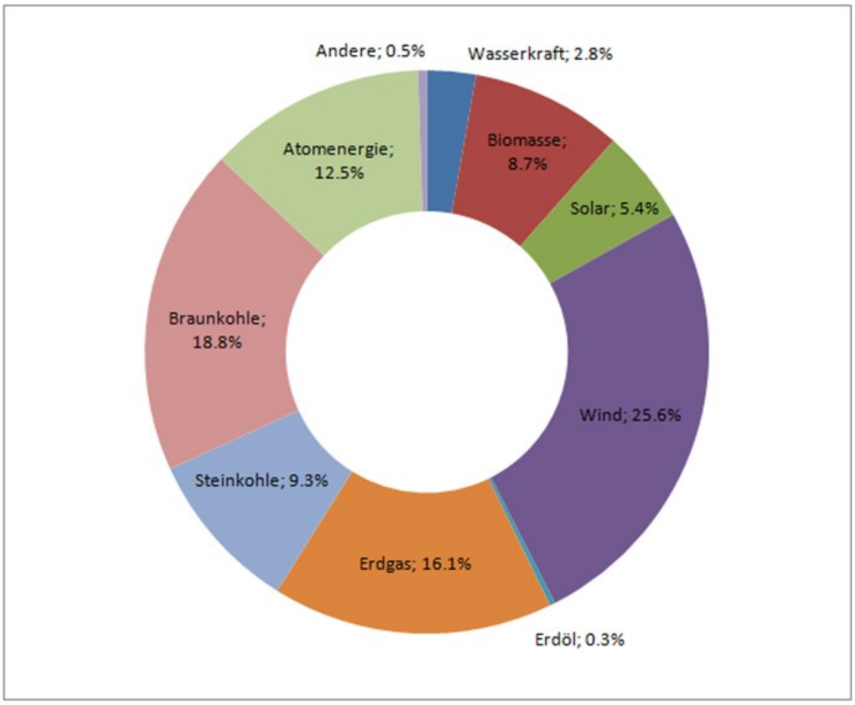

Bild 9: Strommix in Deutschland, 1. Quartal 2021. Erstellt nach Daten von: Fraunhofer, Institut für Solare Energiesysteme (Fraunhofer 2021). Erneuerbare Energien: 42,5 %. Fossile Energien: 44,5 %.

The Federal Association of the German Aviation Industry (BDL) writes: "Only with fuels based on additional renewable energies can flying be made climate-friendly in the medium to long term. Electricity-based kerosene (power-to-liquid = PtL) plays a central role in this When using fuel, the CO2 emitted when flying is previously removed from the atmosphere" (BDL 2021a). If additional renewable electricity is used, then there would be no need to consider the electricity mix. However, the additional renewable electricity could not come from Germany because German green electricity is already needed for the nuclear phase-out and the phase-out of coal-fired power generation (see below) and needs to be expanded further for this purpose. **Aviation would** therefore have **to find its own renewable energy sources** (BMU 2021). Certified green electricity from the desert would be one possibility. Norwegian electricity from hydropower will not be able to supply world aviation because the electricity is already being used in Norway today.

Unimaginably large amounts of green electricity would be required to supply aviation. To refuel an Airbus A350 once a day, 52 of the largest existing wind turbines (4.6 MW, 250 m high) would have to be planned. Direct Air Capture (DAC) would need to be organized, but is still in the early stages of development (https://www.climeworks.com). The energy for DAC is not yet included in the 52 wind turbines. **The DAC system for each aircraft would have a footprint significantly larger than that of the aircraft itself,** based on its length and wingspan (calculated based on data from Sapea 2018).

In summary, **the two energy sources** hydrogen (LH2) and synthetic kerosene (e-fuel) make it possible to continue flying when fossil fuels run out (or fuel prices have increased due to low availability). However, due to the conversion losses (especially with e-fuels), a lot of green electricity is required, which will be noticeable in the energy costs. **LH2** has the advantage for the climate that there is no **direct accumulation of legacy CO2** (except through the electricity mix). However, the **climate impact of aviation with LH2 remains unchanged** due to the non-CO2 effects. The same could be said for e-fuels if there were an electricity mix without fossil energy. That's not the case. Therefore, **e-fuels do not bring any advantages for the climate for the time being**.

Question 6: Can fuel consumption and emissions be reduced?

Fuel consumption **per capita and kilometer** was reduced by 1.5% each year. This is only partly due to technical progress. The rest was achieved by giving the aircraft a cabin layout that accommodated more passengers and by increasing the capacity utilization of the aircraft. From 1968 to 2018, utilization increased from 52.5% to 84%. That's an increase of about 1% per year (TransportGeography 2018).

Let's look at a concrete example of **reducing fuel consumption through the use of technology**. Between 1988 and 2016, the Airbus A320 became the Airbus A320neo. Fuel consumption could be reduced by using new engines and wings with raised ends (winglets). According to the manufacturer, the fuel consumption of the A320neo is 15% lower than the previous model. In this case, that is 0.5% fuel savings per year, which was technologically achieved between 1988 and 2016, i.e. in 28 years.

Airplanes are already very technically developed. This **makes it increasingly difficult to further reduce the fuel consumption of passenger aircraft**. In addition, you always have to pay attention to the weight on the plane. A change to the aircraft that increases efficiency but makes the aircraft heavier does not ultimately have to bring any advantage in terms of fuel consumption. Processes that take place on the ground have advantages because there is no need to pay attention to the weight of the components. This is where the old statement comes from: "The last drop of fuel will go into the plane", and we will have to look for propulsion alternatives elsewhere. Trading **in emissions certificates** aims to put this trade-off on an economic basis. Emissions should be reduced where it is economically advantageous.

Due to the efficiency chains, it is e.g. B. It is much more helpful to replace coal-fired power plants with renewable energy than to use kerosene in airplanes. Figure 10 shows a CO2 avoidance per kWh of renewable energy of 0.9 kg in a coal-fired power plant compared to only 0.057 kg in an airplane. **The use of renewable energy in the power plant avoids 15 times more CO2** (at the assumed efficiencies).

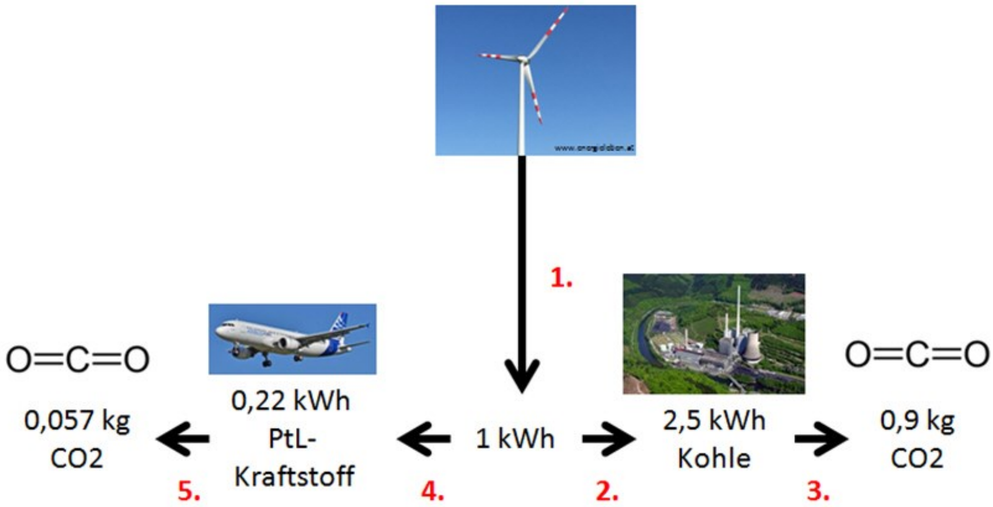

Bild 10: 1.) 1 kWh erneuerbarer Energie ...
2.) ... kann 2,5 kWh Braunkohle im Kohlekraftwerk ersetzen (Wirkungsgrad 40 %);
3.) das entspricht 0,9 kg CO2 (0,36 kg CO2 für 1 kWh Energy durch Braunkohle*).
4.) ... umgewandelt in Sustainable Aviation Fuel (SAF) bleiben davon nur 0.22 kWh (Wirkungsgrade: 70 % Elektrolyse, 32 % Fischer-Tropsch, EU 2020, S. 44),
5.) die nur 0.057 kg CO2 einsparen (0.26 kg CO2 für 1 kWh of Kerosin*).

* UBA, 2016: CO2 Emission Factors for Fossil Fuels. https://bit.ly/3r8avD1

Question 7: What are the fuel consumption and emissions of passenger aircraft?

The **fuel consumption of passenger aircraft** is not defined and not publicly stated and is therefore **beyond public discussion**. However, it is possible to calculate fuel consumption from publicly available manufacturer information. For those who would like to delve further into the topic, here is a simple estimate. Four numbers are required, which can usually be found and are not subject to secrecy: the maximum take-off mass (MTOW), the mass of the fully loaded aircraft without fuel (MZFW), the maximum range (R) when fully loaded (i.e. at MZFW) and the number of seats (SP). That's it then

Consumption = (MTOW – MZFW) / (R · SP) · 100

Example Airbus A320neo:

2.2 kg per 100 km and seat = (73500 kg – 62800 kg) / (3180 km · 150) · 100

The consumption calculated so simply is a bit too high. Multiplied by the distance (as the crow flies) between two locations, the fuel consumption for the flight route is quite suitable. A comparison between two aircraft is also possible.

A more precise calculation (Scholz 2021a) is shown in Figure 11a/11b. It is noticeable that **the fuel consumption of passenger aircraft** depends heavily on the flight route. Fuel consumption is comparatively constant over a wide range of applications (medium flight distances). **Fuel consumption per seat increases sharply when flying very short routes or, for the aircraft, very long routes**. An aircraft can only achieve extreme ranges if it is operated with a reduced payload (with fewer passengers) and is therefore lighter. This increases consumption per person. Fuel is used for take-off and landing as well as for the gain in altitude when climbing, which cannot be fully used when descending. This leads to an increase in consumption per kilometer on short journeys. In the example (Figure 11a), the consumption at 500 km is twice as high as the minimum consumption of the aircraft. **Passenger aircraft are therefore not suitable for extreme short-haul flights due to flight physics alone.**

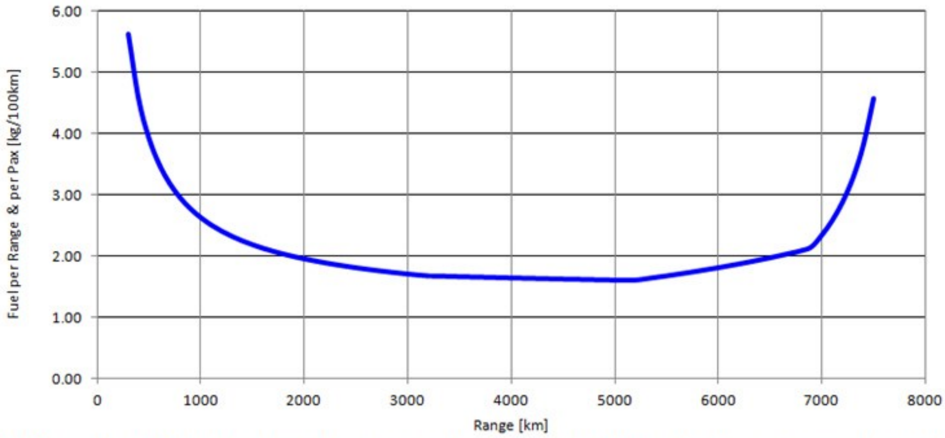

Bild 11a: Der Kraftstoffverbrauch eines modernen Kurz- Mittelstreckenflugzeugs am Beispiel des Airbus A320neo abhängig von der Flugstrecke in kg pro Sitzplatz und 100 km.

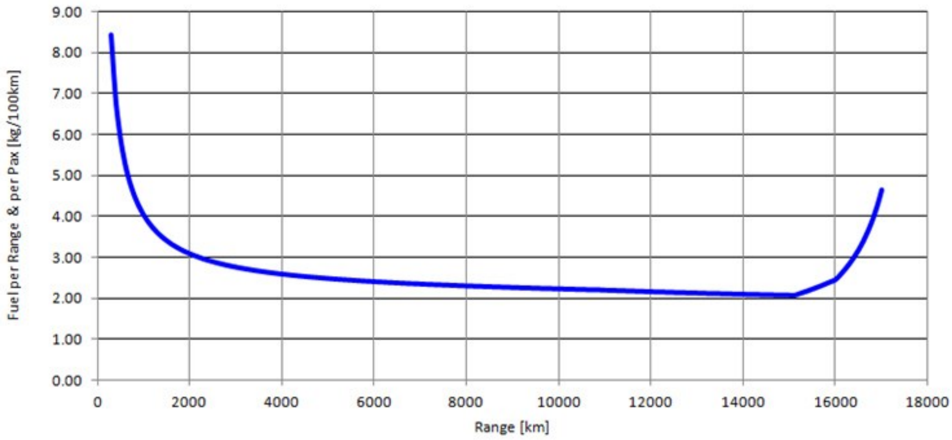

Bild 11b: Der Kraftstoffverbrauch eines modernen Langstreckenflugzeugs am Beispiel des Airbus A350-900 abhängig von der Flugstrecke in kg pro Sitzplatz und 100 km.

For a **comparison with a car,** one could assume a typical fuel mass of 3 kg per seat and 100 km for an airplane (BDL 2013). However, we are assuming the lower fuel consumption of a modern short-medium-haul aircraft. According to Figure 11a, this is 1.7 kg per seat and 100 km if the aircraft is operated in its optimal flight range. With the density of kerosene, that's about 2.1 liters per seat per 100 km, but 2.7 liters per person per 100 km if the plane is only 80% full. **A fully occupied car consumes significantly less per person than a fully occupied airplane**. However, if you are traveling alone in a car, then the plane would be cheaper in terms of energy consumption. However, when it comes to aircraft emissions, the non-CO2 effects (see below) must be taken into account with a factor of 3. A car would then **be better for the climate, even if it is only used by one person**.

The valuable asset in the aircraft cabin is the cabin space. Strictly speaking, the **consumption would have to be calculated per square meter of cabin space**. If you fly in first class with a wide seat and plenty of legroom, you will use more cabin space and will also have a higher fuel consumption than the person who has squeezed into tourist class.

In principle, the airlines fly the same few aircraft types that are available on the market. Consumption per person can only be reduced by increasing the number of passengers on the plane. This is achieved through tight seating and high occupancy. Low-cost airlines are known for tight seating and high occupancy. **In practice, cheap ticket prices go** hand **in hand with low consumption per capita and kilometer** and a low environmental impact. Nobody wants to ban flying or even make flying holidays impossible for low-income earners with many children. **Government intervention in ticket prices at the lower end of the scale should therefore** be avoided. If, despite the otherwise invoked free market, the price structure of airline tickets is to be intervened, then it would be where there is high consumption per capita and that would be where a lot of cabin space is used per seat. So additional charges could be levied on first class tickets. This could result in demand falling, this class being reduced in size, more passengers being able to fit on a plane and therefore fewer planes having to fly, thus reducing emissions.

The CO2 is distributed evenly in the atmosphere over very long periods of time. **The non-CO2 effects** (due to NOX and AIC) also arise depending on the flight altitude. Its effect is limited in time, but intense. There is the warming effect of **nitrogen oxides** (NOX) on the complicated chemistry of the atmosphere. There is also the overall warming effect of the contrails and the cirrus clouds that can form from the contrails. This is called **Aviation-Induced Cloudiness** (AIC). AIC acts differently during the day and at night, in summer and winter, at the equator and at the pole.

The **impact of aviation's non-CO2 effects** is approximately twice as large as the impact of CO2 alone. So **the overall effect is about three times as large**. The amount of equivalent CO2 describes the amount of CO2 that has the same effect on the climate as the sum of CO2 and non-CO2 effects. The **amount of equivalent CO2** is therefore about three times as large as the amount of CO2. The factor depends on the flight altitude. The factor three applies to a typical cruising altitude.

Back to **Aviation-Induced Cloudiness**. If we look at medium latitudes, the effect is particularly high at an altitude of around 10 km - for example where passenger planes fly. **AIC can** therefore be avoided entirely or **greatly reduced by flying slightly lower (and slower)**. This only needs to happen if current atmospheric conditions require it. Fuel consumption and therefore CO2 emissions would increase slightly. A little more fuel costs a little more. **However, the environmental impact of air traffic could** be significantly reduced in this way **today**. A careful consideration must be made between the AIC characteristics and the slightly increasing CO2 emissions. The best compromise can be found via the flight altitude. Basically, the connections are known. Unfortunately, the airlines refuse, saying "further research is needed on this" (BDL 2021b). The behavior is understandable; this is not about declarations of intent for the year 2050, but about now and today. But it costs money – even if only a little. Not every airline will therefore be convinced by this measure. The airlines do not want to bear the costs themselves. The costs would then have to be passed on to the passengers. In tough competition, the airline that applies the AIC reduction measure would be at a disadvantage. So, it will be a long time waiting for the final results of the research. **An opportunity is missed**.

According to a simple estimate for a short/medium-haul aircraft: At a flight altitude of 6500 m, the climate impact would be reduced by 70%, while fuel consumption would increase by 6% and costs by 0.6%. https://nbn-resolving.org/urn:nbn:de:gbv:18302-aero2019-07-28.013

Question 8: Which is better for the environment – plane or train?

When comparing modes of transport, the **comparison between planes and trains** is the subject of current discussion.

There are **connections** where only the plane can make an offer (over oceans, mountains, deserts, ...). Where both the plane and the train make an offer, it must be weighed up. The train is often ruled out because the tickets are too expensive, or no connection or price can be determined across borders via the Internet. If you want to make good use of the longer travel time on the train, you could travel overnight. But that requires appropriate offers. Night connections are often missing. There is therefore still considerable potential for improvement, particularly in international rail transport.

The energy consumption of a train is low on the route. Energy for acceleration that cannot or only partially be recovered when braking is crucial. The distance between the stations and the speed that should be achieved between them is therefore important. Consumption increases sharply in the tunnel. The train's consumption can actually only be stated for one train together with the route traveled. Despite these fundamental difficulties, an average consumption of **60 Wh per seat and km** should be assumed (Fraunhofer 2020, Figure 4.2). The comparison does not take into account the fact that passengers have more space on the train. A comparison with an airplane will only be possible when the primary energy used for the train's electrical energy is calculated. This is the amount of energy (e.g. diesel) that is required to generate electrical energy in the power plant. The electricity mix plays a role here. It is therefore like this: the conversion losses in the power plant have a negative impact on the train. The aircraft struggles with these conversion losses in its own engine. A typical fuel mass of 3 kg per seat and 100 km is assumed for the aircraft (BDL 2013). **The energy consumption of the plane is then 2.8 times higher than that of the train**.

Next, the **CO2 emissions** are compared. If the train is operated with the general electricity mix, it already runs with a lower fossil fuel content and the plane therefore has 6.1 times higher CO2 emissions. The equivalent CO2 at cruising altitude is three times higher for an airplane. In this example, the aircraft **has 18.3 times the environmental impact**. If the aircraft then makes the comparison with the train on extremely short routes, the aircraft's consumption may be higher than 3 kg per seat and 100 km (Figure 11) and the comparison would be even less favorable for the aircraft. In this case, it would be helpful for the aircraft if the normal cruising altitude is not reached on the short route and the factor 3 for calculating the equivalent CO2 is reduced somewhat.

If we look into the future, the comparison between airplanes and trains will become increasingly worse for airplanes. **The train benefits from the increasing proportion of green electricity in the electricity mix** (while the proportion of fossil fuels is decreasing). The aircraft, however, flies unchanged on kerosene. However, if the aircraft flies with e-fuel, then the comparison for the aircraft with the introduction of e-fuels suddenly deteriorates due to the poor efficiency of the e-fuels due to the many conversions and the energy consumption for CO2 capture from the air. The absolute values for the aircraft improve over time as the proportion of green electricity increases. However, this also applies to trains, so that the poor performance of aircraft compared to trains is cemented and the comparison no longer improves with a higher proportion of green electricity. The plane then uses over 20 times more energy than the train. The calculations for the plane-train comparison are available at Scholz 2021c.

Further criteria for comparing planes and trains are only addressed qualitatively here. To fly from A to B, the aircraft only needs the infrastructure in A and B, i.e. the airports. In addition to the train stations, a train also needs the infrastructure to connect from A to B. The terminal buildings at an airport are comparable to the train stations. In addition, there are areas for runways in the air traffic system. The size of the area required for this is not insignificant. The **reservation of space** for air or rail traffic is **the subject of social disputes**. One example is the dispute over the west runway at Frankfurt Airport. The expansion of railway lines is also controversial. In both cases, the protest is directed against **traffic noise** and against **land use** with corresponding negative effects on nature. For short-haul flights, a large number of square meters of airport space are covered by a few kilometers of route. For long-haul flights, the space required is low in relation to the flight route. The area required by the railway is proportional to the length of the route and can be reduced if the route is on stilts. Many high-speed lines have been built in China. Additional traffic noise from the railway can be limited by routing along the motorway. The aircraft causes **local air pollution** and noise only at the airport. The electrified railway causes local air pollution at the power plant depending on the fossil share of the electricity mix. These are comparatively small. However, noise pollution occurs along the entire railway line. On longer journeys, trains therefore cause more traffic noise than planes (EEA 2020).

Whether it will ultimately be possible to motivate airline passengers to switch to trains depends on the overall offering. If the railway's offering is correspondingly attractive, then other new rail passengers could be attracted in addition to the airline passengers. However, these would cause additional emissions with every additional passenger kilometer. If efficiency improvements lead to an increase in passenger kilometers, then the original savings will be completely or partially offset. This effect is called **the rebound effect**. Conversely, we have already observed this during the pandemic. The travel offer just has to be sufficiently unattractive, then it will not be accepted, and emissions will fall.

Question 9: Where are we?

Germany has big plans. The exit from nuclear power and coal-fired power generation should be successful at the same time, while the expansion of renewable energies is already showing problems. **Domestic renewable electricity must therefore first replace the lignite-fired power plants**. Because of the efficiency chains, this makes more energy sense than using renewable electricity in the aircraft (Figure 10). On the other hand, aviation also has to make its contribution. Countries that still export oil today could shift to producing eco-certified e-fuels. The airlines could get supplies here. However, corresponding offers are not yet in sight and the political circumstances are fraught with risk. The certified additional green electricity could be used to produce e-fuels (SAF) using Direct Air Capture (DAC). The carbon cycle would not release any more CO2 into the atmosphere. However, the climate is further heated up by the non-CO2 effects. **Without a reduction in passenger numbers, aviation cannot achieve its** climate **goals**.

There are no patent solutions. **The hope that technology will fix it is unfortunately unfounded**. It would be nice if we could get the environmental challenges under control while both the aircraft fleets and our travel habits could remain as they are now. But that won't happen. The realization seems to have prevailed that "business as usual" doesn't necessarily end well – at least not for the younger generation. Manufacturers will continue to work on improving efficiency, but this will be more than offset by the growth in air traffic. Airlines will continue to optimize flight operations, but only in terms of costs, which is not always optimal for the environment. They have so far refused to consider the possibility of avoiding Aviation-Induced Cloudiness (AIC) by flying lower. **So, it's up to the passengers to vote with their feet again**. This requires an **independent understanding of the connections**. It is not easy to gain this understanding when interest groups have power to spread their own view of things.

Question 10: What ideas and possible solutions are there?

Even if Sustainable Aviation Fuel (SAF) is problematic as a solution to the environmental issues of aviation (see above), the path to achieve this must at least be taken with pilot plants for SAF production. Germany could become a technology leader in the production of **systems for SAF production and systems for direct air capture (DAC)** . Such systems could then **be produced in Germany and exported to the countries from which we could then import SAF with a certificate**.

Ultimately, aviation emissions can only be brought under control by reducing air traffic (see above). It is helpful to understand the **unequal distribution of flights and emissions.** 1% of the world's population causes 50% of the CO2 emissions from civil aviation (Gössling 2020). 1% of the EU population produced 41% of CO2 emissions (Hopkinson 2020). Passengers from 5 nations share 33% of international flights (IATA 2019). So, it is the frequent flyers who are responsible for a disproportionate share of emissions (BBC 2021). **Frequent flyer programs** may bring customer loyalty for airlines, but they are no longer appropriate in times of climate change and **need to be examined**. In extreme cases, frequent flyer programs lead to addictive behavior when "mile runners" (Fox 2015) want to enhance their self-esteem in a questionable way with their frequent flyer status.

The question arises: **Can flying be banned or restricted by law?** Is there a fundamental right to travel by air? There is no independent fundamental right to mobility using a specific means of transport. However, mobility must fundamentally be guaranteed by the legislature and is protected as an individual exercise of freedom. Airplanes may be the only means of transport on certain routes, making it impossible to replace air travel with another means of transport. In general, it is about the development of personality, self-determination, participation, interaction, communication, professional freedom, freedom of assembly, freedom of contract, freedom to leave the country and the subsistence minimum (in terms of mobility). Our constitution assumes that every person is initially free until the freedom of the other. However, the state also has a duty to protect the life and health of its citizens. This duty of protection is relevant when people are exposed to emissions or climate change. "The 'freedom of mobility' is therefore not a special, unnamed fundamental right, but rather a further specification of the general freedom of action of Article 2 Paragraph 1 of the Basic Law." " **It turns out that the state has many options open to it from a constitutional point of view to bring about a change in transport.** Here, fundamental rights guarantees of mobility do not restrict the legislature in its options for action by interfering with fundamental rights, but rather act as an incentive and guide for it to develop innovative concepts mobility... to find." (Greitens 2018, emphasis by the author)

The state can control behavior through taxes and fees. Taxing **fuel** would be easy to implement. Estimates (EU 2021g) have shown that only around 0.65% of the revenue from the kerosene tax would be incurred for its administration. This is because there are only a limited number of places where kerosene is sold. A kerosene tax would affect everyone financially in proportion to the kerosene consumption. The introduction of a kerosene tax would ensure more fairness in the competition between different modes of transport. In its proposals, the EU has in mind that, if possible, there should be no shift in traffic to non-European airlines. Keyword: “Level Playing Field for Sustainable Air Transport” (EU 2021h).

We know from tax law that there is a **basic allowance** - a guaranteed minimum subsistence level for flying, so to speak - **followed by progressive taxation**. Applied to flying, one would have to determine the (equivalent?) **CO2 emissions per year and then tax them** accordingly. A basic allowance would also ensure that poorer parts of the population can continue to participate in air transport at the same costs. Average earners would be financially slowed down if they fly excessively. The super-rich would pay what is required and carry on as before. Business flights could be charged to companies and not to individuals, who as employees may not decide on the frequency of travel or the choice of mode of transport. Income should be used appropriately. Corresponding suggestions are available (Possible 2021). The administrative hurdles are high and well-known: complexity, data protection, correct assignment to the passenger and various necessary exemptions that would have to be organized (BBC 2021).

Analogous to the CO2 certificates that were issued free of charge to industry, **every person could receive a free CO2 budget**. If the budget is exceeded, payment would have to be made. It would then be possible to set individual priorities in life, because the personal CO2 footprint includes: mobility (journeys and travel with different means of transport), living and heating, electricity consumption, nutrition, consumption and pets (Federal Environment Agency 2021). Theoretically, for example, there would be B. the possibility of “saving yourself” the long-distance journey. It is clear that the state administration of such billing is currently impossible and may not be desirable for data protection reasons.

It would be easier to **rely on a change in values in society**. More locality, more modesty and deceleration. There will continue to be pioneers and brakes, but the change in thinking will come with increasing evidence of climate change and its consequences and causalities. Sweden made the start and the young generation with Fridays for Future. The term "**flight shame**" has become established. However, the change in values will be driven more by a self-confident understanding of the circumstances than by our conscience, which generates a feeling of shame. Traveling to distant countries will no longer automatically elicit recognition, explains Prof. Nawrocki (2021), lecturer in the subjects "Renewable Energy Systems" and "Post-Growth Economics". "**A lot of CO2 – a lot of honor" was yesterday**. Instead, it will soon be good manners to include a brief explanation of the need and efforts to minimize CO2 in a travel description. It would be hoped that politicians and public authorities would get involved in disseminating factual information on the topic. Advice like that from Transport Minister Andreas Scheuer: "I also warn against promoting flight shame now" (FAZ 2019) is of little help and only serves the interests of the associations.

The aviation industry is fighting against "flight shame" (Hagagy 2019). The International Air Transport Association (IATA) has created the website https://www.flyaware.com/your-journey on the Internet. **First note to passengers: "Compensate"!** The result for the environment is questionable (see above). Scott Kirby, CEO of United Airlines describes it like this: "And what I hate about traditional carbon offset programs is so many companies are using them, and they are a fig leaf for a CEO to write a check, check a box, pretend that they 've done the right thing for sustainability when they haven't made one wit of difference in the real world." (CAPA 2021) What is worrying about the IATA campaign is that the responsibility for compensating (if it should be) is pushed onto the passengers. **Second note to passengers: "pack less"!** It is true, of course, that every kilogram helps. But the argument “just a kilo less, once multiplied across every passenger and every flight, can make a huge difference to CO2 emissions" is banal. Of course, any small effect becomes larger when multiplied. Instead, this consideration helps: even with tight seating, between 300 kg and 1000 kg of the aircraft's take-off weight per passenger. Statistically, that's around 500 kg on average. The value depends on the range and technology of the aircraft. **With one kilogram less of luggage you can save roughly 0.2%** (=1/500) **of the emissions for which you are personally responsible**.

Question 11: What can we actually do ourselves?

This is specifically possible:

- Fly less (e.g. replacing the flight with a video conference; vacationing close to home),
- Fly in tourist class (take up little cabin space),
- Question the necessity of long-haul flights in particular,
- Choose direct flights instead of detours and stopovers,
- Avoid aircraft that squeeze out the last bit of range and therefore travel with a significantly reduced number of seats (consumption per seat is high),
- Avoid short journeys by plane (consumption per km is high),
- Use Rail & Fly (arrival to the international airport by train),
- Choose new efficient aircraft (but: the old aircraft fly somewhere else),
- Choose low-cost airlines (high efficiency due to narrow seating and high utilization),
- Avoid unnecessary luggage (a lighter aircraft consumes less, every kilogram counts, but it only brings a small percentage, see above),
- Check train offers for longer routes (night train?),
- Talk to airlines about avoiding Aviation-Induced Cloudiness (AIC) by flying slightly lower and slower (reducing the climate impact of flights now before the climate changes).

For references, please see the German version of this text.

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