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AVIATION SECTOR POSSIBILITIES TO REDUCE GLOBAL WARMING IMPACT

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ABSTRACT

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The aviation sector nowadays is responsible for 2% of the global carbon dioxide emissions, but its warming effect is much higher due to the indirect warming impacts at altitudes. It is estimated to be by a factor of 5.2 higher than from carbon dioxide emissions only, although there is still uncertainty related to the factor. The global decarbonization trend is challenging to be applied in aviation because of technological and safety limitations. Currently, aviation has a 12-year time lag between efficiency improvement targets and its state of the art. This master’s thesis aims to analyze and assess aircraft induced emissions and their warming effects as well as options to mitigate them.

There are several pathways for the aviation industry to meet global environmental goals. Jet engine efficiency improvements alone can contribute to 25% emissions reduction, and updated flight procedures to 12%. Moreover, weight reduction options and improved aerodynamic can further pursue emissions reduction. Warming impact reduction from using synthetic jet fuels with carbon capture was assessed as a possible aviation pathway towards a carbon-neutral future. The results show that such fuels can lead to a significant cut of aircraft induced warming impacts altogether with fuel consumption efficiency improvements. However, even though synthetic fuels produced with renewable energy and carbon capture can have net-zero carbon dioxide emissions, they still produce emissions, which induce indirect warming impacts. Thus, further research on the total aircraft warming effect mitigation options is needed.
ACKNOWLEDGMENTS

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Thank you.
Vitalii Lundaev

Lappeenranta, November 16, 2019
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<th>Description</th>
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<tbody>
<tr>
<td>AIC</td>
<td>Aviation-Induced Cloudiness</td>
</tr>
<tr>
<td>ANSP</td>
<td>Air Navigation Service Providers</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>BAU</td>
<td>Business-As-Usual</td>
</tr>
<tr>
<td>BtL</td>
<td>Biomass-to-Liquid</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>CO2-eq</td>
<td>Carbon Dioxide Equivalent</td>
</tr>
<tr>
<td>COP</td>
<td>Conference of the Parties</td>
</tr>
<tr>
<td>CORSIA</td>
<td>Carbon Offsetting and Reduction Scheme for International Aviation</td>
</tr>
<tr>
<td>CSR</td>
<td>Corporate Social Responsibility</td>
</tr>
<tr>
<td>DAC</td>
<td>Direct Air Capture</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Demand Product</td>
</tr>
<tr>
<td>GHGs</td>
<td>Greenhouse Gases</td>
</tr>
<tr>
<td>GTP</td>
<td>Global Temperature Potential</td>
</tr>
<tr>
<td>H/C</td>
<td>Hydrogen/Carbon ratio</td>
</tr>
<tr>
<td>INDCs</td>
<td>Intended Nationally Determined Contributions</td>
</tr>
<tr>
<td>LOSU</td>
<td>Level of Scientific Understanding</td>
</tr>
<tr>
<td>LTO</td>
<td>Landing/Take-off Cycle</td>
</tr>
<tr>
<td>NMVOC</td>
<td>Non-Methane Volatile Organic Compounds</td>
</tr>
<tr>
<td>PtL</td>
<td>Power-to-Liquid</td>
</tr>
<tr>
<td>PtX</td>
<td>Power-to-X (gas/liquid)</td>
</tr>
<tr>
<td>RF</td>
<td>Radiative Forcing</td>
</tr>
<tr>
<td>RFI</td>
<td>Radiative Forcing Index</td>
</tr>
<tr>
<td>RVSM</td>
<td>Reduced Vertical Separation Minima</td>
</tr>
<tr>
<td>SSPs</td>
<td>Shared Socioeconomic Pathways</td>
</tr>
<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
</tbody>
</table>


1 INTRODUCTION

Global warming is one of the biggest threats the humankind faces nowadays. The global mean temperature has been increasing at 0.2°C per decade and reached 1°C of warming above the pre-industrial level. Human actions mainly cause anthropogenic emissions, and this trend is not going to stop. The impact of global warming has been observed even nowadays. It has to do with sea-level rise, increasing number of climate cataclysms, precipitation problems, and droughts, forest fires, food supply risks, decreasing extent of snow and glaciers, loosing of biodiversity, and ecosystems changes. (IPCC, 2018, pp. 4-8)

Global warming leads to climate change. However, it is not the only reason of it. While global warming is associated with human-produced emissions, climate change, in turn, also includes natural processes such as ocean patterns variabilities, volcanic activities, the planet’s orbit changes, and differences in the energy output of the Sun (NASA, 2019). The global mean temperature growth is primarily a consequence of the anthropogenic related greenhouse gas emissions (GHGs) rise in the atmosphere. These GHGs do not allow heat to dissipate by trapping the terrestrial radiation, which in turn creates the greenhouse effect and heats the planet (EPA, 2019, pp. 58-59). GHGs comprise water vapor, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), ozone (O₃), and some other gases, which catch the surface radiation due to their high thermal capacity (Barbera, et al., 2019, pp. 1-2; Romm, 2018). Carbon dioxide equivalent (CO₂-eq) is used to compare a potential warming effect of different greenhouse gases in the atmosphere. It is obtained from the mass, global warming potential of the gas, and its lifetime in the atmosphere (OECD, 2013).

The global GHG emissions are expected to rise even further. A level of 1.5°C temperature rise most likely will be passed by the middle of the century, while other scenarios of 2°C warming and even more are possible. The main reason is the growing energy demand, which caused mainly by population growth and increasing gross demand product (GDP), especially in developing countries. Since nowadays, energy generation is mostly based on fossil fuels, a transition towards renewable energy is urgently needed. Renewable energy allows for generating carbon-neutral electricity, heat, and fuels. Such resources as solar energy have no availability limitation, while wind energy, hydropower, geothermal, and bioenergy
technologies also have a mature status of development and can compete with conventional energy carriers even today. (IPCC, 2018, pp. 4-8)

Transportation is a sector of the economy that is very energy-intensive and difficult to decarbonize. Direct emissions from all kinds of vehicles globally were 7 GtCO₂-eq in 2010 or almost one-fourth of energy-related carbon dioxide emissions in the world. The emissions have had the fastest growth among all of the energy end-use sectors since 1970, even though efficiency improvements in vehicles and policy regulations on climate change mitigations being implemented. If any other rules are not adopted, developing countries will significantly pursue transport GHGs emissions growth to the annual level of 12 GtCO₂-eq by 2050 due to their growing economies and transportation demand per capita. (IPCC, 2014, pp. 603-605)

In the future, the transportation sector has to be fully sustainable to meet the Paris agreement, and this is a new challenge for the whole industry. While road vehicles are promising to be fully electrified with renewable energy, the aviation sector seems to be more problematic (ICCT, 2019, p. 1). The recently published report by ICCT says that the aviation-related emissions will drastically increase without any actions taken by a factor of 3 by 2050. This trend is worse than one expected by previous studies, and this calls into question the achievement of the global warming mitigation strategy (Graver, et al., 2019).

In 2018 the global aviation produced about 895 Mt CO₂-eq, which equals to 2% of global emissions or 12% of all transportation emissions. 80% of emissions from aviation come from flights with distances more than 1500 km (ATAG, 2018). Moreover, if aviation were a country, it would be the 6th most significant source of CO₂ from energy consumption in the world (Graver, et al., 2019).

However, there are a few strategies for reducing emissions available in the aviation sector. First of all, improving jet engine efficiency would lead to reduced fuel consumption, hence cutting emissions. Aircraft efficiency can also be enhanced by better aerodynamics and weight reduction of aircraft. From a long-term perspective, the aviation industry can be run on electricity, but realistically it is not possible shortly. Electric aircrafts production is limited to high energy storage (batteries) demand. Even though some electric aircrafts concepts exist, they cannot be implemented in civil aviation today due to a massive battery
capacity demand. Alternative fuels to kerosene can become a great replacement to fossils in the transition towards a 100% renewable energy system worldwide. Whether they are biofuels or synthetic fuels, they have a significantly lower carbon footprint than conventional energy carriers. (Lee, et al., 2009, p. 3531)

Biofuels may be a solution if they are produced economically. Nevertheless, there are such problems as civil aviation safety standards and sustainable land use required for the significant quantity of biofuels production. In turn, synthetic jet fuels may be produced with renewable electricity, capturing CO₂ even from the air. It is a promising technology, but it requires time to rebuild the whole system of the aviation sector. New transport hubs with easy access to cheap renewable electricity should be built, and the life cycle of such technologies is needed to be assessed. (Lee, et al., 2009, p. 3531)

This thesis investigates the environmental impact of the aviation sector and challenges, which have to be solved to mitigate climate change. In frames of the investigation, all types of aviation pollutants’ impacts on global warming are to be explored, as well as possible solutions to diminish them. Nevertheless, the main focus of this master’s thesis is to analyze different flight factors such as route planning, aircrafts design, and jet efficiency, traditional jet fuel substitution with biofuels and synthetic fuels and their possible contribution to the global warming impact of flying reduction in the future.
Global warming is a result of anthropogenic actions, and related GHGs emissions rise in the atmosphere since the beginning of the industrial revolution. This process accounts for hundreds of years since 1750, and nowadays, the cumulative emissions of developed countries are of the most significant percentage. Anthropogenic emissions form more than 50% of the added global increase temperature from the middle of the 20th century. Nevertheless, the developing countries have a significant growth of their population and economies, which means growing emissions and further dominating positions in the global carbon budget. In order to combat climate change, fast emissions reduction is needed globally. However, even though climate change occurs on all of the territories around the Earth, developing countries should be treated separately in terms of emissions reduction, taking into account their early economic development stages. (Tavakoli, 2018)

2.1 Mitigation actions

In order to adapt efforts to mitigate the climate change United Nations Framework Convention on Climate Change (UNFCCC) was established in 1988. The Conference of the Parties (COP) was recognized as the supreme body of the Convention. One hundred sixty-five nations signed the Convention. The objective of the Convention is to limit GHGs emissions to the level, which can let to escape the most dangerous consequences of the anthropogenic activities. Moreover, these limitations should be implemented within time frames, which would allow ecosystems to adapt these changes naturally. The strategy takes into account the interests of developing countries and their further economic growth. In contrast, it requires most of the actions in developed countries. (United Nations, 1992)

Later, the Kyoto Protocol was signed, which obliges countries to reduce emissions based on the principle of shared but differentiated responsibilities. The protocol states that global warming is happening, and it is mainly due to human actions related to carbon dioxide emissions. (UNFCCC, 2008)

One hundred ninety-five nations ratified the Paris New Agreement in 2015 in frames of COP21. The main goal of the agreement is to keep global warming this century well below
2°C and to address efforts to the level of 1.5°C temperature rise above the pre-industrial level. Intended Nationally Determined Contributions (INDCs) are implemented every five years by countries. They must follow the principles of emission reduction, climate action recording, dealing with climate impacts and recover from them, and investing in the carbon-neutral future. (United Nations, 2015)

2.2 Global emissions drivers

The primary composition of the emissions comes from fossil fuels burning, which account for about two-thirds of global GHGs emissions. In 2015, China accounted for 28% of global CO₂ emissions. Other countries, which are among the most significant CO₂ producers, are the USA, India, Russia, Japan, Germany, South Korea, Canada, Iran, and Brazil. However, such factors as the global population and GDP growth, energy consumption, as well as a carbon intensity of technologies (and the lack of energy-efficient and carbon-neutral technologies) are also of great value and lead to even a greater fossils consumption and higher emissions. These factors are expected to grow even further in the future and cause a more harmful impact on the climate without any actions taken to limit emissions. (Tavakoli, 2018)

A quantitative assessment of CO₂ emissions is possible to conduct with a model of Yoshi Kaya. The “Kaya Identity” (Kaya & Yokobori, 1997) model (Equation 1) takes into account demographic, economic, and environmental factors to evaluate several anthropogenic emissions:

\[
E_{CO_2} = \frac{Population}{Population} \cdot \frac{GDP}{Population} \cdot \frac{Energy}{GDP} \cdot \frac{CO_2}{Energy}
\]

\[
E_{CO_2} = \text{Carbon emissions [GtC/yr]}
\]

\[
\frac{GDP}{Population} = \text{Gross Domestic Product per capita [$/person/yr]}
\]

\[
\frac{Energy}{GDP} = \text{Energy intensity per unit of GDP [EJ/$]}
\]

\[
\frac{CO_2}{Energy} = \text{Carbon emissions intensity per unit of primary energy [GtC/EJ]}
\]
The recent United Nations report says that the global population will reach 8.5 and 9.7 billion in 2030 and 2050, respectively, but it will stabilize at the level of approximately 11 billion by 2100 (United Nations, 2019, p. 5).

World GDP is projected to grow by 1.0-2.8% per year to 2100. Developed countries are expected to have an annual growth of about 1-2%, whereas non-OECD countries have a potential of 4-5% annual growth. Growth rates of GDP are higher than population growth, which will result in a higher GDP/capita rate in the future, higher energy efficiency, lower fertility, and population stabilize. (Leimbach, et al., 2017, p. 224)

### 2.3 Global emissions pathways

In 2017 total global greenhouse gas emissions were at the level of 50.9 Gt CO₂-eq (without land-use change emissions). Global GHGs emissions per source of origin and gas type in 2017 are presented in Figure 1. Emissions from energy generation make up most of the global GHGs emissions, while CO₂ itself is a significant part of them. (Olivier & Peters, 2018, pp. 11-12)

![Figure 1. Global greenhouse gas emissions per type of gas and source (Olivier & Peters, 2018, pp. 11-12).](image-url)

The combustion of fossil fuels is the primary source of emissions worldwide. Global CO₂ emissions from fuel combustion did not have any significant growth after 2015 and were at...
the level of 32.31 Gt CO\(_2\) in 2016 (IEA, 2018, p. 3). However, emissions increased in 2017 and reached 37.1 Gt CO\(_2\).

Figure 2 shows that industrial combustion, including manufacturing, fuel production, power, and heat generation sectors, has a significant share of CO\(_2\) emissions. Transportation is the second-largest sector to emit carbon dioxide. (Muntean, et al., 2018, p. 9)

![Figure 2. Total global annual CO\(_2\) emissions from fuel combustion by sector (Muntean, et al., 2018).](image)

Potential future emission scenarios were assessed by Global Carbon Project with Shared Socioeconomic Pathways (SSPs) of such parameters like growth rate, regional competition, sustainability, and inequality (Riahi, et al., 2017; Rogelj, et al., 2018; IIASA, 2018; Global Carbon Project, 2018). These four pathways and one intermediate scenario are integrated for evaluating an emission gap required to mitigate climate change. The global warming projections are illustrated in Figure 3.
Figure 3. 2100 Global warming projections (Riahi, et al., 2017; Rogelj, et al., 2018; IIASA, 2018; Global Carbon Project, 2018).

It is visible from Figure 3 that global warming has a huge potential to grow in frames of business-as-usual (BAU) emissions scenario. Not only it is needed to cut emissions to mitigate climate change, but also net-negative global emissions have to be reached in order to meet the Paris Agreement goals. Keeping global warming well below 2°C requires many changes in human actions, emissions reduction, reaching net-zero, and further harmful global emissions. In return, more efforts are needed to achieve the target of 1.5°C and reach 100% emissions reduction by the middle of the century.
3 GLOBAL WARMING EFFECT OF AVIATION

In order to meet the Paris agreement goals, the aviation sector has several targets. First of all, the average efficiency improvement should be 1.5% annually from 2009 to 2020. Moreover, after 2020, the growth of the sector has to be carbon-neutral (without increasing emissions and keeping them at the same level or lower). Even a more ambitious target of 50% emissions level decline (2005 is the baseline) has to be met by the middle of the century. (ATAG, 2018)

Aircraft emit a considerable part of gases and particles while consuming fuels at cruise altitudes of 8-12 km (the upper troposphere and the lower stratosphere). It makes the aviation a unique part of the transportation sector because emissions at such heights have a more significant impact on climate change than ones on the ground. The aircraft emissions and particles from fuel combustion include carbon dioxide and carbon monoxide emissions (CO$_2$ and CO respectively), emissions of nitrogen oxides NO$_x$ (NO + NO$_2$), water vapor (H$_2$O), hydrocarbons (HC), black carbon (soot, C), and sulphur oxides emissions (SO$_x$). They force the direct global warming impact. These emissions interact with each other and thus also force a higher load on the surrounding atmosphere and its composition of naturally occurred carbon dioxide, ozone, and methane, which is the indirect warming impact. (Brasseur, et al., 2016, p. 562)

3.1 The direct global warming impact

Nowadays, jet kerosene is the most used aircraft fuel, while aviation gasoline is only used in small piston-engine aircraft and its share in the global aviation fuel use is less than one percent. About 70% of all direct aircraft emissions are carbon dioxide, slightly less than 30% - water, NO$_x$, CO, SO$_x$, NMVOC (non-methane volatile organic compounds), and other trace components account for less than 1% in aircraft emissions. Modern aircraft almost do not emit N$_2$O as well as CH$_4$, but methane emissions sometimes can occur during idle. (IPCC, 2006)
3.1.1 Direct carbon dioxide emissions

Emissions of CO\(_2\) are the leading direct contributor to the total aviation sector warming impact. They are proportional to an amount of fuel combusted. Nowadays, the average kerosene consumption in jet engines is about 3.8 L per passenger per 100 km (Braun-Unkhoff, et al., 2017, p. 168). Jet kerosene carbon intensity is approximately 3.16 kg CO\(_2\) per one kg of fuels. It means that the growing transportation demand leads to higher fuel use and emissions growth linearly. Even though CO\(_2\) emissions occur in high altitudes together with other gases, but the warming impact of carbon dioxide is assumed to be the same as on the surface. (Grote, et al., 2014, p. 215)

According to the International Civil Aviation Organization’s report (ICAO, 2016), the global CO\(_2\) emissions from aviation will increase by a minimum of almost one Gt from 2020 to 2050 without supplementing traditional fuels, assuming that burning one kg of fuels emit 3.16 kg CO\(_2\) (Figure 4).

![Figure 4. International aviation CO\(_2\) emissions trend (ICAO, 2016).](image)

A new standard of addressing CO\(_2\) emissions was set by the International Civil Aviation Organization (IATA, 2019a). The idea of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is to control emissions from international flights, which exceed the allowed emissions for carbon-neutral growth. ICAO and its CORSIA scheme are
the only mechanisms to control international flights because UNFCCC and the Paris Agreement have only country-determined action requirements. (IATA, 2019b)

### 3.1.2 Water vapour

Water vapour forms directly from the process of jet fuel combustion. It is the natural greenhouse gas, which creates a habitable temperature regime on the planet. The warming effect of water vapour emissions from subsonic aviation is positive but relatively low. However, supersonic aviation’s water vapour emissions can potentially cause a more significant impact due to higher flight altitudes in the drier stratosphere. (Lee, 2018, p. 5)

### 3.1.3 Other direct emissions

However, the aviation warming impact caused not only by carbon dioxide but also by another blend of particles and gases, which jet fuels consist of. For the complete fuel burn, only water and CO\(_2\) are produced (Equation 2). (Braun-Unkhoff, et al., 2017, p. 169)

\[
C_xH_y + (x + 0.25y)O_2 = xCO_2 + 0.5yH_2O + \text{energy} \tag{2}
\]

Nevertheless, the combustion process is never ideal. Thus, other combustion products exist. Jet fuels exhaust emissions indexes are given in Table 1. (Wulff & Hourmouziadis, 1997, p. 558)

<table>
<thead>
<tr>
<th>Exhaust component</th>
<th>Chemical formula</th>
<th>Emission index, g/kg fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Take off</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>NO(_x)</td>
<td>40</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO(_2)</td>
<td>3100</td>
</tr>
<tr>
<td>Water Vapour</td>
<td>H(_2)O</td>
<td>1300</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>1</td>
</tr>
<tr>
<td>Unburned Hydrocarbons</td>
<td>UHC</td>
<td>0.2</td>
</tr>
<tr>
<td>Soot</td>
<td>C</td>
<td>0.01</td>
</tr>
<tr>
<td>Sulphur Oxide</td>
<td>SO(_2)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 1. Jet fuel emissions indexes. Adapted from Wulff & Hourmouziadis (1997)

Only carbon dioxide and water emissions are proportional to the amount of fuel burnt. However, H\(_2\)O emissions are higher when H/C (Hydrogen/Carbon ratio) of fuel is higher. Sulphur oxide emissions are based on the Sulphur amount in fuel. Such combustion parameters as temperature, pressure, turbulence level, and residence time affect the amount
of UHC, NOx, and CO in exhaust gas composition, while engine power mode is essential to assess CO, UHC, NOx, and PM emissions. Carbon monoxide and unburned hydrocarbon emissions are high while idle and taxi modes of flight, but nitrous oxides and PM are higher while higher engine power modes of taking off and climb operations (Figure 5). (Braun-Unkhoff, et al., 2017, pp. 168-169)

Figure 5. Aircraft emissions dependence on engine power. Taxi is 7% thrust, take-off – 100%, climb – 85%, approach – 30% (Braun-Unkhoff, et al., 2017)

Tier 2 methodology represented in the IPCC report Guidelines for National Greenhouse Gas Inventories (2006) shows the way to account aviation emissions based on the number of LTOs (Landing/Take-off cycle) and cruise distances. LTO includes aircraft’s activities near the airport: taxi-in, take-off, climbing, approach, landing, and taxi-out – all the activities below the altitude of 914 m (3000 feet). The cruise mode is then above the 914 meters altitude. Cruise in frames of the methodology consists of climbing from 914 meters to a cruise altitude and descend from it to 914 meters. Such a flying cycle is given in Figure 6.

Figure 6. Flying cycles of LTO and Cruise operations (IPCC, 2006)
Average fuel use and emissions while LTO and Cruise are presented in Table 2 for Airbus A320. It is assumed that the Sulphur content of the fuel is 0.05%. (IPCC, 2006)

<table>
<thead>
<tr>
<th></th>
<th>Fuel</th>
<th>SO₂</th>
<th>CO</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>NMVOCs</th>
<th>CH₄</th>
<th>N₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LTO (kg/LTO)</strong></td>
<td>770</td>
<td>0.77</td>
<td>6.19</td>
<td>2440</td>
<td>9.01</td>
<td>0.51</td>
<td>0.06</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Cruise (kg/tₖg)</strong></td>
<td>1.0</td>
<td>7</td>
<td>3150</td>
<td>12.9</td>
<td>0.7</td>
<td>0</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Thus, Tier 2 method emissions are estimated using the following Equations 3-6:

\[
Total\ Emissions = LTO\ Emissions + Cruise\ Emissions \tag{3}
\]

\[
LTO\ Emissions = Number\ of\ LTOs \cdot Emission\ Factor\ LTO \tag{4}
\]

\[
LTO\ Fuel\ Consumption = Number\ of\ LTOs \cdot Fuel\ Consumption\ per\ LTO \tag{5}
\]

\[
Cruise\ Emissions = (Total\ Fuel\ Consumption - LTO\ Fuel\ Consumption) \cdot Emissions\ Factor\ Cruise \tag{6}
\]

### 3.2 The indirect global warming effect of aviation

Besides the direct aviation emissions, there are several non-CO₂ gases, particles, and effects from aviation, which eventually and indirectly force atmospheric composition changes and lead to global warming. These gases and indirect effects are introduced in the following subchapters.

#### 3.2.1 Nitrogen oxides

NOₓ emissions are the result of the atmospheric nitrogen interconnection with oxygen under the heat and pressure of the combustion process in jet engines. Combustion of one kg of jet fuels leads to 15 g of NOₓ emissions (ICAO, 2016). Nitrogen oxides emissions contribute to the greenhouse ozone and hydroxyl radical formation. The radical (OH) reacts with CH₄ and leads to its concentration reduction and additional water vapor formation. This O₃, CH₄, and H₂O are greenhouse gases. Thus, NOₓ emissions lead to warming and at the same time to
cooling of the atmosphere. However, nitrogen emissions have a warming effect, ultimately. (Lee, 2018, p. 5)

3.2.2 Sulfate aerosol

The aviation kerosene has sulphur in the composition, which oxidizes to sulphur dioxides when fuels are combusted. The sulphur dioxide then oxidized to sulphuric acid in the atmosphere. The acid forms particles, which do not allow solar radiation to reach the surface and reflect it away from the planet. The particle formation leads to the cooling effect, but it is not significant due to a small concentration of sulphur of 600-800 ppm by mass in jet fuels. (Lee, 2018, p. 5)

3.2.3 Soot aerosol

Soot emissions, also called black-carbon emissions, are non-volatile particles of aircraft emissions. They are the result of incomplete jet fuel combustion in engines. The particles affect clouds and their radiative properties and have a direct positive radiative forcing impact. The process of a positive RF change is the same as for other’s emissions RF: particles of soot trap the radiation and cause a warming effect. Even though soot emissions content is small after burning the jet kerosene in engines, they may have a tremendous indirect effect on cirrus and aviation-induced cloudiness than their direct RF impact. Due to the significant possible warming effect, soot emissions cannot be excluded from emissions and their impact assessment, but nowadays, several uncertainties related to black carbon emissions’ impact on cloudiness still exist. (Lee, 2018, p. 5)

3.2.4 Aviation impact on clouds formation

Aircraft form contrails while flying in altitudes. It occurs because of soot and water vapour emissions. The formation of contrails is also pursued by the atmosphere temperature, humidity, and pressure, causing the thermodynamic process of condensing the background of atmospheric water around soot particles. Under certain conditions of the cold and highly saturated atmosphere, contrails can form long-lived structures called contrail-cirrus. Both contrails and contrail-cirrus have a positive and negative warming impact. They reflect radiation to space and surface at the same time, but the total RF impact of them is still
positive. This impact depends on many factors and demanding to be estimated due to a lack of expertise in the ice-crystals and optical properties. While original aviation contrails are very predictable and follow trajectories of flights, hence can be observed from satellites, contrail-cirrus are even more complicated due to their similarity to natural cirrus and have to be assessed with dynamic climate models. Nevertheless, the latest available researches tell that the total contrails RF has a most significant share of 50 – 60% of the whole aviation RF. (Lee, 2018, p. 5)

3.3 The combined warming effect of aviation

The combined effect on the environment from aviation emissions is not that easy to estimate than direct emissions itself. It is because carbon dioxide has around a hundred years of residence time in the atmosphere. Hence it is long-lived and well dispersed. Based on that, CO₂ emissions from different sources have the same impact as ones from the aviation sector, while other gases are of a shorter lifetime and mainly concentrated near aircrafts itineraries. Short-lived emissions impact atmospheric chemistry. Their total warming effect is not of the highest confidence and scientific quality. (IPCC, 1999)

Nowadays, there are a few metrics used to assess the total global warming impact of aviation. These methods are Global Warming Potential (GWP), Global Temperature Potential (GTP), and Radiative Forcing (RF). Due to a unique situation of aviation sector emissions and their impact patterns, all of the methods have many relevancies and weaknesses, and no standard practices to calculate the total warming impact (including indirect emissions effect) exist our days. Next, the methods of global warming impact assessment are described. (Dessens, et al., 2014, pp. 14-15)

3.3.1 Global warming potential

The global warming potential (GWP) is a commonly used metric to account for emissions of different greenhouse gases in accordance with well-known CO₂ emissions. The method was adopted in frames of Kyoto Protocol to compare the climate impact of different emissions in a 100 years range, however intervals of 20 and 500 years are also used. The principle idea of the metric is to evaluate pulse and sustained emissions by calculating their
radiative forcing over a specific time interval and compare it with an equal to carbon dioxide emission mass proportion. Hence, GWP has no unit, and it is a quantitative measure (coefficient) of different GHG warming impact factors when GWP of carbon dioxide is a baseline (GWP of CO$_2$ = 1). 100-Year GWP of CH$_4$ and N$_2$O are 25 and 298, respectively. The total impact of gasses then expressed in kg CO$_2$-eq. (Wuebbles, et al., 2010, pp. 491-492)

However, the global warming potential method has several restrictions, mainly when the aviation sector's environmental impacts are assessed. First of all, the radiative forcing of aviation is not only based on emissions but also includes changes in the atmospheric gases' compositions. Moreover, these forcing are of different dimensions in the atmosphere. Some aviation emissions' lifetime is very short-term and considerably less than 100 years. For instance, the warming effect of contrails cannot be easily related to a GHG impact, as well as such effect of ozone production in the atmosphere is not correlated to nitrous emissions, but depends on seasonal and geographical factors. Following these limitations, GWP is not recommended to be used in the global warming impact of aviation assessment procedures. (Wuebbles, et al., 2010, pp. 491-492)

3.3.2 Global temperature potential

The global temperature potential is another metric option to calculate aviation warming impact. It is based on accounting thermal changes in the atmosphere rather than the warming effect of emissions. The principle of GTP is almost equal to GWP. However, it shows a ratio of emissions-induced temperature changes to changes produced by the same mass amount of carbon dioxide. Although the method of GTP shows more relevant for climate change mitigation strategy and global warming monitoring information, it has some limitations, such as a lack of experience using it and the inability to include local impacts. (Wuebbles, et al., 2010, p. 494)

3.3.3 Radiative forcing

In order to compare these different impacts, concepts of radiative forcing (RF) and radiative forcing index (RFI) were suggested by IPCC instead of GWP. Radiative forcing is a measure of the Earth's atmosphere energy balance’s perturbation from atmospheric gases and particle
composition changes. It is measured in watts per square meter (Wm$^{-2}$) at high layers of the atmosphere. (IPCC, 1999)

There are two types of RF effects: positive and negative, which imply net warming and cooling of the atmosphere accordingly. CO$_2$, NO$_x$, H$_2$O, and soot emissions, as well as persistent linear contrails and aviation-induced cloudiness (AIC) formation, have positive RF values. In contrast, SO$_x$ emissions, and such consequences of NO$_x$ emissions as a long-term CH$_4$ and O$_3$ reduction have a negative RF potential. These emissions and clouds formations affect the upper atmosphere, changing its properties, and global RF values. All of the mentioned factors lead to climate change and damages to ecosystems (IPCC, 1999).

The principle aviation emissions, caused by them atmospheric processes, changes in RF components, and impacts are illustrated in Figure 7. (Lee, et al., 2009)

![Figure 7. Aircraft emissions and climate change (Lee, et al., 2009)](image-url)
As seen from Figure 7, all of the principle emissions except carbon dioxide cause various physical and chemical reactions in the atmosphere, hence indirect and complex changes in the total radiative forcing.

Aviation Radiative Forcing Components are evaluated from preindustrial time as a cumulative effect. Figure 8 shows aviation radiative forcing of emissions and other impacts, such as contrails and contrail-cirrus, their geographical distribution, and the level of scientific understanding (LOSU). Due to the very low LOSU of cloudiness, the total effect is presented for both cases: including and excluding contrails formation. (Lee, 2018, p. 5)

![Aviation Radiative Forcing Components in 2005](image)

**Figure 8.** Aviation radiative, forcing components in 2005 (Lee, 2018, p. 5)

The total radiative forcing of all the aviation emissions and caused cloudiness can be several times more than forcing from carbon dioxide only. However, the confidence level for these forcing is too low, and there are spatial scale uncertainties. It is still not fully understood
how regional impacts can affect global warming and vice versa. In turn, the effect of cloudiness, which can add a valuable part to the total warming impact, is only an estimation.

The radiative forcing index (RFI) was introduced as an alternative method to account for all the forcing from aircraft. It is the ratio of total radiative forcing to radiative forcing of CO₂. RFI accounts for all the direct emissions and induced atmospheric changes in the atmosphere, so it highlights the importance of including not only emissions from fossils combustions but other impacts. The total aircraft RFI is often higher than two, which means that the indirect warming effect cannot be neglected. (Prather & Sausen, 1999, p. 200)

However, it should be noted that both RF and RFI are metrics for emissions that occurred in the past and their impacts on accounting only. It cannot be used for future emissions estimations. Furthermore, these approaches do not comprise regional climate effects variations impact. (Wuebbles, et al., 2010, p. 494)

### 3.3.4 Uncertainties of climate change impacts assessment

The aviation sector has a unique situation while discussing its total warming impact. There are no proven and comprehensive methodologies to account for all of the aircraft's induced forces, which affect the environment. In the case of carbon dioxide, there is a clear correlation with fuel use and relative emissions from its combustion, but indirect impacts cannot be calculated in the same manner. Linear contrails and induced cirrus cloudiness are both of very complicated implications, it cannot be easily calculated based on emissions, and their impact usually has a local contribution to warming. However, they both have a potentially significant warming force, which is higher than one from carbon dioxide only. Other emissions and caused by the changes in the atmospheric composition are also not that easy to assess, but they must be included in assessments.

The latest assessment report of IPCC (IPCC, 2013) does not provide any details concerning the comprehensive aviation sector contribution to warming assessments. However, it is quite clear that the GWP concept for long-term emissions cannot be adopted in total aviation impact warming effect assessment. RF concept has more precise estimations on radiative forcing of different components of aviation induced emissions and effects, hence their warming potential, but this is still only a partial solution due to any level of confidence,
geographical distribution, and causes uncertainties. RFI factor, in turn, shows a multiplying factor of all climate impacts of aviation to only carbon dioxide from fuel combustion RF. Best available estimates nowadays suggest to use RFI of 1.9, but only as a recommendation. (Department of Business Energy & Industrial Strategy (BEIS), 2016, pp. 63-66). Other researches, however, suggest RFI of up to 4.7 (Grassl & Brockhagen, 2007, p. 7). Table 3 shows recommendations of the aviation radiative forcing index based on metric values, time horizons, and different components of aviation induced effects on warming. The values of GWP (20 and 100 years) and GTP (100 years) metrics of aircraft induced emissions and effects are presented on the left side of the table. The carbon dioxide emissions equivalents for these emissions and effects are presented on the right side based on the fuel consumption in 2005, and metric values from the left side of the table. The bottom right part shows ratio values of the combined impact of emissions and effects (in CO$_2$-eq) to the carbon dioxide only impact (RFI). There are four RFI indexes for each of the metrics presented (low/high NO$_x$; including/excluding AIC) due to the very low scientific understanding of the effects from NO$_x$ and AIC. (Department of Business Energy & Industrial Strategy (BEIS), 2016, pp. 63-66)

Table 3. Aviation RFI recommendations for different time horizons and metrics. RFI factors are presented for both scenarios with included and excluded AIC from the assessment (Department of Business Energy & Industrial Strategy (BEIS), 2016)

<table>
<thead>
<tr>
<th>Metric values</th>
<th>CO$_2$-eq emissions (MtCO$_2$ eq/yr.) for 2005</th>
<th>LOSU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWP$_{20}$</td>
<td>GWP$_{100}$</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Low NO$_x$</td>
<td>120</td>
<td>-2.1</td>
</tr>
<tr>
<td>High NO$_x$</td>
<td>470</td>
<td>71</td>
</tr>
<tr>
<td>Water vapour</td>
<td>0.49</td>
<td>0.14</td>
</tr>
<tr>
<td>Sulphate</td>
<td>-140</td>
<td>-40</td>
</tr>
<tr>
<td>Black carbon</td>
<td>1600</td>
<td>460</td>
</tr>
<tr>
<td>Contraill</td>
<td>0.74</td>
<td>0.21</td>
</tr>
<tr>
<td>AIC</td>
<td>2.2</td>
<td>0.83</td>
</tr>
<tr>
<td>CO$_2$/CO$_2$-eq emissions for 2005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low NO$_x$, inc. AIC</td>
<td>4.3</td>
<td>1.9</td>
</tr>
<tr>
<td>High NO$_x$, inc. AIC</td>
<td>4.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Low NO$_x$, exc. AIC</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>High NO$_x$, exc. AIC</td>
<td>2.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The indirect warming impact of aviation occurs at altitudes of the lower stratosphere and upper troposphere. It means that the indirect emissions have an additional warming impact
only at a specific time of a flight. From the one side, it limits the forcing in time, but hence the RFI at altitudes is even higher than the RFI of different impacts throughout the total flight time. Jungbluth and Meili (2019, p. 407) suggest an evaluation of the warming effect of emissions in the stratosphere. It is based on the total RFI of aviation, and the share of emissions occurred at altitudes (Equation 7).

\[
CF_{\text{CO}_2, \text{str}} = \frac{RFI_{\text{tot}} - (1 - Share_{\text{CO}_2, \text{str}})}{Share_{\text{CO}_2, \text{str}}}
\]

\(CF_{\text{CO}_2, \text{str}}\) = characterization factor for emissions of CO\(_2\) in the atmosphere  
\(RFI_{\text{tot}}\) = total radiative forcing index of aircraft  
\(Share_{\text{CO}_2, \text{str}}\) = share of emissions in the stratosphere

The share of emissions in the high atmosphere is taken by Jungbluth and Meili (2019, p. 408) at the level of 23.9% from the ecoinvent database. The RFI parameters of one to 2.7 are acknowledged by the authors to be the most accurate after analyzing several studies on aviation RFI assessment (Lee, et al., 2009; Lee, et al., 2010; Peters, et al., 2011; Azar & Johansson, 2012). The resulting factor is then 5.2 for the emissions at aircraft altitudes. It equals to two kg CO\(_2\)-eq per total direct emissions of aircrafts carbon dioxide or the total RFI of 2. Following the above methodology, emissions from aircraft taking off and landing are equal to the direct emissions from fuel combustion, but while flying at cruise altitudes, the total emissions are by the factor of 5.2 higher than carbon dioxide emissions only. (Jungbluth & Meili, 2019, pp. 408-409)

A comparison of warming impacts from different means of transport is presented in Figure 9.
As seen from the figure, without implementing the recommended RFI, warming impacts of aviation and passenger cars are very close. The adoption of radiative forcing index for aircraft emissions in the higher atmosphere, however, shows the drastically increased warming impact of aviation, making it the worst source of transportation from a global warming point of view. Carbon dioxide emission forms the majority of the warming impact, while other greenhouse gases are of a relatively small share.

Nowadays, there are no clear recommendations and methodologies for assessing the combine warming impact of aircraft. Nevertheless, the abovementioned method is the most holistic option, which includes a significant portion of aviation induced warming impacts and up to date recommendations on their assessment. Still, it requires clarifications from the scientific community, especially on the level of contrails and cloudiness effects understanding. Even though both the global warming potential and the radiative forcing index are not entirely applicable for the total warming impacts calculations, the method described suggesting their jointly use until any further guidelines by IPCC are provided.
4 METHODS TO REDUCE GLOBAL WARMING IMPACT OF AVIATION

The sector of aviation has many challenges to reach the ambitious global warming mitigation targets. Since the very beginning of the history of the aerospace industry, it has been improving continuously in terms of economic, ecological, and safety aspects. The total aircraft efficiency has drastically increased, and nowadays, very long-distance, safe, and comfortable flights are possible. Nevertheless, aviation today has many issues to figure out. (IPCC, 1999; Ranasinghe, et al., 2019, pp. 1-2)

First of all, the current flight demand growth is higher than the efficacy improvements. It means that without any further actions and development, it will not be possible to reach the environmental targets. While other sectors of the economy have a trend of using renewable energy to be electrified, carbon-neutral, and have sustainable growth, aviation has a unique situation. Transportation occurs in the air, and it requires reliable and trusted solutions. However, while the transition to the electric aircraft is under development and not yet done, other advancements alternatives such as reduced fuel consumption and alternative fuel use, more advanced engine design, lighter aircraft housing materials, and progressive route planning are seemed to be a solution towards the carbon-neutral future. (IPCC, 1999; Ranasinghe, et al., 2019, pp. 1-2)

Different methods to reduce global warming impact of aviation are described in the next subchapters.

4.1 Aircraft design efficiency improvement options

Modern aircraft design is a mature technology, which went through many improvements over the last decades. However, aircraft design is a key technology, which affects the amount of fuel used directly, and therefore emissions and warming potential of aviation. Aircraft weight has a direct relationship with the jet fuel burn index. Moreover, the more massive an aircraft, the more fuel it needs, and then an additional fuel mass to carry the additional weight must be taken into account. Jet engine performance is another possible field of opportunity to enhance aircraft total efficiency. With new advanced turbines and better combustion
technology processes, there is a potential to reduce fuel demand as well. Total aerodynamic characteristics of aircraft, among others, are core physics processes of performing flights, and it is room to reduce an aircraft’s aerodynamic drag. Thus, these technologies are of the highest priority on the way of aircraft design efficiency improvements. (The World Bank, 2012, pp. 39-40)

4.1.1 Jet engine performance

The large part of aviation-related warming effects come from the direct fuel combustion in jet engines. Hence, they arouse the interest of researchers as the most evident option to reduce fuel consumption and emissions. Presently, turbofan engines are the most frequently used engines in aircraft, which divide the airflow into a bypass flow, producing the majority of the thrust and a core flow to perform compression and combustion. (Ranasinghe, et al., 2019, pp. 1-2)

Bypass ratio increasing

A larger fan diameter can increase the bypass flow and hence, engine efficiency. However, such kind of design improvements in weight aircraft, and they are also limited by ground clearance. Due to the higher income, airflow degradation of fan blades can also occur. Geared turbofan engines can help with increasing the fan size by implementing a gearbox between the engine fun and compressor. It leads to increased efficiency and reduced weight and noise by avoiding conflicting rotation speeds of fun and compressors being driven by the same shaft in traditional turbofans. But for these engines, additional heat and need for cooling is the main drawback (Ranasinghe, et al., 2019, pp. 3-5)

The 1000G series geared engines developed by Pratt & Whitney were launched in 2016 in Airbus A320neo. They have 20% lower fuel consumption and much-reduced noise. With the current development trend, a further increase in bypass ratio is possible, as well. The only problem of such types of turbofans is the lack of experience in their maintenance. Rolls-Royce, CFM International, GE Aviation have their geared engine developments on the market as well, with up to 25% efficiency increased and plans for further investigations in this respect. (Trimble, 2017; Rolls-Royce, 2019; Safran, 2019; GE Aviation, 2019)
Blade composite materials

Aluminum and Titanium alloys are mostly used as a base material for fan blades because they are lighter than other metallic elements. However, alternative carbon fiber composite materials have even lower weight, which provides a room for engine mass cut and a possibility for fun diameter increase. Moreover, these composite materials allow reducing the number of blades due to their higher strength, even more reducing engine weight and noise. New Rolls-Royce engines with fiber composites have about 700 kg lower weight and 20% fuel consumption reduction. However, the thermal resistance is the well-known drawback of composite materials, which requires preventing the open fire. (Ranasinghe, et al., 2019, pp. 8-10)

Low-emission combustion technologies

The combustion of fuels is a core process of jet engine operations. Thus, the development of such a combustion process with the highest possible engine cycle efficiency and the lowest rate of emissions is of the most considerable importance. However, standards of safety and productivity cannot be neglected. Among any other combustion technologies such as rich-burn quick-quench lean-burn combustion, double annual combustion, axially staged combustion, which have a number of problems to be solved, and especially with dangerous and undesired high temperatures, and multipoint integrated injection, which backward sometimes cannot reach combustion temperatures and experiences pressure losses, twin annular premixing swirler combustion has an excellent potential to achieve very low NOx emissions and high efficiency in the future. Concepts of lean premixed pre-vaporized combustors and flameless combustion face relatively the same problems of a high probability of auto-ignition, flashbacks, and increased engine weight, while the last-mentioned concept was prohibited due to the lack scientific knowledge and high risks. Thus, even though these technologies have a high potential, they have not yet reached a mature level of development to be implemented widely in aircraft. (Ranasinghe, et al., 2019, pp. 10-14)
Other options

The trust-to-weight ratio parameter is a crucial characteristic of the total aircraft propulsive efficiency. There are several low and high-pressure compressors in a typical jet engine, which are responsible for a valuable part of the weight. The weight of jet engines can be possibly reduced by implementing a higher-pressure ratio, but with a decreased number of compressors. However, this would lead to a much higher compressor’s blades and possible stops or even failures because of unstable air flows between the compressor’s casing and blades. Thus, careful design and further research are required. (Ranasinghe, et al., 2019, pp. 14-16)

The transformation of thermal energy into mechanical energy in jet engines is based on the Brayton-Joule thermodynamic cycle, in which efficiency is equivalent to the relation of the difference of inflow and exhaust heat to inflow heat. The intercooler and recuperated aero-engines concept apply a method of reducing the inflow work by cooling the air at the end of the cycle. On the other hand, additional heat is added to the system by implementing the hot exhaust gas at the heat exchange system (FFF). While the concept has the promising results of reduced fuel consumption, its utilization in aircraft is still controversial due to additional elements in the system and increased weight. (Ranasinghe, et al., 2019, pp. 16-18)

![Figure 10](image_url). The intercooler and recuperated aero-engines concept thermodynamic cycle (Ranasinghe, et al., 2019, p. 18)
4.1.2 Aerodynamic characteristics of aircraft improving

The aerodynamic principle of any aircraft is to overcome a drug with thrust generated by engines. The lower the drag, the lower the push must be obtained, which leads to a smaller amount of fuel needed to be combusted. Several optimizations of airplanes aerodynamics simulations have been made over the past. Clear evidence of these is the winglets improvements in the Airbus A320 family, which has raised the efficiency of the aircraft by more than 3%. Other concepts on maintaining laminar flow instead of turbulent ones are also developing nowadays (The World Bank, 2012, pp. 42-43).

One such concept is to place film surface grooves or riblets on the aircraft’s fuselage in the area of the wings surface to reduce the drag and maintain laminar airflow. The total fuel consumption can be reduced by 1.6% by implementing the grooves on the aircraft wings. However, there are concerns related to different types of dust stuck in riblets, and hence reduced the durability and increased maintenance demand of wings (The World Bank, 2012, p. 43). The concept is presented in (Luo, et al., 2015, pp. 68-70).

![Bio-inspired micro grooves](image)

Figure 11. Place film surface grooves application on aircraft wings (Luo, et al., 2015, p. 70)

4.1.3 Aircraft weight reduction

Alongside the demand for a lighter jet engine design, other parts of an aircraft can also be made from lighter materials to reduce weight and fuel demand. Nowadays, titanium and its alloys are of the most significant interest of aircrafts’ producers to use it as a construction material for different parts of a plane. Generally, engines amount to 5-7% of aircraft initial
take-off-weight, the fuselage is 7-12%, and wings are 8-14%, so the room for improvements exists. Materials chosen for aircraft applications must be first of all reliable and safe to use, meet design and operation conditions, and be cost comparable, recyclable, and disposable. Only a small percentage of the vast amount of available materials available can be utilized in aircraft components due to the requirements. Titanium is almost half of the weight of steel, but even more strong than steel from the other side. Even more, it has far better exfoliation, corrosion, and thermal properties than aluminum alloys and steels. However, the cost of titanium and its alloys is higher due to the mining and refining operations. (Singh, et al., 2017, pp. 8971-8973, 8975)

Aircraft interiors can also be lightened by using modern materials. French company SMTC presented a thermoplastic panel called Dynatech, which is made of polyethylenimine and has two layers of fiber-reinforced polyethylenimine facing and foam layer in between. SMTC reports that such materials have the potential to reduce weight and cost by up to 40% and 30%, respectively. It was estimated that the average weight saved for the Airbus A350 aircraft types is about 750 kg (Figure 12), while for A320, it can be up to 500 kg. Moreover, such kind of materials have better physical properties, and aircraft manufactures fully verify them. (Feature, 2014)

Figure 12. The weight saving potential of Dynatech materials in aircraft interiors (Feature, 2014)
Tsai et al. (2014), in their research, implemented mathematical programming model methods in frames of Corporate Social Responsibility (CSR) to assess environmental and economic impacts of cabin seat weight and a number of seat reduction in aircraft. The results show that balancing between quantities of seats in cabins and reducing them to cut fuel consumption can lead to significant benefits. Lighter seats itself provide a valuable weight and cost cuts. The total weight can be reduced up to 5500 kg in Boeing 747-400 and safe up to almost the same amount of emissions. Such seat modernizations can be done while a necessary aircraft maintenance check occurs, which must be done every five to ten years. However, due to the reduced flight ticket cost, a share of taken seats in an average flight can potentially increase and lead to an increase in fuel consumption and emissions.

4.1.4 Aircraft fuel efficiency trends

The annual efficiency improvement targets, which were set by ICAO, were mentioned in the previous chapter 3.1.1 and in Figure 4 to be approximately 2% from 2020 to 2050. However, this target is probably not going to be reached because of the existing aviation sector 12-year time lag already between the goal and the current state of the art (Kharina & Rutherford, 2015). Because fuel costs make almost half of every operational flight cost, it is not only an environmental reason to reduce fuel consumption to cut emissions, but also an economic interest from airlines. (Kozuba & Ojciec, 2019, p. 12)

The historical outlook on average fuel efficiency improvements of new aircraft is presented in Figure 13 (Kharina & Rutherford, 2015, p. 11).
As seen from the figure above, the overall historical fuel consumption efficiency is almost 50%. The most significant improvement occurred between 1980 and 1990, mainly because of the popularization of high-bypass turbofan engines and launching such aircraft as Boeing 737 and Airbus A320, which became a global driver on fuel consumption reduction due to their enhanced characteristics. (Kozuba & Ojciec, 2019, p. 13)

The plan presented by ICAO in 2010 with several technologies to implement in aircraft to improve their efficiency has not been reached. Only a few technologies were applied and entered the market. Hence, there is the abovementioned technology improvement timeline lag that exists for both 2020 and 2030 goal ranges (Figure 14). Even though several major new aircraft are below the goal value (Airbus A320-200, A330-200; Boeing 737-800, 777-200), additional policies except only technological improvements are needed to reach the goals set and mitigate global warming impact of aviation at the end. (Kharina & Rutherford, 2015, p. 16)
4.2 Route planning and air traffic management

An ideal aircraft route aims to be followed while flying to reach a destination point in the shortest distance and the lowest amount of fuel burnt. However, due to many circumstances, it is sometimes not possible to reach a 100% efficient flight route, and about eight percentages of aviation fuel is lost because of it. Air traffic management (ATM) is a system to achieve the best environmental and fuel-efficient routes. Nevertheless, several interdependencies, which limit the ability of the system, exist. They are to do with aircraft safety, weather conditions, airspace and airport capacity limitations, noise impact restrictions, longstanding airline practices, restricted airspace zones, and with institutional and political limitations in different regions. The historical development in ATM efficiency, current potential efficiency gains’ components, and interdependencies are illustrated in Figure 15 and Figure 16. (The World Bank, 2012, pp. 46-48)
Nowadays, there are several options available to reduce the effect of interdependencies and enhance ATM procedures. Air navigation service providers (ANSP) work in close cooperation with military services to allow the shared use of airspace in restricted areas to be available. Reduced Vertical Separation Minima (RVSM) is another example, which allowed aircraft to have a shorter altitude band of 1000 feet separation instead of 2000 feet. Modern aircraft can operate safely within such bands, but it opens a possibility to reduce fuel consumption by following an optimal cruise altitude. Moreover, such deregulation allows for increasing airspace capacity. The combined effect of RVSM alone globally is estimated to be 1.8% of fuel consumption reduction. Improvements in aircraft noise levels
can as well provide an opportunity to fly in previously restricted areas. It will help aircraft to follow the most optimal route as well. (The World Bank, 2012, pp. 48-50)

Moreover, IPCC claims that updated flight control procedures to minimize delays at every step of a flight can reduce emissions by 12%. Also, a brand-new Boeing Tailored Arrivals procedure on continuous and optimized descent and landing have resulted in 1.6 million kg of carbon dioxide emission reduction in tested flights over a year. (The World Bank, 2012, pp. 48-50)

Several researches being conducted on flight routes and their maneuvers suggest several options to further optimization. Gardi, et al. (2016) presented a study on the 4-Dimensional Trajectory method “to enable real-time planning and re-planning of more environmentally efficient and economically viable flight routes by simultaneously addressing the dynamic nature of both weather and air traffic conditions.” In turn, Girarded, et al. (2014), in their research, analyzed the contribution of wind and its impact on aircraft optimal trajectories. It showed that following a continuous wind-optimal path, it is possible to speed up a flight by up to almost 2%.

Xu, et al. (2014) presented a way of utilizing the method of formation flights previously used in military aviation in commercial flights to reduce fuel burn. The physical effect of formation flights is to create the outboard upwash from a previous flight (Figure 17). Such upwash leads to the reduction of drag and fuel consumption by up to 5.8% and 7.7% for short and medium distances flights and long transatlantic ones respectively. The technology can be utilized with an existing aircraft fleet with a minimum of modifications needed.

Figure 17. The reduction of drag by following the route of formation flight (Xu, et al., 2014, p. 6)
4.3 Renewable jet fuels

Fossil based jet fuels are the major contributor to the aviation sector emissions and environmental impacts. Maintaining current standards of aircraft safety and performance while enhancing its efficacy with reducing its weight, increasing fuel efficiency, implementing new route planning technologies as well as new designs have a great potential to reduce the impact. However, it is not enough to reach a net-zero emissions future without implementing radical changes to the system. Mainly, the problem of aviation’s running force is of the highest importance. (The Royal Society, 2019, p. 4)

Fossils emit various harmful elements to the atmosphere while being burnt, so they must be replaced with sustainable solutions as soon as possible. Nowadays, there is an ongoing trend in the electricity sector and many transport modes decarbonization, but the aviation industry requires different solutions, mainly because of the low batteries energy density. Alternative fuels such as modernized kerosene, biofuels, carbon-based synthetic electro- and biofuels, as well as other non-carbon fuel solutions (i.e., hydrogen and ammonia), can become a solution in a medium-term perspective. (The Royal Society, 2019, p. 4)

The idea to have a fully electrified energy system based on renewable sources has a very perspective future. However, in frames of aviation, it is challenging to achieve, and these days, EasyJet announced that by 2030, it would be possible to launch electric planes only for short-haul flights (Mallinson, 2018). In turn, carbon-based synthetic jet fuels have a well-known production process technology, which has technology readiness levels (TRL) of 5-8 out of 9 (Schmidt, et al., 2016, p. 15), and can be divided into electro fuels (efuels) and synthetic biofuels (Figure 18). Both of them use renewable energy sources to have a carbon-neutral production process. The advantage of such fuels is that it can be made with the existing infrastructure and used with a minimum of modifications in engines. Efuels, also known as power-to-gas or -liquid fuels (PtX), is made from carbon dioxide (captured from different sources), and hydrogen recovered from the water with electrolysis. Synthetic biofuels in respect can be made either from biomass, waste or biofuels through chemical, biological or thermal treatment. (The Royal Society, 2019, p. 4)
4.3.1 Carbon-based synthetic jet fuels

The production of synthetic efuels has been performed for several decades using methanol synthesis and Fischer-Tropsch processes. The majority of currently existing production processes use fossil carbon as a source, however renewable carbon sources are assumed in the future. Methanol synthesis (Figure 19) is the process of methanol production from carbon dioxide and hydrogen with a copper catalyst under high pressure and temperature. (Schmidt, et al., 2016, p. 13)
Fischer Tropsch process (Figure 20) utilizes the reverse water gas shift reaction to produce carbon monoxide from carbon dioxide and water, which is then reacted with hydrogen over cobalt or iron catalysts into hydrocarbons (C1 – C12+). (The Royal Society, 2019, pp. 7-8)

In turn, synthetic biofuels are produced from biomass feedstock. The biomass is then upgraded via gasification and cleaning to syngas. As well as for the efuels, synthetic biofuels are also produced using methanol synthesis and Fischer Tropsch processes but from the pretreated syngas. However, as it is shown in Figure 18, synthetic biomass fuels can also be
produced through thermochemical processes, such as pyrolysis, and hydrotreatment, and through biological process of fermentation as well. (The Royal Society, 2019, p. 22)

However, these processes are based on carbon. Hence, burning such fuels will lead to emissions anyway. The solution is a sustainable carbon cycle, which means that carbon is taken from carbon dioxide for the case of efuels, which is captured from the air or other sources of exhaust gases. For the case of synthetic biofuels, carbon is taken from sustainable biomass sources. Both cases ideally assume utilizing the same amount of carbon while production processes as the amount of carbon released while combusting such fuels. A sustainable carbon cycle of synthetic fuel production is shown in Figure 21. (The Royal Society, 2019, p. 9)

It should be noted that in the case of biofuels, the growth rate of feedstock has to be taken into account and be sustainable, allowing to substitute released emissions from combusted fuels with new growing feedstock. Overall, such a cycle can contribute to the reduction of needed carbon capture and storage capacities on the pathway to meet net-zero emission targets. (The Royal Society, 2019, p. 9)

Figure 21. A sustainable carbon cycle, where a - synthetic biofuels production, b – efuels (The Royal Society, 2019, p. 9)
One of the challenges, which exist today in the field of decarbonization options for the transportation sector is the energy density of energy carriers. Alternative solutions must have a comparable with traditional fossil-based fuel energy density, among many other characteristics such as safety and cost. Figure 22 shows that only a few alternative fuels available can satisfy the needs of aviation. However, the energy density of synthetic fuels is comparable with the existing fuels, which means that they can be adapted to the existing aircraft without any additional design changes except the policy regulations regarded to the safety standards. Nevertheless, existing regulations only allow several non-fossil fuel production ways and up to 50% of alternative fuels in blends with fossils. (The Royal Society, 2019, pp. 4, 10)

![Figure 22. The energy density of different fuel options (The Royal Society, 2019, p. 10)](image)

**4.3.2 New synthetic jet fuels production technologies**

All of the efuels are produced with such processes as the hydrogen production, the capture of carbon dioxide, and their synthesis. Nowadays, hydrogen is generated mostly from
methane reforming with carbon capture and storage (CCS) because it has carbon dioxide as a by-product. However, there is an option to produce hydrogen also from the water with electrolysis, which is run on renewable electricity. Although renewable electricity becomes more and more affordable, it still contributes a lot to the total price due to its intermittencies. Carbon dioxide, in turn, can be captured directly from air (DAC) or industrial processes such as power or iron production. The synthesis is done with Fischer Tropsch and methane synthesis methods. In order to use carbon dioxide as a carbon source in such synthesis methods, several modifications are needed. Moreover, there are several existing large- and small-scale plants producing synthetic fuels. (The Royal Society, 2019, pp. 14-18)

Also, a number of ongoing researches suggest a possible efficiency improvements not only by reducing renewable electricity prices, but also from enhancing the electrolysis process or even using of new technologies of a direct conversion of carbon dioxide to fuels with electricity (Al-Omari, et al., 2018) and bacterial conversion (Electrochaea, 2019). The solar light can also be used directly to convert carbon dioxide to fuels (Tuller, 2017) or water vapor to hydrogen (Heremans, et al., 2017).

4.3.3 Cost of synthetic biofuels and efuels

The major constraint of efuels and synthetic biofuels nowadays is their cost. The current efuel cost is about 4.5 euros per liter, and it mainly depends on renewable electricity costs. Since there are no industrial efuel production plants our days, a forecast is presented in Figure 23 and Figure 24. (The Royal Society, 2019, p. 29)
It is essential to mention that the fossil fuel price can be much higher in the future due to allocated emissions costs and removed subsidies programs (OECD, 2011, p. 66; The World Bank, 2019). In contrast, renewable electricity prices could be drastically decreased by 59% by 2025 because of the solar PV efficiency improvements trend, which means that by the 2030s, solar will become the world’s cheapest source of energy (Institute of Energy of South East Europe, 2019).
The cost breakdown of PtX jet fuels for different types of processes and carbon sources is shown in Figure 25. Still, the cost of fossil-based jet fuels is presented without a carbon price and taxes. (Schmidt, et al., 2016, p. 19)

![Figure 25](image)

**Figure 25.** PtX Jet fuel cost breakdown in 2050 (Schmidt, et al., 2016, p. 19)

### 4.3.4 Sustainability aspects of Power-to-Liquids

Among the many different options of sustainable jet fuels, power-to-liquid (PtL) solutions have several advantages. First of all, while discussing available biofuel pathways, most of them are highly dependent on water sources due to their feedstock-based production, irrigation demand, and climate conditions. It is found that PtL production from renewable sources like solar PV and wind electricity requires up to a factor of 15000 less water than most biofuels production routes. However, even though the water demand for PtL seems to be almost negligible, it has to be taken into account when assuming production in regions with high water stress. (Schmidt, et al., 2016, p. 21)

Land area needed for producing a certain amount of jet fuels both from biomass feedstock or renewable wind electricity, or solar PV is highly essential as well. Wind or solar PV plants require much less land area that it is needed for biomass production. Moreover, a type of land does not matter for renewables, while land has to be able to produce biomass. Hence, a
lot more of the suitable land area is available for renewable electricity production even in such locations as deserts. In turn, biomass production has not to compete with food production, which also limits the technology. Overall, Figure 26 shows that the gross land area demand for the PtL applications is much lower in contrast with a higher area-specific fuel yield. (Schmidt, et al., 2016, p. 23)

![Figure 26](image)

**Figure 26.** Gross area-specific yields of PtL and biomass applications (Schmidt, et al., 2016, p. 23)

The emission factor is the most critical driver to develop alternative jet fuels. To mitigate global warming and achieve international environmental goals, the global warming impact of aviation has to be drastically decreased and then reach carbon neutrality. The main advantage of alternative fuels is their ability to absorb carbon dioxide; however, in the case of biofuels, it has to be grown sustainably. In contrast, PtL fuels can compensate for emissions from fuel combustion by carbon capture technologies. Moreover, there are several carbon sources available. It can be captured from power and industrial processes with a further expanding to the direct carbon capture from air. Firstly, it allows reducing the cost of carbon capture in the short-term perspective. Later in the future, PtL production will become possible even in rural areas with high solar irradiation. GHG emissions from different types of jet fuels are presented in Table 4. (Schmidt, et al., 2016, p. 24)
Table 4. GHG emissions from different types of jet fuels in gCO$_2$-eq/MJ$_{\text{fuel}}$ (Schmidt, et al., 2016, p. 24)

<table>
<thead>
<tr>
<th>Jet fuel types</th>
<th>GHG emissions (excl. land-use)</th>
<th>GHG emissions (incl. land-use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil (reference)</td>
<td>87.5</td>
<td></td>
</tr>
<tr>
<td>Crude oil (ultra-low Sulphur)</td>
<td>89.1</td>
<td></td>
</tr>
<tr>
<td>Oil sand</td>
<td>103.4</td>
<td></td>
</tr>
<tr>
<td>Oil shale (in situ)</td>
<td>121.5</td>
<td></td>
</tr>
<tr>
<td>Natural Gas (GrL)</td>
<td>101.0</td>
<td></td>
</tr>
<tr>
<td>Coal (CtL)</td>
<td>194.8</td>
<td></td>
</tr>
<tr>
<td>Switchgrass (BlL)</td>
<td>17.7</td>
<td>-2.0</td>
</tr>
<tr>
<td>Soybean oil (HEFA)</td>
<td>37</td>
<td>97.8-564.2</td>
</tr>
<tr>
<td>Palm oil (HEFA)</td>
<td>30.1</td>
<td>39.8-698.0</td>
</tr>
<tr>
<td>Rapeseed oil (HEFA)</td>
<td>54.9</td>
<td>97.9</td>
</tr>
<tr>
<td>Jatropha oil (HEFA)</td>
<td>39.4</td>
<td></td>
</tr>
<tr>
<td>Algae oil (HEFA)</td>
<td>50.7</td>
<td></td>
</tr>
<tr>
<td>PtL (wind/PV in Germany)</td>
<td>1</td>
<td>11-28 (incl. constr. and produc.)</td>
</tr>
</tbody>
</table>

Jet fuels can also be produced using hydroconversion from organic waste streams (waste cooking oils), which cannot be avoided or treated. Such fuels have by 70% lower GHG emissions, 90% lower particulate emissions, and they are Sulphur free (Wade, 2019). However, even though such waste cooking oils are up to 3 times cheaper than plant oils, the main limitation of such fuels is their feedstock (food processing industry, public caterings, and households) availability. (Zhang, et al., 2019)

Power-to-Liquid synthetic jet fuels can also reduce the impact of the non-CO$_2$ effect. It was mentioned during the Aviation Decarbonization Forum (ICSA, 2019) that biofuels can increase the impact of contrails while PtL based 50% blend can reduce the impact by 20%. Moreover, as a synthetic fuel, PtL has provided a better combustion process. Due to the small number of aromatic compounds and Sulphur in synthetic jet fuels’ composition, the combustion of such fuels has a smaller value of other than carbon dioxide and water vapor emissions and an entire absence of SO$_x$. The indexes of emissions reduction from burning and Synthetic Paraffinic Kerosene in comparison with conventional jet fuels are shown in Table 5. (Chakraborty & Samanta, 2019, pp. 3-4; Janic, 2018, p. 239)

Table 5. Synthetic fuel emissions reduction in comparison with fossil-based jet fuels (Janic, 2018)

<table>
<thead>
<tr>
<th>GHG</th>
<th>Jet kerosene</th>
<th>Synthetic fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>1</td>
<td>0.982</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>1</td>
<td>0.778-0.889</td>
</tr>
<tr>
<td>SO$_x$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>PM</td>
<td>1</td>
<td>0.0005-0.025</td>
</tr>
<tr>
<td>HC</td>
<td>1</td>
<td>0.75-0.82</td>
</tr>
</tbody>
</table>
5 CASE STUDY

The aviation sector has a significant warming impact, which is beyond its carbon dioxide emissions. While flying at cruise altitudes, aircraft induced direct emissions and indirect effects altogether contribute up to a factor of 5.2 more to the warming potential than CO₂ related emissions only. Hence, in order to evaluate warming impacts from aviation, it is essential to compare short-, medium-, and long-haul flights. Next, such a comparison based on is presented.

5.1 Case flights characteristics

Flights from Helsinki to Oulu, Munich, and Lisbon were taken as a case study. These flights are operated by Airbus A320 and have great circle distances of 514, 1577, and 3369 km, respectively. The flight information is taken from the Flightradar database (2019). Flight parameters are presented in Figure 27 – Figure 29.

![Figure 27. Helsinki – Oulu flight parameters (Flightradar24 AB, 2019)]
The estimations of flight emissions are done through the calculation of jet fuel consumption. A methodology to compute the aircraft fuel burn presented by Yanto and Liem (2018) is based on the segment-by-segment fuel burn calculations. The flight missions are divided into the climb, cruise, and descent segments. In turn, warm-up, taxi, takeoff, approach, and landing phases are combined into the maneuver segment. Airbus A320 aircraft specifications are given in Table 6.
Table 6. Airbus A320 specifications (Yanto & Liem, 2018)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEW</td>
<td>37500</td>
<td>kg</td>
</tr>
<tr>
<td>R_{takeoff}</td>
<td>2190</td>
<td>m</td>
</tr>
<tr>
<td>R_{landing}</td>
<td>1440</td>
<td>m</td>
</tr>
<tr>
<td>V_{climb}</td>
<td>252</td>
<td>knots (466.7 km/h)</td>
</tr>
<tr>
<td>V_{cruise}</td>
<td>450</td>
<td>knots (833.4 km/h)</td>
</tr>
<tr>
<td>V_{descent}</td>
<td>250</td>
<td>knots (463.0 km/h)</td>
</tr>
<tr>
<td>L/D</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>TSFC</td>
<td>0.573</td>
<td>N(Nh)</td>
</tr>
<tr>
<td>H_{cruise}</td>
<td>35000</td>
<td>ft</td>
</tr>
<tr>
<td>P_{int}</td>
<td>15562.5</td>
<td>kg</td>
</tr>
<tr>
<td>f_{res}</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Fuel burn calculations

The first step of the fuel burn calculations is to define the amount of reserve fuel. Even though the reserve fuel is not burnt during a flight, it has to be always loaded due to safety reasons. The reserve fuel is defined as a fixed fraction of the aircraft zero-fuel weight (Equations 8-9).

\[
W_{ZF} = OEW + P_{\text{int}} \tag{8}
\]

\[
W_{ZF} = \text{Aircraft zero-fuel weight [kg]}
OEW = \text{Operating empty weight [kg]}
P_{\text{int}} = \text{Aircraft payload [kg]}
\]

\[
W_{f,\text{res}} = W_{ZF} \cdot f_{\text{res}} \tag{9}
\]

\[
W_{f,\text{res}} = \text{Reserve fuel weight [kg]}
f_{\text{res}} = \text{Reserve fuel fraction}
\]

The results of the aircraft zero-fuel weight and reserve fuel are presented in Table 7.
Table 7. Aircraft zero-fuel weight and reserve fuel calculation results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oulu</th>
<th>Munich</th>
<th>Lisbon</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{ZF}$</td>
<td>53062.5 kg</td>
<td>53062.5 kg</td>
<td>53062.5 kg</td>
<td>kg</td>
</tr>
<tr>
<td>$W_{f,res}$</td>
<td>4245 kg</td>
<td>4245 kg</td>
<td>4245 kg</td>
<td>kg</td>
</tr>
</tbody>
</table>

The descending traveled distance is related to the aircraft payload. According to the Yanto and Liem (2018) research, the descent range ($R_{descent}$) of Airbus A320 is constant and equals to 207.575 km. The aircraft total payload weight is calculated by Equation 10:

$$P = P_{int} \cdot W_{f,res}$$  \hspace{1cm} (10)

$P$ = Aircraft take-off weight [kg]

The climb range is defined from the total payload by the regression model (Equation 11):

$$R_{climb} = 0.005 \cdot P + 109.4$$  \hspace{1cm} (11)

$R_{climb}$ = Climb range [km]

The cruising range is calculated by Equations 12-13:

$$\sum R_{other} = R_{takeoff} + R_{climb} + R_{descent} + R_{landing}$$ \hspace{1cm} (12)

$R_{takeoff}$ = Take-off range [km]

$R_{descent}$ = Descent range [km]

$R_{landing}$ = Landing range [km]

$$R_{cruise} = R_{total} - \sum R_{other}$$ \hspace{1cm} (13)

$R_{cruise}$ = Cruise range [km]

$R_{total}$ = Total range or great circle distance [km]

The results of the total payload, climb, and cruise ranges are given in Table 8.
Table 8. Total payload, climb, and cruise ranges calculation results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oulu</th>
<th>Munich</th>
<th>Lisbon</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>19807.5</td>
<td>19807.5</td>
<td>19807.5</td>
<td>kg</td>
</tr>
<tr>
<td>R&lt;sub&gt;climb&lt;/sub&gt;</td>
<td>208.4</td>
<td>208.4</td>
<td>208.4</td>
<td>km</td>
</tr>
<tr>
<td>ΣR&lt;sub&gt;other&lt;/sub&gt;</td>
<td>419.6</td>
<td>419.6</td>
<td>419.6</td>
<td>km</td>
</tr>
<tr>
<td>R&lt;sub&gt;cruise&lt;/sub&gt;</td>
<td>94.4</td>
<td>1157.4</td>
<td>2949.4</td>
<td>km</td>
</tr>
</tbody>
</table>

The landing weight is calculated by Equation 14:

\[ W_L = W_{ZF} + P \]  

\( W_L \) = Landing weight [kg]

The amount of fuel burnt during the descent is defined through the Breguet range equation for the same flight range and the descent fuel factor (Equations 15-17):

\[ \tilde{W}_{f,cruise}^{eq} = W_{ZF} \cdot e^{V_{descent} \frac{L}{D}} - W_{ZF} \]  

\( \tilde{W}_{f,cruise}^{eq} \) = Cruise fuel weight from the Breguet range equation [kg]

\( TSFC \) = Thrust specific fuel consumption [N(Nh)]

\( V_{descent} \) = Descent velocity [km/h]

\( \frac{L}{D} \) = Aerodynamic lift-to-drag ratio

The descent fuel factor is based on the Base of Aircraft Data (BADA) simulations results and correction parameters (Yanto & Liem, 2018):

\[ \Delta W = f_{WL} \cdot W_L + f_R \cdot R_{descent} - C \]  

\( \Delta W \) = Descent fuel factor [kg]

\( f_{WL}, f_R, C \) = Descent fuel factor correction parameters (= 0.023, 2.63, 1410.35)

\[ W_{f,descent} = \tilde{W}_{f,cruise}^{eq} - \Delta W \]  

\( W_{f,descent} \) = Descent fuel weight [kg]
Table 9 shows the results of the landing weight and the descent fuel weight calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oulu</th>
<th>Munich</th>
<th>Lisbon</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_L$</td>
<td>57307.5</td>
<td>57307.5</td>
<td>57307.5</td>
<td>kg</td>
</tr>
<tr>
<td>$\Delta W$</td>
<td>453.6</td>
<td>453.6</td>
<td>453.6</td>
<td>kg</td>
</tr>
<tr>
<td>$W_{\text{cruise}}^{\text{eq}}$</td>
<td>742.0</td>
<td>742.0</td>
<td>742.0</td>
<td>kg</td>
</tr>
<tr>
<td>$W_{\text{descent}}$</td>
<td>288.3</td>
<td>288.3</td>
<td>288.3</td>
<td>kg</td>
</tr>
</tbody>
</table>

The cruise fuel weight is calculated as a difference between the final weight of the climb and cruise segments by Equations 18-20:

$$W_1 = W_{f,\text{descent}} + W_L$$  \hspace{1cm} (18)

$$W_1 = \text{The final weight of the cruise segment [kg]}$$

$$W_0 = W_1 \cdot e^{-\frac{L}{\text{cruise} \cdot \text{TSFC} \cdot V_{\text{cruise}}}}$$  \hspace{1cm} (19)

$$W_0 = \text{The final weight of the climb segment [kg]}$$

$$V_{\text{cruise}} = \text{Cruise velocity [km/h]}$$

$$W_{f,\text{cruise}} = W_0 - W_1$$  \hspace{1cm} (20)

$$W_{f,\text{cruise}} = \text{Cruise fuel weight [kg]}$$

The results of the cruise fuel weight calculations are shown in Table 10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oulu</th>
<th>Munich</th>
<th>Lisbon</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_1$</td>
<td>57595.8</td>
<td>57595.8</td>
<td>57595.8</td>
<td>kg</td>
</tr>
<tr>
<td>$W_0$</td>
<td>57798.1</td>
<td>60127.2</td>
<td>64268.0</td>
<td>kg</td>
</tr>
<tr>
<td>$W_{f,\text{cruise}}$</td>
<td>202.3</td>
<td>2531.4</td>
<td>6672.2</td>
<td>kg</td>
</tr>
</tbody>
</table>

The climb fuel weight is calculated by the following formula (Equation 21):
The maneuver fuel weight is calculated as a part of the aircraft take-off weight (Equations 22-23):

\[ W_{f,\text{climb}} = \frac{\tilde{W}_{f,\text{cruise}} + f_{\text{climb}} \cdot W_0}{(1 - f_{\text{climb}})} \]  

\[ W_{TO} = W_{f,\text{climb}} + W_0 \]  

\[ W_{f,\text{man}} = W_{TO} \cdot f_{\text{man}} \]

\[ W_f = W_{f,\text{descent}} + W_{f,\text{cruise}} + W_{f,\text{climb}} + W_{f,\text{man}} \]

The total fuel weight is then defined as follows:

\[ W_f = \text{The total fuel weight [kg]} \]

The results of the climb, maneuver, and total fuel weight calculations are presented in Table 11.

**Table 11. Climb, maneuver, and total fuel weight calculation results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oulu</th>
<th>Munich</th>
<th>Lisbon</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{f,\text{climb}} )</td>
<td>Climb fuel weight</td>
<td>1730.1</td>
<td>1769.4</td>
<td>1839.3</td>
</tr>
<tr>
<td>( W_{TO} )</td>
<td>Takeoff weight</td>
<td>59528.3</td>
<td>61896.7</td>
<td>66107.3</td>
</tr>
<tr>
<td>( W_{f,\text{man}} )</td>
<td>Maneuver fuel weight</td>
<td>416.7</td>
<td>433.3</td>
<td>462.8</td>
</tr>
<tr>
<td>( W_f )</td>
<td>Total fuel weight</td>
<td>2637.5</td>
<td>5022.5</td>
<td>9262.6</td>
</tr>
</tbody>
</table>
The comparison of case flight fuel burn by segments is given in Figure 30.

![Fuel burn by segments](image)

**Figure 30.** Fuel burn comparison of the case flights by segments

The descent segments of the three case flights are equal. The reason is that the same type of aircraft with the same payload right before the descent will have the same amount of fuel needed for landing. The maneuver and climb fuel weights are not that significantly different. The climb fuel burn amount has a visible share of the total fuel consumption of the flights, especially for the short flight to Oulu. However, as well as for the maneuver fuel consumption, the values of the case flights are relatively close, mainly due to the same type of aircraft and equal payloads. In turn, the cruise fuel consumption is linearly dependent on the flight lengths and is highest for the long-haul flight to Lisbon.

### 5.3 Warming impact calculations

Carbon dioxide emissions linearly depend on aircraft fuel consumption. Hence, they are obtaining by multiplying the fuel consumption of every flight segment by 3.16 kg of CO₂ per 1 kg of fuel burn. However, the indirect warming impact of the flights occurs only at the high altitudes or during the cruise segment. The RFI of the indirect warming impact at the cruise altitudes is 5.2, and a total flight warming effect can be obtained from Equation 7 and a share of cruise emissions compared to total emissions. 7.7%, 50.4%, and 72% of emissions
of the flights Helsinki – Oulu, Helsinki – Munich, and Helsinki – Lisbon respectively occur in the stratosphere. Hence, their total warming impact is by the factor of 1.32, 3.12, and 4.03 higher than from carbon dioxide emissions only (Figure 31).

![Warming impact by segments](image_url)

**Figure 31.** Warming impact comparison of the case flights by segments

The indirect warming impact is significant for every of the case flights. However, the indirect warming impact of the flights to Munich and Lisbon is even higher than the total carbon dioxide emissions from their fuel burn.

### 5.4 Warming impact reduction perspectives

#### 5.4.1 The effect of aircraft efficiency improvements

Aircraft efficiency improvement leads to reduced fuel consumption, which equals lower emissions from aviation. The aviation’s goal of the Paris agreement is to increase efficiency by 1.5% annually and have a carbon-neutral growth after 2020. It means that by 2050, the efficiency has to be improved by the factor of 1.56 from now on. The warming impact in 2050 of improved, according to the Paris agreement goals, aircraft is shown in Figure 32.
The total warming impact of more efficient aircraft is equally reduced by 36% in 2050 for the short-, medium-, and long-haul flights. The implementation of the efficiency goals, however, only leads to the reduction of carbon dioxide emissions. The indirect aviation impact remains the same due to the same fuel used for combustion in engines.

### 5.4.2 The warming impact of using synthetic efuels

The synthetic jet efuels have a different chemical composition than fossil fuels. As it was presented in Table 5, only water vapor emissions are equal to the emissions from conventional fuels, while others are reduced or do not exist like SO\(_x\) emissions. According to this, the indirect impact from the synthetic efuels is also lower. It can be estimated based on Figure 8 and emissions reduction factors from Table 5 that the RFI of the synthetic efuels can be 1.86 the highest compared to the previously used RFI = 2. Hence, the total aircraft emissions CF is calculated following Equation 7 and equals to 4.59. The impact of using synthetic jet efuels is shown in Figure 33.
As it can be seen from the figure above, the synthetic efuels have the maximum warming impact reduction of 10.86% for the long-haul flight if carbon sequestration is not included. However, it should be taken into account that the production chain of such fuels supposes the utilization of carbon capture technologies, which means that carbon dioxide emissions can be excluded from the assessment in order to avoid double counting. Hence, it can be assumed that the emissions of CO₂ from combusting the synthetic efuels are zero. With such estimations, the only effect left is warming because of the other than carbon dioxide emissions. The impact of synthetic efuels with carbon capture technologies is given in Figure 34.

Figure 33. Warming impact reductions from indirect emissions by using synthetic efuels
Figure 34. The warming impact of the synthetic fuels with carbon sequestration

The synthetic fuels produced with carbon capture technologies have significant aircraft warming impact reduction. The biggest warming impact cut occurs for the short-haul flight due to the lowest share of indirect warming impacts compared to other flight segments. Nevertheless, there are still emissions leading to the indirect warming impacts occur while the cruise segment of the flight, and even though the option is carbon-neutral, it still causes the warming impact.

In turn, using the synthetic fuels in more efficient aircraft in 2050 can further pursue the total warming impact from aviation to decline. Figure 35 provides the results of the total impact from efficiency improvements in aircraft and using the synthetic jet fuels with carbon capture options calculation.
The combined effect of aircraft efficiency improvement and utilizing the efuels with carbon capture technologies is the highest for the short-haul flight from Helsinki to Oulu. The option assumes the carbon-neutral fuel burn, but due to the indirect warming impact from other than carbon dioxide emissions left at cruise altitudes, the warming impact reduction is linearly lower for longer flights.

Figure 36 presents the results of the warming impact of flight reduction methods comparison.
As can be seen from the figure above, the synthetic efuels have to be produced with carbon capture options in order to cover carbon dioxide emissions from combustion. While covering the emissions, the option provides a closed and sustainable carbon-neutral cycle. Ideally, when the amount of captured emissions to produce the fuels equals to emissions released while burning, the fuels are an excellent option for the aviation sector to mitigate climate change. However, further aircraft performance improvement shows a visible effect on the warming impact reduction. Nevertheless, only synthetic efuels or efficiency improvements separately is not enough, and even their combined implementation in the aviation sector has to be further developed to mitigate the warming impact completely.


6 CONCLUSIONS

Global warming is a significant threat that the human race is facing nowadays, and its impact continues to grow. It requires decisive actions from people to prevent devastating environmental changes from one side while maintaining the modern standard of living from another. Renewable energy resources can be a solution in global decarbonization and meeting the Paris agreement. However, the aviation sector due to its specificity is more complicated, and such a transition is challenging.

Emissions from fuel burn induce the warming impact of aircraft. Moreover, the review part showed that not only direct emissions from fossil-based fuel combustion lead to warming, but there is an additional indirect impact. Because flights occur at altitudes, several reactions in the atmosphere composition cause more warming impact than from aviation’s carbon dioxide emissions only. Nowadays, there is no consensus on any precise methodology to estimate such impacts, and additional investigations in this field are needed. However, to estimate the total warming impact of aircraft, the currently available studies recommend using the factor of 5.2 as a multiplier to carbon dioxide emissions at altitudes. In this master’s thesis, the radiative forcing index is suggested to be used as the most evident and suggested by different environmental organizations methodology.

Nevertheless, there are ongoing researches on improving aircraft efficiency by reducing aircraft weight and design, enhancing jet engines and aerodynamic, upgrade route planning instructions. All of these actions eventually are helping to reduce fuel consumption, but not to nullify it. The review of sustainable jet fuels showed that synthetic fuels produced from captured carbon dioxide and hydrogen could be carbon neutral without competing for food production. Running their production process on renewable electricity can provide near net-zero life-cycle greenhouse gas emissions, and capturing carbon dioxide from different carbon sinks, in turn, provides a closed carbon cycle. Moreover, such fuels have a different chemical composition than fossil fuels, which causes fewer emissions and warming effects.

Three flights, short-, medium-, and long-haul, from Helsinki to Oulu, Munich, and Lisbon, respectively, were taken as a case study to assess the potential of aircraft warming impact reduction. The current aircraft fuel consumption, emissions, and the warming impact, as well
as their possible reduction by increasing the aircraft efficiency and using synthetic jet efuels with carbon capture, were assessed.

The results showed the significant warming impact reduction from aircraft efficiency improvements and using efuels with carbon sequestration by 87%, 63%, and 59% for the short-, medium-, and long-haul flights accordingly. However, even though synthetic efuels with carbon capture, together with the total enhancing of aircraft efficiency, showed the great potential to reduce the aircraft-induced warming impact, it is not eliminated. There is still room for research in the field of reducing indirect warming impacts from fuel burn, a transition to the electric propulsion, and a better total aviation warming impact assessment techniques.
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