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COMPARISON OF THE POTENTIAL ENVIRONMENTAL IMPACT IMPROVEMENTS OF FUTURE AIRCRAFT CONCEPTS USING LIFE CYCLE ASSESSMENT

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ABSTRACT

In today's aeronautical research, several future aircraft concepts are being discussed. Among them are electric, hydrogen and alternative fuel powered aircraft. Often, their potential environmental impact improvement compared to conventional aircraft is measured by the reduction of harmful emissions during the flight. However, a serious comparison with conventional aircraft is only possible if the total environmental impact over the entire life cycle is analyzed. This paper aims at calculating the total environmental impact of electric, hydrogen and alternative fuel powered aircraft and at comparing it to that of the reference aircraft Airbus A320-200. In a first step, the future concepts are being conceptually designed based on the requirements of the reference aircraft. In a second step, their environmental impact is calculated using a life cycle assessment. Finally the environmental impact of the future concepts is compared to that of the A320. Results show that the way of generating electricity has a dominating influence on the environmental impact of all considered future concepts. Using today's electricity mix, their environmental impact is mostly even worse than that of the reference aircraft. Only if a high share of renewable energy sources is used for the generation of electricity, the future concepts can substantially improve environmental impact.

1 INTRODUCTION

The protection of the environment gets increased importance in civil aviation [1]. However, today aircraft are designed mainly for lowest Direct Operating Costs (DOC). Clearly, a better environmental protection can be achieved, if Environmental Impact (EI) is minimized and used as the objective function in aircraft design optimization. EIs over the entire life cycle can be calculated with a Life Cycle Assessment (LCA) defined in ISO 14040. LCA is the „compilation and evaluation of the inputs, outputs and the potential EIs of a product system during its life cycle" [2]. Admittedly, in a practical design of future civil aircraft, DOC will remain the most important objective, but better environmental protection could be achieved already with a multi objective design optimization in which EI are included and are given a least a certain weight. As often explained, most characteristics of an aircraft are fixed and determined already in the early phases of aircraft design. The same is true for the EI of an aircraft which is also locked in by decisions made in conceptual aircraft design. Therefore, it is so important to include an LCA already in conceptual design and not merely an analysis of the pollutant emissions resulting from aircraft operation. Summing up: Environmental protection is made a more important design criterion by including an LCA (calculating EI) into the objective function for aircraft optimization already during conceptual aircraft design.

The authors showed already that with a simplified LCA methodology the EI of an aircraft can be calculated already during conceptual aircraft design [3]. The authors showed further that using the EI as the objective function in conceptual aircraft design instead of using DOC has an influence on resulting aircraft parameters [4]. Not only aircraft parameters are influenced in new ways using EI as the objective function. This paper shows that EI can also be used to select the best alternative among several future aircraft concepts.

The paper presents several promising future aircraft with different fuel concepts and reviews their pros and cons concerning EI. The considered aircraft and fuel concepts are:
a) hydrogen powered aircraft,
b) electric powered aircraft,
c) alternative fuel powered aircraft.

The paper analyzes by how much future technologies could possibly reduce the EI of an aircraft and what concepts are favorable concerning their EI.

2 METHODS

To analyze the different future aircraft concepts, they have been conceptually designed first and their EI has been calculated afterwards. For the design of the aircraft, the conceptual aircraft design software PrOPerA has been used. PrOPerA has been adapted to be able to design not only conventional aircraft but also the considered future concepts. This adaption is based on the research of hydrogen powered aircraft by Dib [5], electric powered aircraft by Pérez Reyes [6], and alternative fuel powered aircraft by Ramachandran [7]. To analyze the EI of the concepts, PrOPerA contains a previously developed methodology for an LCA in conceptual aircraft design [3]. This LCA covers the entire life cycle from cradle to grave. The ReCiPe method [8] is used for the impact assessment. Several environmental issues of concern can be calculated and expressed using so called midpoint and endpoint categories. Additionally, the total EI of an aircraft can be summarized in one score, the so called Single Score. More details about the used LCA methodology can be found in [3]. Figure 1 shows the structure of the conceptual aircraft design software and how the LCA method has been integrated.

The reference aircraft for the comparison of the future concepts is the weight variant WV000 of the Airbus A320-200 with CFM56-5A engines [9]. The future concepts have to fulfill the same requirements as the A320. PrOPerA has been used to redesign the reference aircraft and to calculate its EI. The results of the future concepts have then been compared to those of the reference aircraft.

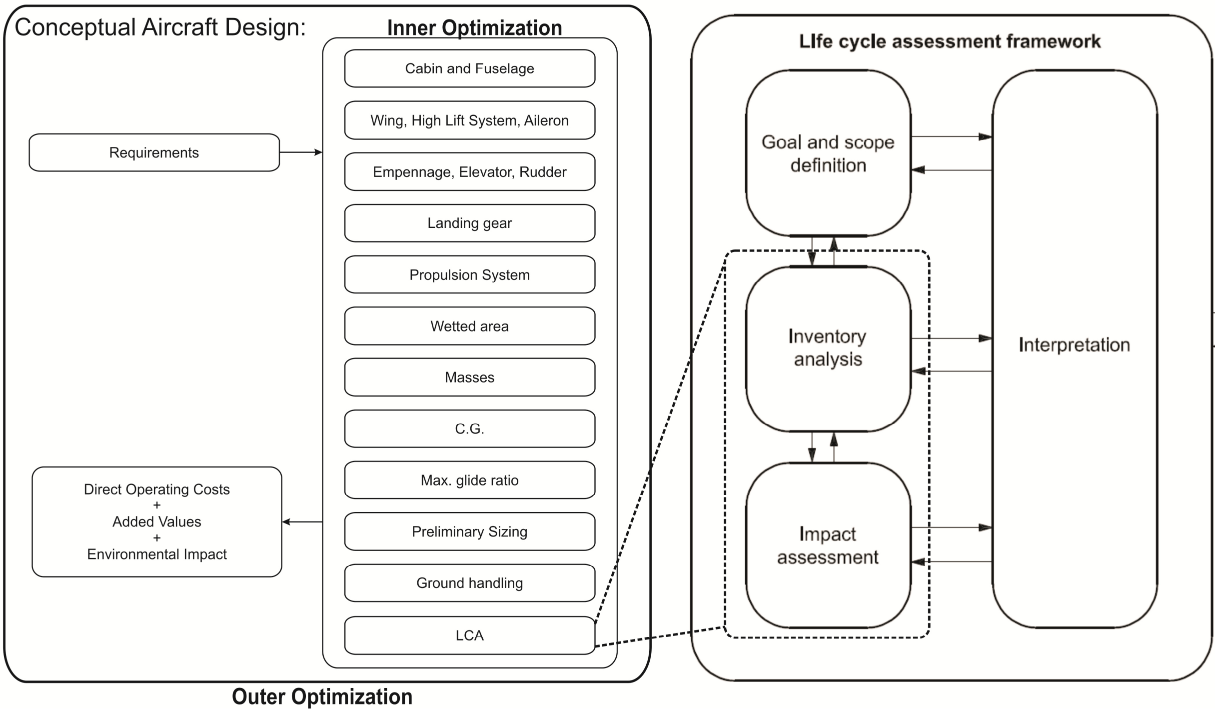

Figure 1: Structure of PrOPerA and the integrated LCA methodology (own diagram in combination with figure from [2])

The general aim was to design the future concepts based on the design of the reference aircraft while changing as little as possible. It is clear that a clean sheet design of the considered future concepts might lead to other and maybe better design solutions. Nevertheless, the resulting trends and main contributors to EI stay the same. Therefore it has been decided that the simplified conceptual designs of the future concepts are good enough to analyze the general characteristics as well as the pros and cons concerning EI.

The investigated future concepts are all based on a different energy carrier. Considered as energy carrier are hydrogen, batteries and alternative fuel.

There are many different alternative fuels and only one is considered here. The following list contains an overview about different approaches for the production of alternative fuels, even though a clear distinction is difficult:

- Alternative fuel can be produced as synthetic fuel from regenerative energy. The energy is used to split H_2O into H_2 and O_2. After that, H_2 and CO_2 are converted into syngas (H_2 and CO) which is finally converted to fuel by the Fischer-Tropsch process. Possible energy sources are:
  - Solar energy (as in the sunlight-to-jet fuel process [10])
  - Renewable electric energy (as in the Power-to-Liquids process [11])
- Alternative fuel can be produced as biofuel from organic matter. The organic matter has harvested energy from the sun. Additional energy is needed in the production process. Different forms of organic matter can be used [12]:
  - First generation biofuels use vegetable oil, sugar or starch from the fruit of plants for the fuel production

  - Second generation biofuels use the entire plant for the fuel production so that the production is based on various types of biomass
  - Third generation biofuels are based on algae. This is the form of alternative fuel considered here in further detail. Some hopes of the aviation industry are set in this form of alternative fuel [13]. It does neither depend on limited fresh water nor on limited farm land, contains high oil and carbohydrate concentrations and as such may be available in larger quantities [14].

The following main requirements, assumptions and simplifications have been used for the design of the concepts:

Hydrogen powered aircraft:
- Tanks for the liquid hydrogen are placed between cockpit and cabin and behind the cabin.
- An additional small tank for the liquid hydrogen is placed in the cargo compartment close to the wing box (the design mission requires not all the space available in the cargo compartment).
- The tank in front of the cabin leaves enough space for an aisle between cockpit and cabin.

Electric powered aircraft:
- As proposed by the Ce-Liner project [15]:
  - Futuristic mass energy density of the batteries of 1.87 kWh/kg (including systems, wirings, attachments).
  - Futuristic volumetric energy density of the batteries of 938 kWh/m³.
  - Batteries are stored in containers in the cargo compartment (again, the design mission requires not all the space available in the cargo compartment).
- Additional battery containers are stored in front and behind the cabin.
- The container in front of the cabin leaves enough space for an aisle between cockpit and cabin.
- Battery life involves 1500 cycles.
- Possible issues with magnetic shielding or superconductivity technology have not been considered.
- In contrast to the other designs, the range requirement at maximum payload has been reduced by 50 % to 755 NM. Even assuming the above mentioned futuristic battery technology, the range requirement of the reference aircraft could not be met.

Alternative fuel powered aircraft:
- No need to change the design of the aircraft
- It is assumed that possible issues concerning thermal stability, density, viscosity and freezing point of the alternative fuel are solved.
- The percentage of the alternative fuel is 100 % (i.e. no blend).

For the calculation of the EI of the future concepts, the existing LCA methodology had to be adapted as well. The following adaptions and assumptions have been made for the LCA of the future concepts.

Hydrogen powered aircraft:
- The process "kerosene production" is replaced by the process "hydrogen production".
- Production and liquefaction of hydrogen are considered. The transport of the liquid hydrogen from the production site to the airport is not considered.
- Hydrogen is produced using natural gas steam reforming covering 97 % of nowadays hydrogen production [5].

- Emissions due to the burning of kerosene are replaced by emissions due to the burning of hydrogen.
- It is assumed that the amount of contrails and aviation induced cirrus clouds is proportional to the amount of water emitted during flight in a certain altitude.

Electric powered aircraft:
- The process "kerosene production" is replaced by the process "generation of electricity".
- There are no emissions during the flight.
- EI due to the batteries has not been considered.

Alternative fuel powered aircraft:
- The process "kerosene production" is replaced by the process "alternative fuel production".
- Emission factors during the flight stay the same.
- The selected alternative fuel is gained from the hydration of vegetable oil based on the cultivation of the algae "Auxenochlorella protothecoides" [16].

There are many different ways of producing the energy sources required for the considered future concepts. Each production method has a different EI changing also the EI of the aircraft. Therefore a preselection of the respective production method is required. In all cases, the European electricity mix from the ELCD database [17] has been used for the provision of electrical energy ("Electricity Mix; AC; consumption mix; at consumer; <1 kV" (EU-27)). By choosing the most common method for the production of hydrogen, the European electricity mix for the generation of electricity and biofuel from algae as one promising alternative fuel type, the resulting EI of the future concepts is considered to be a good representation of the EI that these concepts would nowadays have.

3 RESULTS

3.1 The Hydrogen Powered Aircraft

The main parameters and a three view of the hydrogen powered aircraft are shown in Figure 2. Due to the high energy density of hydrogen, its mass can be reduced by 53 % compared to the kerosene mass of the reference aircraft. However, due to the low volumetric density of the liquid hydrogen, the fuselage has to be stretched to be able to accommodate the hydrogen tanks. Because of the higher tank mass and the longer fuselage resulting in higher drag and impaired glide ratio, the overall Maximum Take-Off Mass (MTOM) cannot be reduced but is similar to that of the reference aircraft.

Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	1510 NM	0%
M_{CR}	0.76	0%
max(s_{TOFL} , s_{LFL})	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%
Main aircraft parameters		
m_{MTO}	74200 kg	1%
m_{OE}	48800 kg	18%
m_{F}	6200 kg	-53%
S_{W}	124 m²	1%
$b_{W,geo}$	34.3 m	0%
$A_{W,eff}$	9.50	0%
E_{max}	17.00	≈ - 3%
T_TO	100 kN	12%
BPR	6.0	0%
h_{ICA}	40000 ft	2%
s_{TOFL}	1770 m	0%
s_{LFL}	1450 m	0%
Mission requirements		
R_{Mi}	589 NM	0%
$m_{PL,Mi}$	13057 kg	0%
Results		
$m_{F,trip}$	2800 kg	-39%
SS	0.0692	300%

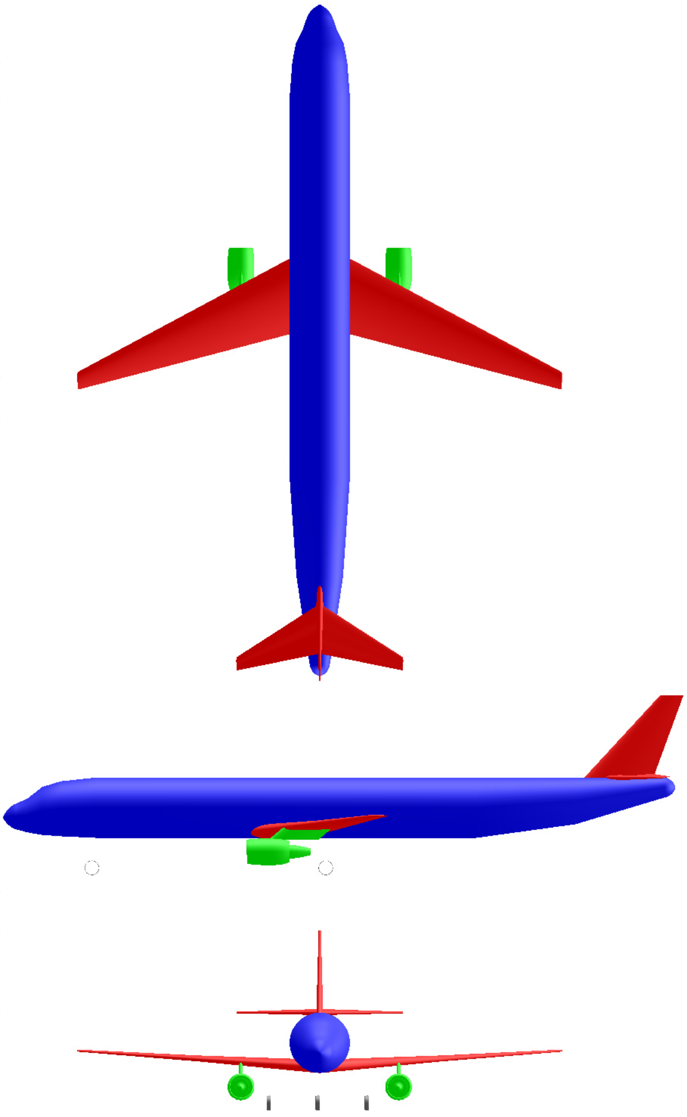

Figure 2: Main design parameters and three view of the hydrogen powered aircraft

3.2 The Electric Powered Aircraft

The main parameters and a three view of the electric powered aircraft are shown in Figure 3. The high mass of the batteries results in additional negative snowball effects like bigger and heavier wings, bigger and heavier tail and stronger and heavier engines. In addition, the fuselage has to be stretched because of the low volumetric density of the batteries. Even though the electric aircraft has only half the range of the reference aircraft, MTOM rises by 30 % to 95600 kg. The battery mass is increased by 70 % compared to the kerosene mass of the reference aircraft.

Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	755 NM	-50%
M_{CR}	0.76	0%
$\max(s_{TOFL}, s_{LFL})$	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%
Main aircraft parameters		
m_{MTO}	95600 kg	30%
m_{OE}	54300 kg	32%
m_F	22100 kg	70%
S_W	159 m²	30%
$b_{W,geo}$	36.0 m	6%
$A_{W,eff}$	9.50	0%
E_{max}	18.20	≈ + 3%
T_TO	200 kN	38%
BPR	6.0	0%
h_{ICA}	41000 ft	4%
s_{TOFL}	1770 m	0%
s_{LFL}	1450 m	0%
Mission requirements		
R_{Mi}	294 NM	-50%
$m_{PL,Mi}$	13057 kg	0%
Results		
$m_{F,trip}$	7800 kg	72%
SS	0.0095	-45%

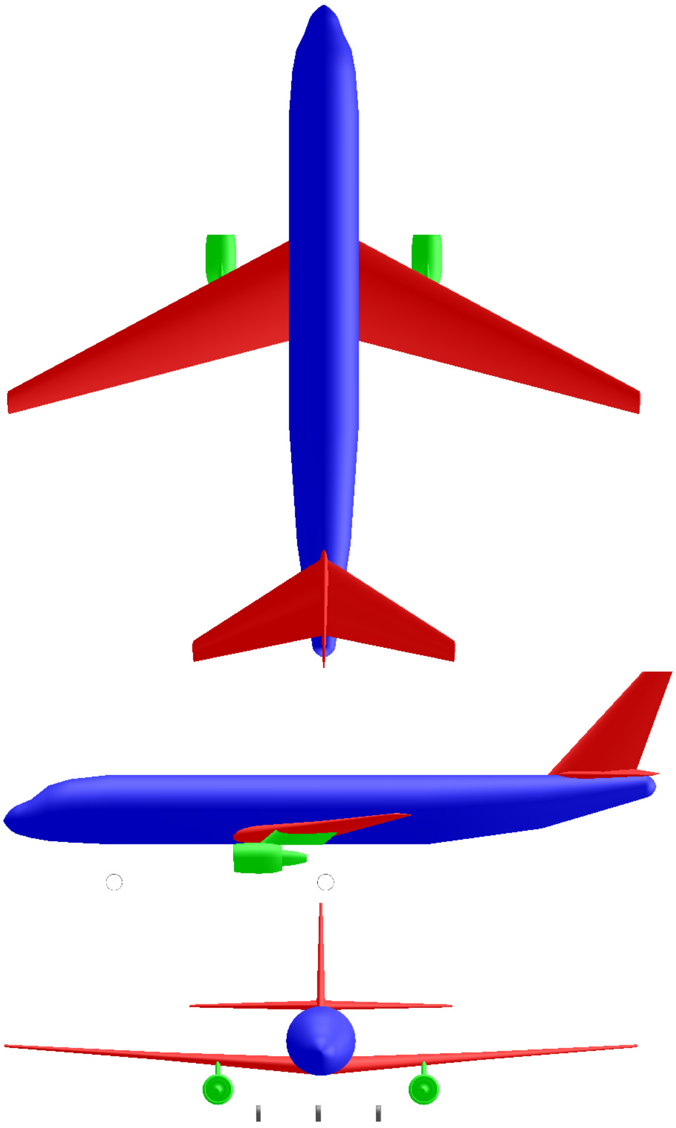

Figure 3: Main design parameters and three view of the electric powered aircraft

3.3 The Alternative Fuel Powered Aircraft

The main parameters and a three view of the alternative fuel powered aircraft are shown in Figure 4. It can be seen that the resulting design parameters are exactly those of the reference aircraft. This is because of the assumption that the kerosene can simply be replaced by the alternative fuel without any additional changes required for the design.

Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	1510 NM	0%
M_{CR}	0.76	0%
max(s_{TOFL} , s_{LFL})	1770 m	0%
n_{PAX} (1-cl HD)	180	0%
m_{PAX}	93 kg	0%
SP	29 in	0%
Main aircraft parameters		
m_{MTO}	73500 kg	0%
m_{OE}	41200 kg	0%
m_F	13000 kg	0%
S_W	122 m²	0%
$b_{W,geo}$	34.1 m	0%
$A_{W,eff}$	9.50	0%
E_{max}	17.60	≈ 0%
T_TO	100 kN	0%
BPR	6.0	0%
h_{ICA}	39000 ft	0%
s_{TOFL}	1770 m	0%
s_{LFL}	1450 m	0%
Mission requirements		
R_{Mi}	589 NM	0%
$m_{PL,Mi}$	13057 kg	0%
Results		
$m_{F,trip}$	4600 kg	0%
SS	0.0594	243%

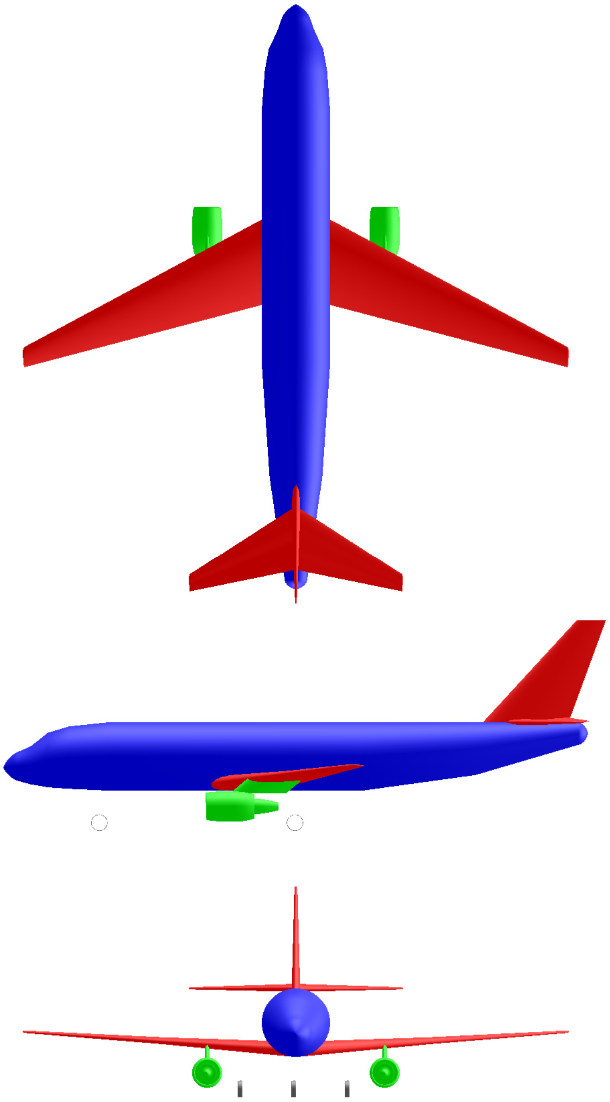

Figure 4: Main design parameters and three view of the alternative fuel powered aircraft

3.4 Evaluating the Environmental Impact of the Reference Aircraft

Figure 5 shows the contribution of the in- and outputs (left side) and the considered processes (right side) to the Single Score (i.e. the total environmental impact) of the reference aircraft. Only processes and in- and outputs with a contribution of at least 0.5 % are shown (this is the case for all following LCA analyses). It can be seen that crude oil, CO2, NOx as well as contrails and induced cirrus clouds together dominate the EI of the reference aircraft. Concerning the processes, it can be seen that the cruise flight dominates EI followed by kerosene production and the LTO-cycle. The Single Score is 0.0173 points/pkm.

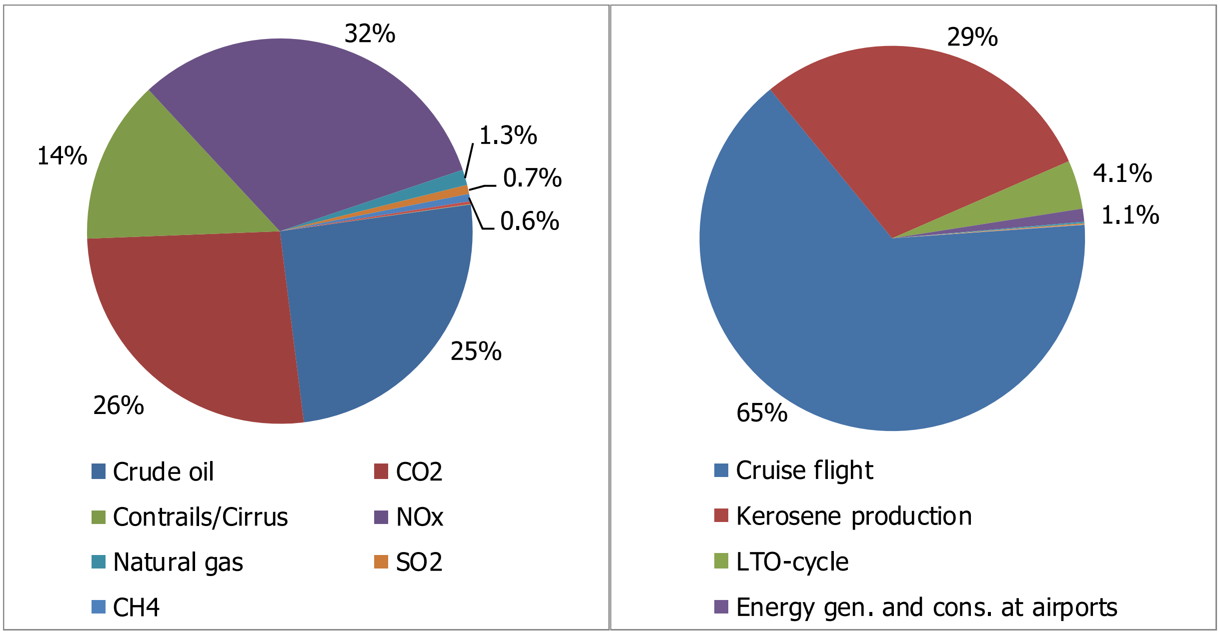

Figure 5: Contribution of the in- and outputs (left) and the considered processes (right) to the Single Score of the reference aircraft

3.5 Evaluating the Environmental Impact of the Hydrogen Powered Aircraft

Figure 6 shows the contribution of the in- and outputs (left side) and the considered processes (right side) to the Single Score of the hydrogen powered aircraft. It can be seen that for such a design contrails and cirrus clouds have the highest influence on EI (68 %), followed by CO2 (20 %). Several other in- and outputs cover the remaining 12 % of the EI (mainly: CH4: 4.6 %, Hard coal: 2.1 %, Natural gas: 1.7 %, Brown coal: 1.3 %, NOx: 1.3 % and Crude oil: 0.8 %). Concerning the processes, it can be seen that the distribution is similar to that of the reference aircraft. Cruise flight is dominating EI with a share of 69 %. The remaining contribution to EI is mainly covered by the production of hydrogen with a share of 30 %. The Single Score is 0.0692 points/pkm which is 300 % more than that of the reference aircraft. **If the production of hydrogen is realized by electrolysis and the required energy for the entire production process (including liquefaction) comes from electric energy generated by renewable energy sources** (here: hydropower), the Single Score can be reduced to 0.0445 points/pkm which is 157 % more than that of the reference aircraft. Using hydrogen in an aircraft designed for cruise altitudes that are not favorable for the formation of contrails and cirrus clouds allows to further reduce EI. Below 23000 ft, there is almost no contrail formation so that hydrogen powered aircraft designed for such altitudes would have a very small Single Score close to 0 points/pkm.

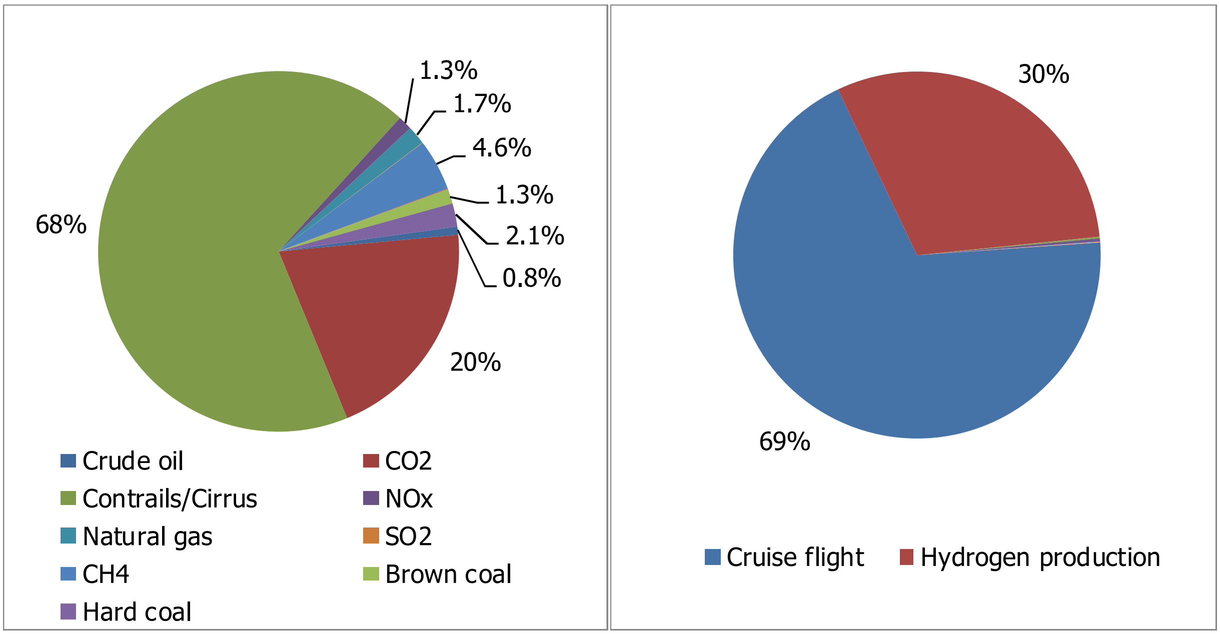

Figure 6: Contribution of the in- and outputs (left) and the considered processes (right) to the SS of the hydrogen powered aircraft (current electricity mix)

3.6 Evaluating the Environmental Impact of the Electric Powered Aircraft

Figure 7 shows the contribution of the in- and outputs (left side) and the considered processes (right side) to the Single Score of the electric powered aircraft. It can be seen that for such a design CO2 has the highest influence on EI with a share of 52 %. Hard coal (13 %), SO2 (10 %), natural gas (10 %), brown coal (9 %) and crude oil (5 %) are responsible for most of the remaining half of the EI. Concerning the processes, it can be seen that the generation of electricity completely dominates EI with a share of 95 %. The Single Score is 0.0095 points/pkm which is 45 % less than that of the reference aircraft. But it has to be kept in mind, that the range at maximum payload has been lowered by 50 % to enable a design solution at all. Strictly speaking, this means that the electric aircraft is not good enough to enter into a fair comparison with the other aircraft concepts. With such low range, the aircraft also competes against surface modes of transportation like high speed trains which are based on physics better suited for energy saving transportation. **If the electric energy is generated by renewable energy sources**, the Single Score can be reduced to 0.0008 points/pkm representing a reduction of about 95 % compared to the reference aircraft.

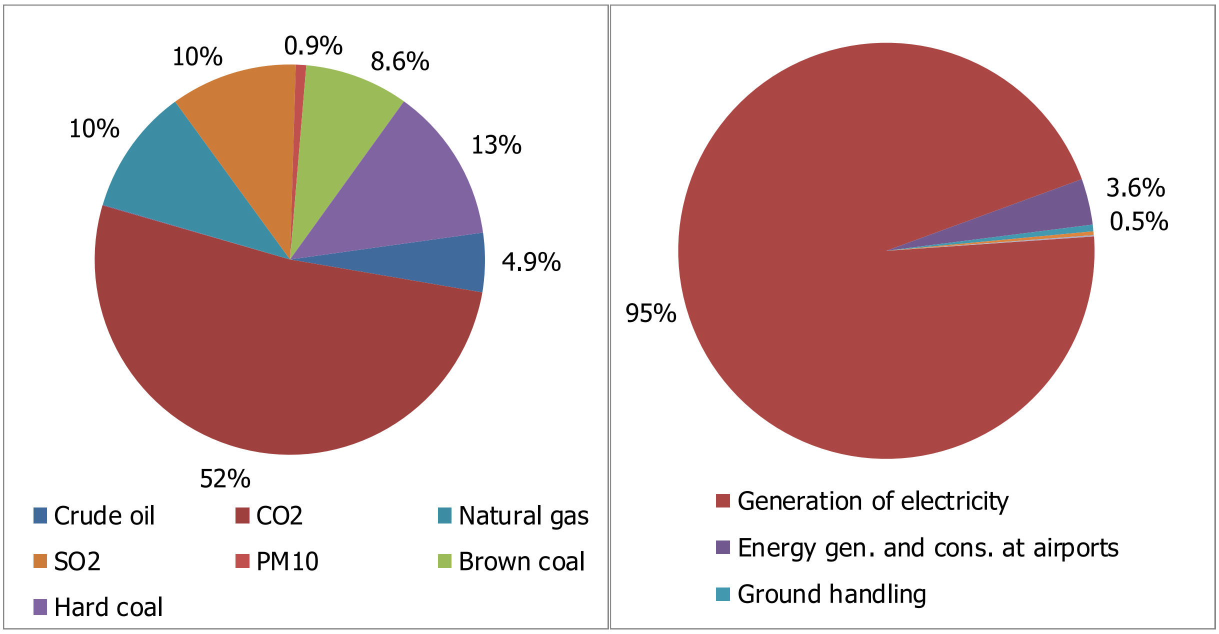

Figure 7: Contribution of the in- and outputs (left) and the considered processes (right) to the SS of the electric powered aircraft (current electricity mix)

3.7 Evaluating the Environmental Impact of the Alternative Fuel Powered Aircraft

Figure 8 shows the contribution of the in- and outputs (left side) and the considered processes (right side) to the Single Score of the alternative fuel powered aircraft. It can be seen that for such a design CO2 has the highest influence on EI (37 %). It is followed by several other in- and outputs (e.g.: Hard coal: 14 %, Natural gas: 11 %, SO2: 11 %, Brown coal: 9 %, …) also having a certain impact. Concerning the processes, it can be seen that the production of the alternative fuel dominates EI with a share of 79 %, followed by cruise flight with a share of 19 %. The Single Score is 0.0594 points/pkm which is 243 % more than that of the reference aircraft. **If the electric energy needed for the production of the alternative fuel is generated by renewable energy sources**, the Single Score is drastically reduced to -0.0005 points/pkm which means that there is even a slightly positive EI. This is due to the fact that the production of the alternative fuel requires a big amount of CO2 which is bound by the algae. In the considered production method, 4.15 kg dry matter is required for the production of 1 kg fuel. Each kg dry matter fixes 1.8 kg CO2 [16]. This means that the algae bind 7.47 kg CO2 per kg fuel while the burning of this amount of fuel only leads to the emission of 3.15 kg CO2. This positive environmental effect over-compensates all other negative effects so that the resulting EI is slightly positive. This positive effect is achieved because some organic matter from the algae production is left over as waste and acts as carbon capture and storage depot. The depot is growing in size as more alternative fuel is produced.

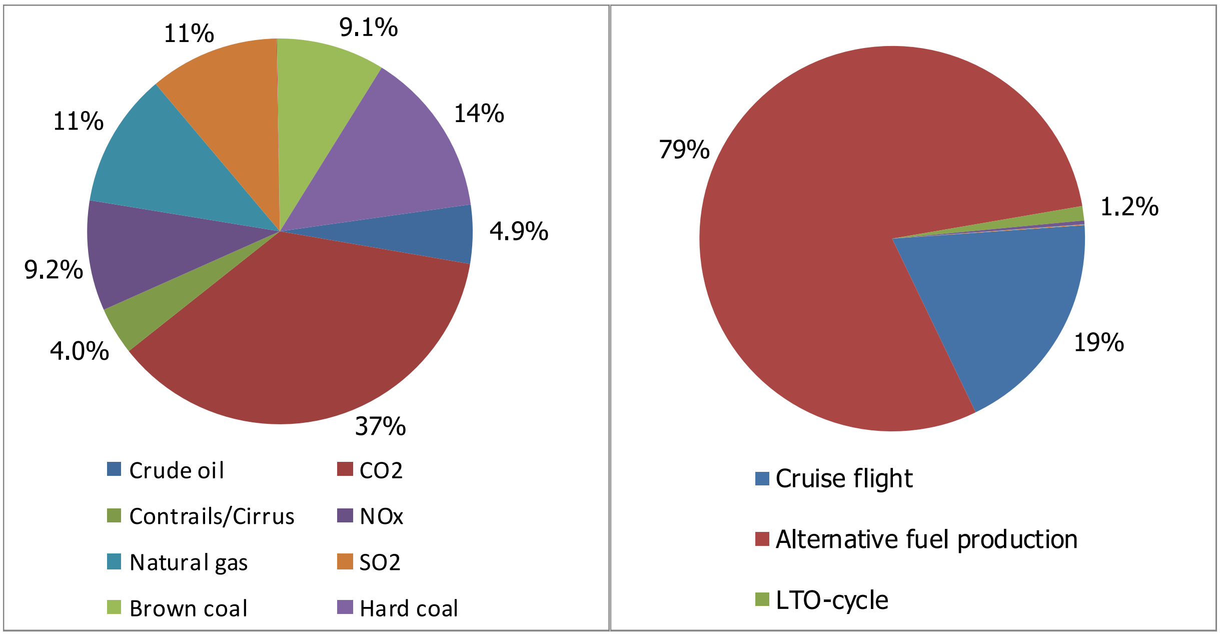

Figure 8: Contribution of the in- and outputs (left) and the considered processes (right) to the SS of the alternative fuel powered aircraft (current electricity mix)

3.8 Comparison of the Total Environmental Impact of the Investigated Concepts

Figure 9 compares the Single Score (i.e. the total EI) of all investigated aircraft concepts. The figure distinguishes between the use of the current electricity mix (left side) and renewable energy sources (right side). The value of the reference aircraft using the current electricity mix is normalized to 100 %. It can be seen that the use of renewable energy sources has almost no effect on the EI of the reference aircraft while it drastically reduces the EI of the electric and alternative fuel powered aircraft. By designing an aircraft for lower cruise altitudes, the hydrogen powered aircraft with renewable energy sources would also be able to reach very low EI. As already mentioned, the electric aircraft is not directly comparable because of its reduced range.

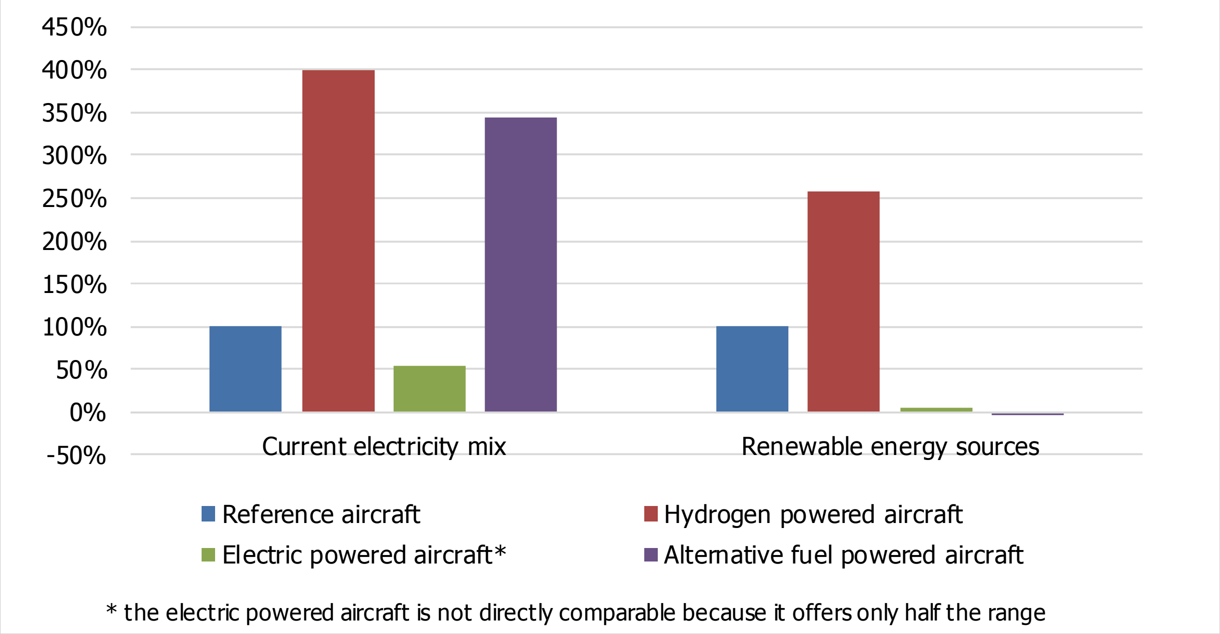

Figure 9: Comparison of the Single Score of the investigated aircraft using the current electricity mix (left) and renewable energy sources (right)

4 DISCUSSION

The production of the considered alternative fuel requires a lot of electric energy so that this becomes the dominating process. The in- and outputs dominating EI due to the generation of electricity are therefore also the dominating in- and outputs of an alternative fuel powered aircraft. The use of the considered alternative fuel only makes sense if electricity from renewable sources would be used for the production of the alternative fuel. The use of synthetic fuel produced with regenerative energy (as mentioned in Section 2) might lead to similar results concerning EI even though this cannot be said for certain as synthetic fuels were not the focus of this research.

For an electric powered aircraft, the generation of electricity is the dominating process while cruise flight or LTO cycle have no more influence. Therefore the dominating in- and outputs again are those from the generation of electricity. Obviously electricity from renewable sources would again allow to drastically reduce EI.

The cruise flight of a hydrogen powered aircraft has such a high contribution to EI because of the increased water emissions during the flight leading to stronger contrail and cirrus cloud formation. Additionally, the production of hydrogen requires a lot of energy and therefore also has a certain contribution to EI. By designing hydrogen aircraft for cruise altitudes below 23000 ft, contrail and cirrus cloud formation can be drastically reduced. The use of electricity from renewable energy could reduce the EI due to the production of hydrogen even further.

In general, it becomes clear that the considered future concepts tend to shift environmental problems from the flight to the production of the respective energy source. Within this production, electricity always plays a dominating role. Therefore only if environmentally friendly generated electricity is used within the production of the energy sources, the future concepts can actually reduce EI.

A very general consideration already explains the observed effect: If fossil fuels are extracted from the ground and are converted with limited efficiency into hydrogen stored in a tank or electricity stored in battery on board, then the overall EI must be higher due to the conversion losses compared to the quite efficient way of propelling an aircraft with fossil fuel stored directly on board, as we know it today.

At the end of 2013, the estimated renewable energy share of the global electricity production was about 22 % [18]. By 2040, this share could rise up to 33 % [19]. Nevertheless this means that in a realistic scenario, even in 2040, only one third of the electricity needed for the production of the energy sources would come from renewable sources. Of course one could use only electricity from renewable sources for the production of the energy sources required for aviation. But this would only shift environmental problems to other industries because this part of the environmentally friendly generated electricity would not be available for other processes that would have to be powered by conventionally produced electricity.

5 CONCLUSION

Considering the European electricity mix, the selected alternative fuel made of microalgae surprisingly lead to a drastic increase of the EI of aircraft. This is because of the high energy demand during the production of the alternative fuel. Such aircraft can therefore only substantially reduce EI if the energy demand from the production is covered by renewable energy sources also having low EI. In that case, the designed alternative fuel powered aircraft provided the best result concerning EI among the investigated aircraft. Hydrogen powered aircraft also have the issue of high energy demand due to the production of hydrogen as well as water vapor emissions during cruise causing contrails and contrail-induced cirrus clouds both having negative EI. Using the European electricity mix, EI is also substantially increased compared to the reference aircraft. But, by adapting the flight altitude to counteract the effect of contrail formation and by using renewable energy sources for the production of hydrogen, EI could be much lower than that of the reference aircraft. Electric powered aircraft are only feasible on reduced ranges even considering futuristic battery technology. Therefore a fair comparison with the other designs is not possible. At their reduced range, electric aircraft allow to reduce EI especially if their energy needs are covered by renewable energy sources.

Summarized, the top priority for the future concepts is to cover their energy demand by renewable energy sources. This would allow to substantially reducing the EI of all considered concepts.

From an environmental point of view, the selection of a particular concept does change little. As long as the share of renewable energy stays low (which will presumably be the case for the next decades), even the discussed innovative aircraft concepts will not be able to drastically reduce the EI of aviation. But fossil fuels will come to an end eventually, leaving renewable energy as the only means.

From an economic point of view, the question will then simply be, how renewable energy applied in aviation – in whatever form – could be used at overall lowest costs. A low cost solution will require low depreciation due to low investment. Operating existing aircraft types with existing infrastructure limits investment and has the potential of low costs. Only with alternative fuel (biofuel or synthetic fuel) existing aircraft can be used the way they are. In contrast, hydrogen or electric powered aircraft would need to be of new design and would require additional infrastructure on the ground.

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