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Comparison of conventional and electric passenger aircraft for short-haul flights – A life cycle sustainability assessment

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Abstract

Due to the increasing demand for flights, the aviation sector will become one of the main emitters of harmful emissions such as carbon dioxide (CO_2) and nitrogen oxides (NO_x) in the long term. Especially short-haul flights are particularly critical because of the high kerosene consumption per passenger kilometer traveled. To counteract this development, the Flightpath 2050 strategy aims to reduce CO_2 emissions by 75% and NO_x emissions by 90% until 2050. To achieve these ambitious reduction goals, radical technological transitions are required. A promising strategy for short-haul flights is the deployment of battery-electric powertrains, which replace conventional jet engines. In addition, sustainable aviation fuels (SAFs) can replace fossil kerosene as energy carriers without changing the powertrain configuration and offer further reduction potentials. However, both solutions can be associated with negative environmental and socio-economic impacts along the life cycle. Therefore, this article aims to analyze the potentials of powertrain transition and alternative energy carriers to make the air transport system more sustainable. A well-to-wake life cycle sustainability assessment is conducted to analyze the environmental and socio-economic impacts of an electric powertrain and SAFs compared to a conventional powertrain powered by fossil kerosene. The assessment results indicate that especially the electric powertrain offers huge reduction potentials. Besides, the results also show that SAFs can reduce the environmental impacts of conventional aircraft in the short term. Therefore, both solutions will be required to achieve the short- and long-term reduction goals of Flightpath 2050.

Keywords: Life Cycle Sustainability Assessment; Well-to-wake assessment; Electric aircraft; Sustainable aviation fuel;

1. Introduction

Due to the increasing demand for flights, the aviation sector is a continually growing industry [1]. While this growth is desirable from an economic perspective, it leads to new environmental challenges for the air transport system (ATS). The combustion of fossil kerosene causes large quantities of harmful emissions to the atmosphere, such as carbon dioxide (CO_2) and nitrogen oxides (NO_x), which cause damage to climate and health. In 2019, the aviation sector was responsible for 2.6% of the global CO_2 emissions [2]. This is particularly critical because emissions at higher altitudes have a more severe environmental impact than ground-level emissions [3]. Current studies predict that the volume of global air traffic increases by 3.6% annually, which would lead to a doubling of air traffic every 16 years. Considering an increase in fuel efficiency of approximately 25% per new aircraft generation, this would lead to a tripling of aviation-induced emissions by 2050, making the ATS one of the leading emitters of CO_2 and NO_x in the long term [4].

To counteract this increase, the aviation sector has set itself ambitious emission reduction goals defined in the Flightpath 2050 strategy [5]. The strategy envisages the reduction of emissions from aircraft by 75% for CO_2, 90% for NO_x, and 65% for noise by 2050 relative to a new aircraft from the base

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year 2000. In this context, various programs have been adopted in recent years to support the achievement of these reduction goals [6]. However, these programs are predominantly aimed at offsetting the emissions, which is not sufficient in the long term. Further progress towards clean and sustainable aviation requires more radical technological innovations [7].

A promising solution for short-haul flights in the future are electric aircraft associated with low to no emissions in the use phase [4]. Today, already feasible alternatives are drop-in capable fuels based on renewable sources, also known as sustainable aviation fuels (SAFs) [8]. Kerosene based on biomass or hydrogen can significantly reduce harmful emissions due to benefits during their production. However, both solutions can cause negative environmental and socio-economic impacts along with their life cycles [9]. These are barely addressed in the scientific literature, and studies comparing conventional and electric aircraft for short-haul flights considering different fuel options are scarce [8].

Thus, this article aims to analyze and compare electric aircraft and conventional aircraft powered by fossil kerosene and SAFs to determine the potential of being a promising solution for short-haul flights and thus contribute to the sustainable development of the ATS. Using a holistic life cycle sustainability assessment (LCSA), the environmental and socio-economic impacts are captured in a well-to-wake approach. Well-to-wake includes the energy carrier supply chain, the powertrain supply chain, and the flight operation as use phase. By analyzing a total of nine energy carriers, as shown in Table 2, recommendations for action are derived for both the long-term and short-term development of the aviation sector.

The remainder of this article is structured as follows. The system definition of the powertrain configurations, the energy carriers as well as a description of the assessment method are specified in Section 2. The results of the sustainability assessment and the main findings are presented in Section 3. In Section 4, the paper concludes with a discussion of the main findings and an outlook on future research.

2. Method and materials

2.1. Assessment method and fundamentals of the study

The assessment is fundamentally based on the Life Cycle Sustainability Assessment method, and its procedure is derived from the ISO 14040/14044 standards. Explanations of the basic LCSA approach can be found in the pertinent literature (e.g. [10]–[12]). Since the electric powertrain is a technology that is still under development, the approach is applied based on the idea of a prospective LCA [13], transferred to a prospective LCSA.

This study analyzes and compares the use of conventional aircraft and electric aircraft powertrains for short-haul flights. For this purpose, two types of supply chains are considered. On the one hand, the supply chain of the powertrain is investigated, from raw material extraction through production to use. In the use phase, this overlaps with the supply chain of the energy carrier required to operate the powertrain. It consists of energy carrier production, distribution, storage, and use. The supply chains and the required materials are modeled in the foreground system. They are linked to the ecoinvent 3.7.1 database and the Social Hotspots Database (SHDB) in the background system [14], [15]. An overview of the considered systems and the corresponding boundaries is given in Figure 1.

The configuration of the powertrains and their energy carrier consumption in the use phase are designed for a typical mission profile of a short-haul flight. A detailed description of the powertrain configurations, the considered energy carriers, and the mission profile of the flight operation are described in subsections 2.2-2.4.

The functional unit for the analysis is 100 passenger kilometers traveled (pkm) on a 1.000 km short-haul flight with a load of 100 passengers, including luggage.

The conducted impact assessment is based on three types of Life Cycle Impact Assessment (LCIA) methods, one for each of the three sustainability dimensions. The environmental impact assessment is based on three impact categories, according to the ReCiPe Midpoint v1.13 method [16]. Here, the impact category climate change (CC) is chosen due to the high amount of climate-damaging CO_2 resulting from the

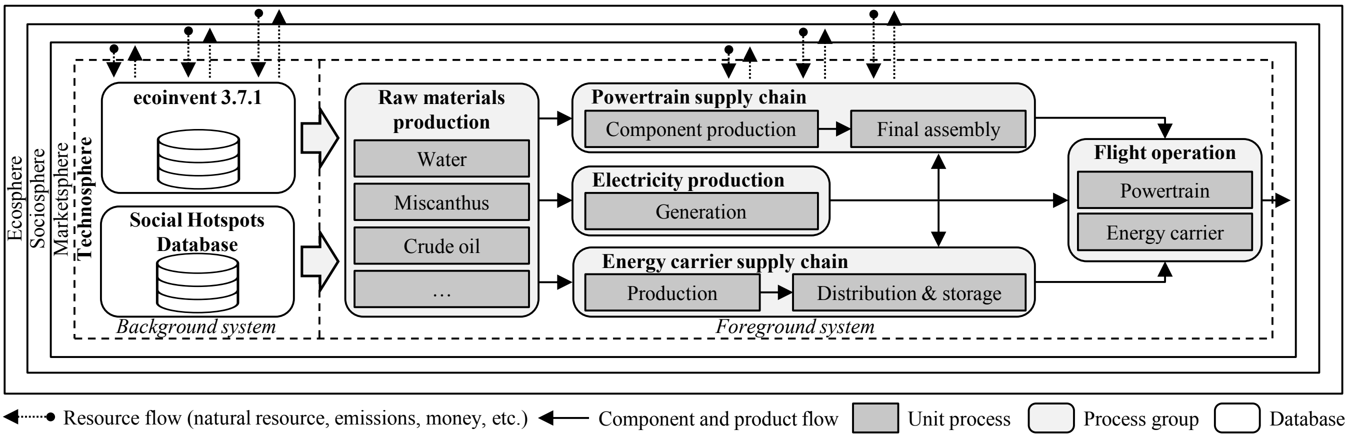

Figure 1. Foreground and background system with corresponding boundaries including component, product, and resource flows

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combustion of fuel, fossil resource depletion (FRD) is chosen due to the fossil sources required for electricity generation and the fossil character of conventional kerosene, and agricultural land occupation (ALO) is chosen due to the required agricultural land for cultivating the bio-feedstock. The economic assessment is based on the life cycle costs (LC) associated with the energy carrier supply chain, the powertrain supply chain, and the flight operation [17]. The social impact assessment is based on the impact assessment method of the SHDB [15]. The impact categories risk of corruption (RoC) and risk of poverty (RoP) are chosen due to socially critical conditions in the country of origin of raw materials required for the energy carriers and the powertrains. Table 1 provides an overview of the considered impact categories within this study.

Table 1. Environmental and socio-economic impact categories

Dimension	Impact category	Unit
Environmental	Climate change (CC)	kg CO_2-eq.
	Fossil resource depletion (FRD)	kg Oil-eq.
	Agricultural land occupation (ALO)	m^2 per year
Economic	Life cycle costs (LC)	US-Dollar
Social	Risk of corruption (RoC)	Medium risk hour eq.
	Risk of poverty (RoP)	Medium Risk hour eq.

The calculation model for the inventory analysis and impact assessment is implemented in python using the Brightway2 framework [18].

2.2. Conventional and electric powertrain

The conventional powertrain analyzed in this study is based on an Airbus A318-100. This powertrain is chosen because the A318-100 has a capacity of around 100 passengers and is a typical short-haul aircraft [19]. The basic composition consists of two jet engines, fuel tanks in the body and the wings, the pipes, and the power electronics for engine control. The powertrain production is based on the Airbus production network with component manufacturing in England, Germany, Czech Republic, Spain, and final assembly in France [20].

The configuration of the battery-electric powertrain is derived from a reference aircraft defined within the cluster of excellence "SE²A – Sustainable and Energy-Efficient Aviation" [21]. The short-haul aircraft can transport up to 100 passengers over a distance of 1,000 kilometers. The powertrain comprises two propellers driven by electric motors, a battery system for energy storage, power electronics, and a cooling system. Due to technical restrictions regarding the maximum take-off and landing weight, high specific energy of the battery is crucial, and therefore, a lithium-sulfur-all-solid-state battery is selected for this study. The production of the components takes place in Germany, Japan, and France [22].

For each of the raw materials, the country with the highest share of global production according to the U.S. Geological Survey [23] is assumed as the origin. The corresponding transport routes are taken into account.

2.3. Kerosene, sustainable aviation fuel, and electricity

Each powertrain requires specific energy carriers for flight operation. For this purpose, fossil kerosene is currently used in conventional powertrains. Its supply chain begins with the extraction of crude oil, which is processed into kerosene by blending in various additives [24]. It is assumed that the crude oil is extracted in Russia and processed in Germany.

In addition to fossil kerosene, three promising SAFs are considered in this study. These fuels are produced via X-to-liquid pathways, more precisely via biomass-to-liquid (BtL) and power-to-liquid (PtL) [25]. The starting point of the processes is the production of hydrogen, which is further processed into kerosene using the Fisher-Tropsch synthesis (FTS). In the FTS, the SAF is produced through different pressures and using CO_2, which is captured from the atmosphere or as a waste product from other industries [26].

Concerning BtL, the focus is on 2nd generation biokerosene [27]. The feedstock for biokerosene is miscanthus, which is cultivated in Germany and processed into biogas. The biogas is refined to biomethane by adding various additives and then processed to hydrogen via steam methane reforming (SMR). In the subsequent production step, the biokerosene is produced using the FTS [28]. The production takes place in Germany.

Concerning PtL, two production pathways are investigated [29]. The first pathway includes the SMR process but uses natural gas and water instead of biomethane for hydrogen production [30]. In the other production pathway, hydrogen is produced via electrolysis. For this purpose, polymer electrolyte membrane electrolysis (PEM) is used to produce hydrogen in an energy-intensive production step from water (55 kWh electricity input per 1 kg of hydrogen) [31] which is further processed to synthetic kerosene via FTS. The whole synthetic kerosene production takes place in Germany.

For each SAF, two scenarios are assumed for the production: 1.) Using the current German electricity mix, and 2.) using an electricity mix generated 100% from renewable energy sources (RE) as expected for the German mix in 2050 [32]. These two electricity mixes are also considered as energy carriers for the electric powertrain.

Overall, nine different energy carriers are analyzed with the fossil kerosene used as benchmark for the subsequent study:

Table 2. Considered energy carriers

Abbreviation	Description
Ker (fossil)	Fossil kerosene
Ker (bio)	Biokerosene produced by SMR
Ker (bio-RE)	Biokerosene produced by SMR using RE
Ker (SMR)	Synthetic kerosene produced by SMR
Ker (SMR-RE)	Synthetic kerosene produced by SMR using RE
Ker (PEM)	Synthetic kerosene produced by PEM
Ker (PEM-RE)	Synthetic kerosene produced by PEM using RE
Elec	Current German electricity mix
Elec-RE	Forecasted German electricity mix for 2050

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2.4. Mission profile and flight operation

For the analysis, a reference flight over a distance of 1,000 km with a load of 100 passengers is considered. This corresponds to a flight from Frankfurt, Germany to Barcelone, Spain, which is potentially feasible with an electric aircraft [21]. The flight lasts 135 minutes, with a take-off/ climb time of 35 minutes and a cruise/ landing time of 100 minutes.

According to the Lufthansa Group, such a flight consumes 7.1 liters of kerosene (specific energy of 68 kWh) per 100 pkm [33], representing the energy carrier consumption within this study. The combustion behavior of the fuels and the resulting emissions are derived from the scientific literature [34].

The energy consumption of a comparable electric flight is estimated at 17 kWh per 100 pkm. The energy requirement of electric aircraft is about 25% of the energy consumption of conventional aircraft due to better efficiency. This efficiency difference is similar in the automotive industry [35].

Next to the impacts related to energy carrier consumption, further impacts resulting from the powertrain production must be considered on a pro-rata basis. These are calculated based on the duration of flight operation relative to the total service life of the powertrain.

3. Results and discussion

3.1. Impact assessment results

An overview of the impact assessment results is given in Table 3. For the investigated setting, the results show that the electric powertrain offers significant environmental and socio-economic improvements compared to the conventional powertrain powered by fossil kerosene concerning the functional unit of 100 pkm traveled.

Using the current German electricity mix, environmental impacts can be reduced by 63% to 71%. Only for ALO, deteriorations of 59% occur, which is due to the current composition of the electricity mix. If the electricity is generated from 100% RE, even higher improvements can be achieved. Compared to the benchmark of conventional powertrain powered by fossil kerosene, reductions of 91% (CC) and 92% (FDP) can be reached, and also the impact of ALO can be reduced by 48%. Overall, there is only one environmental impact category where a higher reduction can be achieved by using SAF. Concerning CC, the use of Ker (PEM-RE) can reduce the environmental impact by 95%, which is due to the high savings during production based on the use of electricity, generated 100% on RE.

With regard to the socio-economic impacts, similar results occur. Here, reductions of 6% to 91% can be achieved by the electric powertrain compared to the benchmark. However, there is no difference between whether the current electricity mix or an electricity mix based on 100% RE is used for flight operation. This is due to the assumption that the electricity is generated in Germany and the electricity price is identical in both cases. In addition, there is no SAF which is more beneficial compared to the electric powertrain concerning a socio-economic impact category.

The assessment results also show that some SAFs are associated with high negative environmental and socio-economic impacts. While the use of biokerosene (Ker (bio) and Ker (bio-RE)) is consistently beneficial in terms of social impacts, the LC are 160% higher compared to Ker (fossil). In terms of environmental impacts, the biokerosene variants offer 30% to 73% reduction potentials concerning CC and FRD. Still, they are associated with sixteen times higher impacts regarding ALO due to the land use for the feedstock.

The results for the synthetic fuels show that based on the current electricity mix, only the use of Ker (SMR) results in improvements concerning the social impact categories and CC. This is due to the high energy requirement of Ker (PEM) and, which is responsible for high negative environmental and economic impacts. Using an electricity mix based 100% on RE can reduce the environmental impacts overall, while the socio-economic impacts remain the same. Here, the Ker (PEM-RE) offers reduction potentials of 95% concerning CC and 24% regarding FRD. Ker (SMR-RE) results in almost identical environmental impacts because only a small amount of electricity is required for the process. From an economic perspective, the LC are in any case higher than for fossil kerosene (121% to 641%).

3.2. Analysis of environmental and socio-economic impacts

Figure 2 provides more detailed insights into the environmental and socio-economic impacts by breaking down the impact scores into the energy carrier supply chain, including electricity generation, the powertrain supply chain, and the final use stage.

For the conventional powertrain using fuels, the results show that the energy carrier supply chain is mainly responsible for the impacts for five of the six impact categories analyzed. Especially regarding the environmental impacts FRD and ALO of the SAFs, 90% to 99% of the total impacts can be attributed to this stage. In the case of biokerosene, the cultivation of the feedstock and kerosene production using SMR are primarily responsible. Concerning synthetic fuels generated via PEM, the

Table 3. Environmental and socio-economic assessment results of the eleven use cases for the functional unit of 100 pkm traveled

Dim.	Impact category	Unit	Per 100 passenger kilometers traveled								
			Ker (fossil)	Ker (bio)	Ker (bio-RE)	Ker (PEM)	Ker (PEM-RE)	Ker (SMR)	Ker (SMR-RE)	Elec	Elec-RE
Env.	CC	kg CO_2-eq.	29.91	20.83	17.36	105.77	1.35	25.92	24.69	11.10	2.44
	FRD	kg Oil-eq.	10.57	3.74	2.82	35.88	8.06	17.97	17.64	3.07	0.76
	ALO	m^2 per year	0.30	5.18	5.05	5.12	1.27	0.53	0.49	0.47	0.15
Econ.	LC	US-Dollar	5.91	15.37	15.37	43.82	43.82	13.08	13.08	5.56	5.56
Social	RoC	Medium risk hour eq.	13.57	2.49	2.49	8.69	8.69	1.86	1.86	1.28	1.28
	RoP	Medium Risk hour eq.	1.36	0.57	0.57	1.84	1.84	0.44	0.44	0.28	0.28

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impacts are due to energy-intensive hydrogen production, while for SMR, the upstream chain of natural gas is responsible. Concerning fossil kerosene, the energy carrier supply chain is responsible for 52% (ALO) and 92% (FRD). This is due to crude oil extraction and petroleum production.

Similar results occur regarding the socio-economic impacts, where 70% to 97% of the total impacts are attributable to the energy carrier supply chain. Concerning LC, the energy-intensive production processes, such as hydrogen production, FTS, and kerosene production, are the main drivers of the impacts. In the case of social impacts, this also applies, but it should be noted that the social impacts are generally low, which is because mainly Germany is used as a production site, where the risk of socially disadvantageous situations is not very pronounced. The exception is the RoC in the case of fossil kerosene, which is generally due to crude oil extraction and transport through several countries.

Concerning CC, however, the impact for every fuel is chiefly due to the use stage, where around 3.15 kg of CO_2 is emitted during the combustion process. Ker (PEM) is an exception. Here, the high energy requirement during PEM is the main driver. The results also indicate that SAFs generated by RE are associated with CC impacts smaller than zero in their supply chain. This is because more CO_2 is captured than released during production. The exception here is Ker (SMR-RE) since hydrogen production is based on fossil sources.

Concerning the electric powertrain, the results indicate that the current electricity mix is mainly responsible for the environmental impacts. This is due to the high proportion of fossil energy sources used in current electricity generation. If the electricity mix is generated via RE, the environmental impacts can be reduced significantly, but the electricity mix is again primarily responsible. This is due to the construction of the renewable energy plants, which are considered in the life cycle inventory datasets.

Similar findings can be made concerning socio-economic impacts. The generation of electricity is mainly responsible for the impacts of LC, RoC, and RoP. Overall, the socio-economic impacts do not differ when RE is used to generate electricity. In both cases, the generation is carried out entirely in Germany under the same conditions.

3.3. Discussion

Overall, the results show that electrically powered aircraft is a promising long-term solution to reduce the environmental impacts of the ATS significantly. In addition, their use appears to be economically competitive with conventional aircraft powered by fossil kerosene. The results also show that SAFs, which are already feasible today, are a good alternative for reducing specific environmental impacts in the short term but are associated with higher costs.

However, there are some uncertainties within this study, especially concerning the electric powertrain. Thus, a hypothetical electric powertrain was configured. Since there are no practically tested electric passenger aircraft yet, the configuration cannot be validated. In addition, novel technologies usually cause far-reaching structural adjustments to the aircraft, not investigated here. For example, lighter materials such as fiber composites are needed to compensate for the dead weight of the battery, but these are associated with new negative environmental and socio-economic impacts. This could significantly downgrade the performance of the electric powertrain investigated in this study. To avoid a potential burden shifting, the study's scope must be expanded to consider the other aircraft components and assess the whole aircraft.

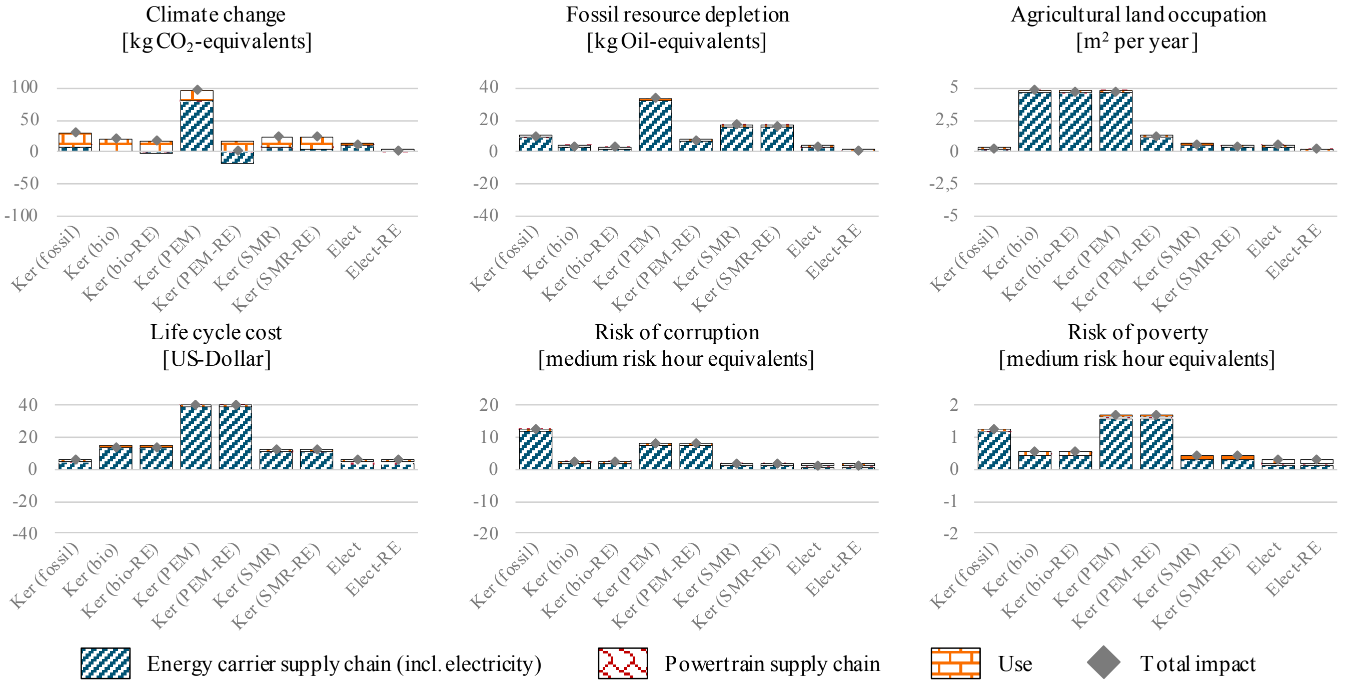

Figure 2. Environmental and socio-economic impacts divided between energy carrier supply chain, powertrain supply chain, and use

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In addition, only 2nd generation biokerosene and hydrogen-based synthetic fuels were investigated in this study. Research on 3rd generation biofuels and alcohol-based synthetic fuels is already available today and can be integrated into the study.

A significant uncertainty results from the spatial consideration of only one country. Especially regarding environmental and social impacts, Germany has advantages in terms of SAFs, electricity, and the electric powertrain due to its high share of RE in the electricity mix and less critical working conditions. If countries with higher shares of fossil sources in the electricity mix and more critical working conditions were chosen as production locations, the advantages of SAFs and electric powertrains could probably not be proven. In any case, more research needs to be done on spatial differences.

4. Conclusion and outlook

The sustainability assessment conducted in this article aims to identify the potential of an electric powertrain and SAFs for short-haul aircraft. The well-to-wake analysis shows that electric aircraft could lead to significant reductions in environmental and socio-economic impacts. If the electricity needed to charge the electric aircraft originates from renewable sources, the reduction potentials are higher. At the same time, it is shown that synthetic fuels have advantages over fossil kerosene in terms of particular impact categories. Especially when it comes to reducing CO_2 emissions, these fuels can be advantageous. However, this only applies if synthetic fuels are produced using renewable energy. Biofuels, on the other hand, offer reduction potential in various environmental and socio-economic impact categories. Still, the question remains to what extent these can be implemented globally due to the partial conflict with food production. Possibly, 3rd generation biofuels can provide a remedy here.

Therefore, both solutions will be required to achieve the short- and long-term reduction goals of Flightpath 2050.

In the context of future research, four topics should gain particular attention to further improve the analysis: 1.) Expanding the study to include full aircraft, 2.) considering other fuel alternatives (e.g., 3rd generation biofuels and alcohol-based synthetic fuels), 3.) analyzing spatially diverse supply chain configurations, and 4.) providing comparisons to other modes of transportation (e.g., train or bus) on short-haul distances.

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References

[1] D. Scott and S. Gössling, "What could the next 40 years hold for global tourism?," *Tour. Recreat. Res.*, vol. 40, no. 3, pp. 269–285, 2015, doi: 10.1080/02508281.2015.1075739.

[2] M. d. Staples, R. Malina, P. Suresh, J. I. Hileman, and S. R. H. Barrett, "Aviation CO 2 emissions reductions from the use of alternative jet fuels," *Energy Policy*, vol. 114, pp. 342–354, 2018, doi: 10.1016/j.enpol.2017.12.007.

[3] D. S. Lee *et al.*, "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," *Atmos. Environ.*, vol. 244, p. 117834, Jan. 2021, doi: 10.1016/J.ATMOSENV.2020.117834.

[4] A. R. Gnadt, R. L. Speth, J. S. Sabnis, and S. R. H. Barrett, "Technical and environmental assessment of all-electric 180-passenger commercial aircraft," *Prog. Aerosp. Sci.*, vol. 105, pp. 1–30, 2019, doi: 10.1016/j.paerosci.2018.11.002.

[5] European Commission, "Flightpath 2050: Europe's vision for aviation," Publication Office of the European Union, Luxembourg, 2011. doi: 10.2777/50266.

[6] J. Scheelhaase, S. Maertens, W. Grimme, and M. Jung, "EU ETS versus CORSIA -- A critical assessment of two approaches to limit air transport's CO 2 emissions by market-based measures," *J. Air Transp. Manag.*, vol. 67, pp. 55–62, 2018, doi: 10.1016/j.jairtraman.2017.11.007.

[7] A. W. Schäfer *et al.*, "Technological, economic and environmental prospects of all-electric aircraft," *Nat. Energy*, vol. 4, no. 2, pp. 160–166, 2019, doi: 10.1038/s41560-018-0294-x.

[8] S. P. Melo *et al.*, "Sustainability Assessment and Engineering of Emerging Aircraft Technologies - Challenges, Methods and Tools," *Sustainability*, vol. 12, no. 14, p. 5663, 2020, doi: 10.3390/su12145663.

[9] A. Barke *et al.*, "Life cycle sustainability assessment of potential battery systems for electric aircraft," in *Procedia CIRP*, 2021, vol. 98, pp. 660–665, doi: 10.1016/j.procir.2021.01.171.

[10] A. Barke, C. Thies, S. P. Melo, F. Cerdas, C. Herrmann, and T. S. Spengler, "Socio-economic life cycle assessment of future aircraft systems," in *Procedia CIRP*, 2020, vol. 90, pp. 262–267, doi: 10.1016/j.procir.2020.01.096.

[11] UNEP/SETAC, "Towards a Life Cycle Sustainability Assessment: Making informed choices on products," 2011.

[12] W. Klöpffer, "Life cycle sustainability assessment of products," *Int. J. Life Cycle Assess.*, vol. 13, no. 2, pp. 89–95, 2008, doi: 10.1065/lca2008.02.376.

[13] J. A. Bergerson *et al.*, "Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity," *J. Ind. Ecol.*, vol. 24, no. 1, pp. 11–25, Feb. 2020, doi: 10.1111/jiec.12954.

[14] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology," *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, Apr. 2016, doi: 10.1007/S11367-016-1087-8.

[15] C. Norris and G. A. Norris, "Chapter 8: The Social Hotspots Database Context of the SHDB," in *The Sustainability Practitioner's Guide to Social Analysis and Assessment*, J. Murray, D. McBain, and T. Wiedmann, Eds. Champaign, IL, USA: Common Ground Publishing LLC, 2015, pp. 52–73.

[16] M. Goedkoop, R. Heijungs, M. Huijbregts, Schryver, J. Struijs, and R. van Zelm, "ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level," Den Haag, 2013.

[17] V. Moreau and B. P. Weidema, "The computational structure of environmental life cycle costing," *Int. J. Life Cycle Assess.*, vol. 20, no. 10, pp. 1359–1363, 2015, doi: 10.1007/s11367-015-0952-1.

[18] C. Mutel, "Brightway: An open source framework for Life Cycle Assessment," *J. Open Source Softw.*, vol. 2, no. 12, p. 236, 2017, doi: 10.21105/joss.00236.

[19] Airbus S.A.S., "Family Figures," no. May. p. 17, 2021.

[20] S. Buxbaum-Conradi, "Global and local knowledge dynamics in an industry during modular transition - A case study of the Airbus production network and the Aerospace Cluster in Hamburg, Northern Germany," University of Hamburg, 2018.

[21] Y. Liu, A. Elham, P. Horst, and M. Hepperle, "Exploring Vehicle Level Benefits of Revolutionary Technology Progress via Aircraft Design and Optimization," *Energies*, vol. 11, no. 1, p. 166, 2018, doi: 10.3390/en11010166.

[22] A. Nordelöf, "A scalable life cycle inventory of an automotive power electronic inverter unit---part II: manufacturing processes," *Int. J. Life Cycle Assess.*, vol. 24, no. 4, pp. 694–711, 2019, doi: 10.1007/s11367-018-1491-3.

[23] U.S. Geological Survey, "Mineral commodity summaries 2019," Reston, Virgina, USA, 2019. doi: 10.3133/70202434.

[24] C. Koroneos, A. Dompros, G. Roumbas, and N. Moussiopoulos, "Life Cycle Assessment of Kerosene Used in Aviation (8 pp)," *Int. J. Life Cycle Assess.*, vol. 10, no. 6, pp. 417–424, 2005.

[25] Y. Bicer and I. Dincer, "Life cycle evaluation of hydrogen and other potential fuels for aircrafts," *Int. J. Prod. Res.*, vol. 42, no. 16, pp. 10722–10738, 2017.

[26] S. Farokhi, *Future propulsion systems and energy sources in sustainable aviation*, 1st ed. Hoboken, NJ: Wiley & Sons, 2020.

[27] A. P. Bessette, A. Teymouri, M. J. Martin, B. J. Stuart, E. P. Resurreccion, and S. Kumar, "Life Cycle Impacts and Techno-economic Implications of Flash Hydrolysis in Algae Processing," *ACS Sustain. Chem. Eng.*, vol. 6, no. 3, pp. 3580–3588, Mar. 2018, doi: 10.1021/ACSSUSCHEMENG.7B03912.

[28] S. S. Doliente, A. Narayan, J. F. D. Tapia, N. J. Samsatli, Y. Zhao, and S. Samsatli, "Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components," *Front. Energy Res.*, vol. 0, p. 110, Jul. 2020, doi: 10.3389/FENRG.2020.00110.

[29] C. Van Der Giesen, R. Kleijn, and G. J. Kramer, "Energy and climate impacts of producing synthetic hydrocarbon fuels from CO2," *Environ. Sci. Technol.*, vol. 48, no. 12, pp. 7111–7121, Jun. 2014, doi: 10.1021/ES500191G.

[30] M. Rutkowski, M. Penev, G. Saur, and D. Steward, "Current Central Hydrogen from Natural Gas with CO2 Capture and Sequestration: NREL." 2018, [Online]. Available: https://www.nrel.gov/hydrogen/assets/docs/current-central-natural-gas-with-co2-sequestration-v3-2018.20210104.xlsm.

[31] D. DeSantis, B. James, and G. Saur, "Hydrogen Production from Central PEM Electrolysis: NREL." 2019, [Online]. Available: https://www.nrel.gov/hydrogen/assets/docs/current-central-pem-electrolysis-2019-v3-2018.xlsm.

[32] M. Z. Jacobson *et al.*, "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," *Joule*, vol. 1, no. 1, pp. 108–121, Sep. 2017, doi: 10.1016/J.JOULE.2017.07.005.

[33] Lufthansa Group, "LH-Factsheet-Sustainability-2020." pp. 1–22, 2020, [Online]. Available: https://www.lufthansagroup.com/media/downloads/en/responsibility/LH-Factsheet-Sustainability-2020.pdf.

[34] M. Braun-Unkhoff, U. Riedel, and C. Wahl, "About the emissions of alternative jet fuels," *CEAS Aeronaut. J.*, vol. 8, no. 1, pp. 167–180, Mar. 2017, doi: 10.1007/s13272-016-0230-3.

[35] D. Bothe and T. Steinfort, "Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector A Meta-Analysis of LCA Studies on Alternative Powertrain Technologies," Frankfurt, Germany, 2020. Accessed: Sep. 06, 2021. [Online]. Available: www.frontier-economics.com.

This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.