Assessment of All-Electric General Aviation Aircraft

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Abstract: The purpose of this paper is to describe the upcoming changes that will bring the transition from piston engines to all-electric aircrafts. The article focuses on the differences in operation of small general aviation aircrafts. This topic is timely, as the first all-electric aircraft was certified by the European Union Aviation Safety Agency (EASA) in 2019. As there are no data concerning this new type of operation available, the data have been derived from other applicable sources. At first, we compared the energy consumption of the same aircraft with the piston engine, and then afterwards with the retrofitted all-electric variant. Our results focus on the difference in fuel price, which is discussed in the context of electricity price comparison with AVGAS prices. Moreover, we discuss the environmental impacts, especially concerning electricity source mix and emissions produced (we estimate both with and without life-cycle assessment). In the discussion, we compare the results and identify the benefits of an all-electric solution. Furthermore, several operational restrictions of all-electric aircrafts are discussed.

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1. Introduction

The focus of the paper is to analyze electric-powered aircrafts. We identified several aspects, which shall be taken into account when considering the alternative sources of power for aviation. It is important to point out that the topic of electric-driven aircrafts is very timely, but there is only a limited amount of data from real-time operations available. In this paper, we would like to fill this information gap with data derived from different areas, but applicable on the all-electric aviation. Therefore, our presumptions are based on aspects of electric driven aircrafts that can be derived from other fields, such as the automotive.

The all-electric aircrafts, de Havilland Canada DHC-2 Beaver and Cessna Caravan, were introduced in the USA in 2019. In the European Union (EU), the first all-electric aircraft, Velis Electro, was certified in June 2020 (type certificate EASA.A.573) [1]. Manufactures of these aircrafts, as well as other aviation experts, predict a bright future for all-electric aviation. In this article, we focus on the advantages that all-electric aircrafts can bring. The interest that the European Union has in transitioning from fossil fuels is defined in several documents [2–4]. These EU directives mostly target ground transportation, but same principles can be applied to aviation. We assume that the introduction of all-electric aviation helps fulfill the targets set in these directives. Therefore, further support of the development of all-electric aircrafts by the EU can be expected in the near future.

Besides the aforementioned retrofitted all-electric aircrafts, there are other approaches to introduce wider usage of electric energy in aviation. One concept is called the More Electric Aircraft (MEA); it is centered on the idea of powering more onboard equipment by electricity. This switch should increase

safety and decrease maintenance costs. The advantages of MEA may also be applied to all-electric aircrafts. Therefore, development in the field of MEA will likely positively influence development of all-electric aviation and vice versa. More details about the MEA concept can be found in [5–7].

2. Materials and Methods

2.1. Limitations of the Paper

In this part of the paper, we focus on all-electric general aviation aircrafts with one propeller. In order to maintain comparability, we focus on retrofitted aircrafts, where the classic combustion engine was replaced by an electric engine with batteries. There are several different concepts, such as hybrid combustion electric engine, hydrogen engines, or solar panel, but as these technologies are very complicated, there is currently no aircraft of this type in operation.

Due to this fact, we do not estimate the best weight size ratio for a new all-electric aircraft in our research (such work can be found in [8]); we solely focus on the existing types and compare their potential parameters, in case of their retrofit, to all-electric versions. The advantage of retrofitting an existing type is that the type certificate can be maintained and the additional certification process is easier. Moreover, experience with type maintenance and operation of these types of aircrafts are available. On the other hand, the design of these aircrafts were projected for combustion engines and their conversion may not always be beneficial.

Moreover, electric-hybrid engines seem to have no special advantages. According to [9], the crucial element of efficiency is the total mass of batteries. In accordance with the mentioned paper, some hybrid electric solutions seem to have better fuel efficiency than the turboprop engine, but no operational safety requirements, such as missed approach and diversion flights, are considered.

In our research, three areas of interest for aircraft operators have been identified, which may lead operators to switch from combustion engines to all-electric. The three areas are operational cost, environmental impact, and operational advantage. We analyzed each of these areas and identified key elements that may play a crucial role in the decision to switch to electric. For each of these areas, a different approach to evaluate the factors is applied.

2.2. Comparison of Usable Energy

For a meaningful comparison between carbon fuel and electricity, it is necessary to express their energy potential on a comparable scale. For this purpose, to compare small piston propelled aircrafts, we can compare the necessary energy, which has to be transferred by shaft from the engine to the propeller. We presume the same retrofitted aircraft in one case with an AVGAS fueled piston engine, and in the second, an all-electric battery propelled aircraft. Therefore, we assume all aircraft dependent variables (such as wing aspect ratio, aircraft lift coefficient, aircraft drag coefficient, propeller efficiency, propeller diameter, etc.) to be equal for both cases. The only difference will be the mass of the aircraft, because of the different engine mass, and mainly because of the additional mass of batteries. Energy is computed with Formula 6.

2.3. Energetic Requirements Comparison

In case of an aircraft equipped with a combustion engine, we presume a spark-ignited piston engine with internal combustion fueled by AVGAS 100 LL fuel, used by an aircraft with maximal power less than 350 horsepower. LL stands for low lead—AVGAS 100 also exists, with about 60% higher volume of lead. In further text, AVGAS refers to the AVGAS 100LL fuel.

Further, we derived the average value of brake-specific fuel consumption (BSFC) for a piston engine. BSFC is a measure of fuel efficiency. It represents how efficiently does the engine exchange the energy stored in the fuel and transfers it to a useful work. In case of piston engines, this is most typically conducted by measuring the shaft output.

The formula for BSFC is:

$$\text{BSFC} = \frac{f}{P} \tag{1}$$

where f is fuel in grams burnt per second and P is shaft delivered power in watts.

Based on the following research values:

- BSFC for spark ignited engine 275–410 g/kWh [10],
- BSFC for Rotax 912 UL flight manual 280–300 g/kWh [11],
- BSFC Rotax 912—observed and simulated value between 300–950 g/kWh [12],
- Lycoming O-540-J and L—BSFC 262 g/kWh—304 [13].

For comparisons, we also studied several compression-ignited engines. For example, conversed Cessna 182 engine Lycoming O-540 to diesel fuel—221 g/kWh [14]. In general, BSFC of compression-ignited engines seems to be slightly lower, but in general comparable with spark-ignited engines. More on this topic can be found in [10].

The aforementioned values typically represent the best-case scenarios for BSFC, as they are typically achievable only with ideal conditions and optimal lean fuel settings. In real operation, BSFC would likely be higher. Therefore, based on these aforementioned BSFCs, and our general knowledge, if the real BSFC cannot be obtained, we recommend a value of 300 g/kWh as the typical BSFC value for the discussed engine types. This value is slightly worse than BSFC of automotive engines or maritime engines with comparable power output [15].

2.4. Electric Engine BSFC

When analyzing the properties of the electric motors, we had to establish a similar BSFC for all-electric engines. As described in the Formula (1), BSFC is typically derived from the fuel consumed per time interval. However, in the case of all-electrical battery aircraft, it is not the same case. In fact, we can assume that the electric energy consumed from the battery is the same as the fuel burnt. Therefore, we need to determine the specific energy of batteries. Specific energy is energy per mass unit. Different types of batteries achieve different specific energy. Because specific energy is one of the crucial parameters to achieve operational usability of all-electric battery aircrafts, research in this field is very intense, and the level of specific energy achieved during several experiments is more than ten times higher than the typical specific energy of batteries today. Therefore, this parameter will likely significantly change in the future. Today, there is a significant gap between battery prototype performance during lab testing and real performance of mass-produced batteries. At this point, the ratio between AVGAS-fueled engines and battery-powered electric motors is twenty-two times in favor of combustion engines. If we would take into consideration batteries, which are yet to come (lithium sulfur, graphene, lithium cobalt oxide), we can presume that this ratio will change. For example, for specific energy 500 Wh/kg, which is, at this point, three times better than today's mass- produced batteries, but was achieved by multiple types of batteries in lab conditions, the ratio would be less than 8.

2.5. All-Electric Aircraft Energy Losses

As mentioned in the previous section, we compare the shaft power of the piston and an all-electric engine. Therefore, we need to determine the percentage of the power stored in batteries, which is actually converted into the shaft. This difference is based on the losses in the charging and discharging process of the battery. There are at least five different types of energy losses during the process, as shown on Figure 1.

- Battery charging loss—Lbch
- Battery round-trip loss—Lbrt
- Battery discharging loss—Lbd

- Thermal loss in wirings—Lwt
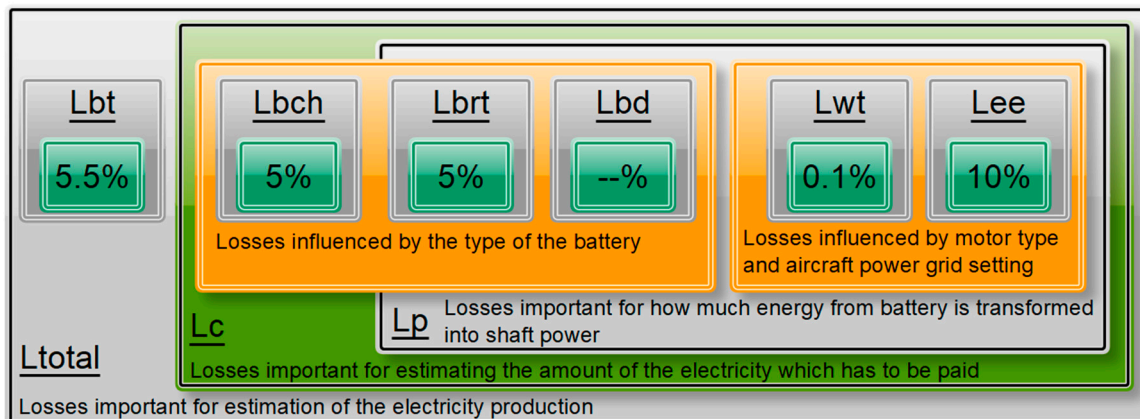- Engine loss (including gearbox, or other power transformation)—Lee

Figure 1. All-electric aircraft energy losses.

Lbrt—battery round-trip energy efficiency depends on the beginning and final state of charge (SOC). It may vary, based on the type of battery and number of cycles, from 3–17%, reasonably we can presume a value of 5% for lithium-ion batteries, which is in line with [16].

For Lbch—we have to consider several losses during the charging process. The volume of these losses take into account the type of battery used and it may vary with the number of charging cycles. Lower losses can be achieved by using a station charger with better-controlled power output, rather than using a portable charger. We assume Lbch to be at least 5%.

Lbd—battery discharge loss. This can be typically neglected, but for some types of batteries, after many charging cycles, this might be more important. For our scenario, we presume li-ion battery and, therefore, we neglect this loss.

Lwt—loss on wirings, switches, fuses, etc.—very dependent on the scale of the system as there is no data on all-electric aircrafts available, we based our estimates on a similar scale system from an automotive, and estimate that there should be a minor impact Lwt, with loss value around 0.1%.

Lee—depends on the type of motor, traction power convertor, and gearbox. This loss is system dependent. The electric motor efficiency is tied directly to the load. Based on [17], the maximal efficiency can reach up to 98% for optimal load, but with changing load it decreases significantly. To estimate Lee, we presume a nearly ideal state with optimal revolutions per minute (RPM) and torque. In this case, we estimate Lee to be 10%. There is also additional loss between the power plant and charging station. This loss does not influence shaft power of the all-electric aircraft, but it is additional electricity that has to be produced, which represents additional emissions.

Lbt—losses from electricity transfer from the power plant to the charging station. This loss is highly dependent on the distance between the charging station and power plant. Our estimate is 5.5% based on [18] the data from the Czech Republic.

$$\sum (\text{Lbch} + \text{Lbrt} + \text{Lbd} + \text{Lwt} + \text{Lee} + \text{Lbt}) = \text{Ltotal} \qquad (2)$$

$$\sum (\text{Lbrt} + \text{Lbd} + \text{Lwt} + \text{Lee}) = \text{Lp} \qquad (3)$$

$$\sum (\text{Lbch} + \text{Lbrt} + \text{Lbd} + \text{Lwt} + \text{Lee}) = \text{Lc} \qquad (4)$$

Ltotal represents all losses between electric energy generation and shaft power.

Lp represents losses that are important for determining how much power the aircraft has available.

Lc represents the sum of losses that are important for determining how much electricity the charging station has to pay.

Based on aforementioned parameters, we approximated the Lp to be 15.1%, Lc 20.1%, and Ltotal 25.6%. Loss Lp are in order of magnitude comparable with data from in-situ measuring of $LiFe(Y)PO_4$ batteries parameters [19].

2.6. Engine and Motor Mass Difference

The difference in mass of an electric motor and a piston engine of similar power can play a slightly positive role for all electric aircrafts. Based on data concerning Motor 268 MV LC VHML [20], EASA certified, and an Rotax 912 engine, which can be used in a Virus SW 121 aircraft, the difference in mass is about 35 kg in favor of the electric motor the motor is 22.7 kg and the Rotax 912 engine, depending on variant, is about 57 kg). There are also other systems, such as fuel pump, exhaust system, or alternators, which are not required for all-electric aircrafts. On the other hand, all electric aircrafts would need additional wiring, transformers, electric management systems, etc. Therefore, we can assume that the net loss of mass of an all-electric solution will be the aforementioned 35 kg. Based on this, we can estimate, as the Rotax 912 maximal power is slightly higher (about 24 hp), the real difference of an engine and a motor with the same power would be around 25 kg in favor of the electric aircraft. This represent about 40% mass loss against piston engines in favor of the electric motor.

2.7. Motor Shaft Energy

To estimate the necessary shaft energy, we used the following formula [21]:

$$E\,shaft = \frac{1}{\eta_v} * (\frac{1}{2} + \frac{1}{2}\sqrt{1 + \frac{S}{\pi R^2}C_d}) * (W_e + W_p) * d * \frac{C_d}{C_l} \qquad (5)$$

where:

- η_v is profile propeller efficiency (viscous loss);
- C_d is aircraft drag coefficient;
- C_l is aircraft lift coefficient;
- d is distance;
- R is propeller diameter;
- W_e empty weight of aircraft;
- W_p weight of fuel;
- S wing area.

For the outputs (Figure 2, Figures 4 and 6), we used following variables values:

- $\eta_v = 0.4$;
- $C_d = 0.0909$;
- $C_l = 1$;
- $W_e = 3433.5$ N (350 kg * g) where g is 9.81 m*s^{-2};
- $W_{e2} = 3090$ N—is weight of electric aircraft, and it is set to be lower than W_e by 10% because of mass difference between engine and motor;
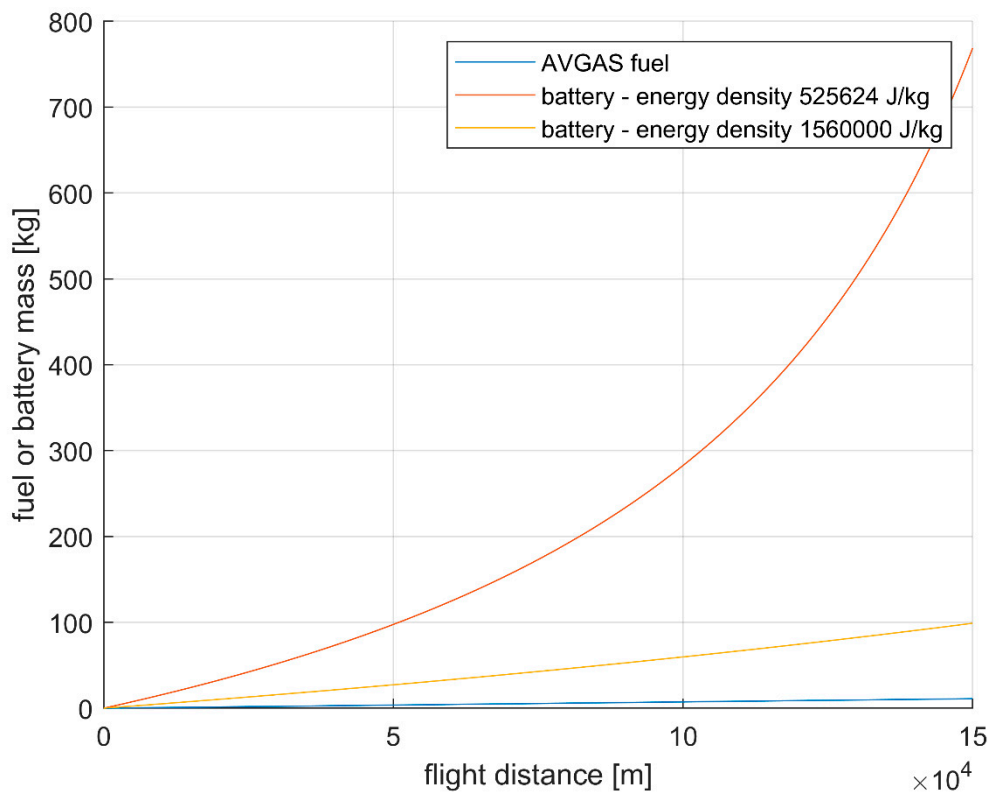- $S = 16$ m^2.

Figure 2. Flight distance for different energy density.

These values are not type dependent, they were chosen as an example of these variables for smaller general aviation aircrafts.

Figure 2 shows how the energy consumption changes with distance. The calculation of fuel or battery mass *m* is based on an iteration algorithm derived from formula (6), which follows:

$$m_k = \frac{\frac{1}{\eta v} * (\frac{1}{2} + \frac{1}{2} \sqrt{1 + \frac{S}{\pi R^2} C_d}) * (W_e + m_{k-1} * g) * d * \frac{C_d}{C_l}}{U},$$
$$k = 1, 2, 3 \ldots n, \; m_0 = 0$$
(6)

where: *U* [J/kg] is the energy stored in one kg of battery (specific energy), *g* is local acceleration of free fall g = 9.81 m*s^{-2}, n is number of iterations (we used value n = 50).

Based on formula (6), the necessary energy for all-electric aircrafts with longer distances increases logarithmically. The reason is that the additional weight of the batteries for a given range increases the necessary weight of the batteries total. For AVGAS, for a fueled aircraft, the situation is different, because as the fuel is burnt during the flight, the weight and necessary energy decrease. For batteries, no change in weight is possible during the flight.

Figure 2 shows the comparison of the importance of the aforementioned effect. We compared shaft energy per kg, for AVGAS fuel—12 MJ per kg (BSFC 300 g/kWh), battery with energy density 6849 g/kWh (Table 1), which represents 525,624 J per kg, and a battery with energy density 2000 g/kWh, which, with added Lc losses, 15%, represents 1,560,000 J per kg. As mentioned earlier, batteries with such energy density (500 Wh/kg) are today achievable only in laboratory conditions.

Table 1. Specific energy of batteries.

Type of Battery	Specific Energy [Wh/kg]
Modern Li-ion	134 [22]
Aqueous	<500 [23]
Lithium-sulfur	<400 [24]
LG Chem NCM 712 battery (best current automotive battery pack)	ca. 168 [1]

[1] We assumed value 168 Wh/kg, with additional loss (15.1%), as reference value for today's batteries for the rest of this article, which represents BSFC equivalent 6849 g/kWh.

3. Results

3.1. Operational Costs

Operational costs are mentioned in several articles as a key factor that should lead to a transition to electricity [17,25]. On the other hand, several papers suggest that, in case of commercial jet aviation, the transition to all-electric narrow body aircrafts will lead to an increase in operational costs [26,27].

3.2. Fuel Prices

Based on [28], the average price for electricity for non-household users in the European Union, is about 0.12 EUR per kWh with tax. Therefore, for the purposes of our paper, we presume the price €0.12 EUR per kWh. However, because of the losses between the actually usable energy on the shaft and the amount of electricity that goes through the main circuit breaker during the charging, we have to presume that we need additional battery charges due to this loss. Loss Lc is discussed in the previous section, and we presume it to be about 20%. Therefore, the price for 1 kWh of shaft power is 0.12 + 20% = 0.144 EUR per kWh.

AVGAS price varies more significantly. In 2020, the lowest prices are found in the USA, with a typical price $3 USD per gallon—which is ca. $1.1 USD per kg [29].

In Europe, the price varies because of different tax levels. The EU 2020 price of AVGAS, based on data obtained from the internet in the third quarter of 2020:

- Germany: €2 EUR per liter—€2.80 EUR per kg;
- Denmark: €1.99 EUR per liter—€2.80 EUR per kg;
- Poland: €1.44–€2.47 EUR per liter [30];
- Czech Republic: 56 CZK (ca. €2.06 EUR as of October 2020) per kg with tax.

We estimated average price in the European Union to be around €2.3 EUR per kg. When the BSFC 300 g/kWh is applied, this results in approximately €0.7 EUR per kWh.

Piston engine emissions from aircraft gasoline engines using the most common AVGAS fuel produce a variety of emissions, which might represent environmental or health risks. The usage of all-electric aircrafts does not produce any emissions at the place of aircraft operation, but moves the emissions to the place of electricity production. Therefore, to estimate the effect of the transition from piston engine to all-electric aircraft, it is necessary to compare the environmental impacts of the production of electricity in comparison to burning corresponding amounts of AVGAS fuel.

3.3. AVGAS 100LL Emissions

Aviation is a great contributor to lead emissions in Europe because, in any other transportation mode, leaded fuel is not used very often. Therefore, AVGAS is the main source of lead emissions from the transportation sector. One liter of AVGAS 100LL may contain up to 0.56 g of lead [31].

Emissions from gasoline represent only a small fracture of total aviation emissions; therefore, we were not able to find any commonly used emission factor specific for AVGAS. For example, the Intergovernmental Panel on Climate Change (IPCC) 2006 emission factor database has zero entries for aviation gasoline. We studied data from multiple sources [32–35]. We found that, often, instead of the emission factor of gasoline, the emission factor of Jet A1 fuel is used, which is more common and better described. Below, we present the outcomes of the Federal Office of Civil Aviation (FOCA) study [36], which are detailed and focus directly on several types of piston engine aircrafts. The difference in the outcomes of different sources seems to be either from the fact that, sometimes, there are used emissions for different fuel, but also because the proportion of the aforementioned emissions changes based on the actual power setting. This is based on [32]: "Hydrocarbon (H)C emissions decrease with power. Carbon monoxide (CO) emissions largely stay the same. Nitrogen oxides (NO_x) emissions increase with power, peak at cruise, and then fall again. Particle matters (PM) distributions behave differently depending on their measure (count vs. mass) and on their composition (total vs. non-volatile only)."

More details regarding these issues can be found in the Aircraft Piston Engine Emissions FOCA study [37]. This study shows that the theoretical emission factor of 3.17 kg of carbon dioxide (CO_2) per kg of fuel is not achievable, probably because there is not a suboptimal burning process; therefore, less CO_2 is produced, but more CO. We follow the recommendation of the FOCA study [37] and FOCA study Appendix 2 [36] and, therefore, we use different emission factors than the standard 3.17 kg CO_2 per kg of fuel. Details about nanoparticle emissions are to be found in [35], we counted these emissions in the general HC emissions.

Per 1 kg of AVGAS 100 LL fuel, we approximate production:

- 2 kg of CO_2;
- 1.2 kg water vapor;
- 1 kg of CO;
- 15 g of HC;
- 5 g of NOx;
- 0.8 g of lead.

Per 1 kWh (based on BSFC 300 g/kWh):

- 0.6 kg of CO_2;
- 0.36 kg water vapor;
- 0.3 kg of CO;
- 4.5 g of HC;
- 1.5 g of NOx;
- 0.24 g of lead.

3.4. LCA Emissions for AVGAS

In the next chapter, we estimated the life-cycle assessment (LCA) emissions for electric energy production. The LCA emissions of electricity, especially in connection with renewable sources, is a widely discussed topic, and estimates of electricity production of LCA are already in place. In order to obtain comparable results, we tried to draw comparisons with the emissions of AVGAS, including LCA (emission connected with production and transport of crude oil and finished AVGAS from refinery to the airport). Unfortunately, there is only a limited estimate about the scale of these LCA emissions connected with AVGAS. Additionally, because of different technologies and different processes and volumes of transport of crude oil and finished products, the LCA emissions will be dependable on the area of aircraft operation. To be able to estimate the impact of the LCA emissions, at least on the level of magnitude, we used the value 35.4 kg of CO_2 per one million British Thermal Units (BTU), for jet fuel [38]. This represents about 1.6 kg CO_2 emissions for each 1 kg of fuel. From the FOCA report [37],

recommended values for direct emission, we use the value 2 kg of CO_2 per kg of fuel. Additional emissions from LCA represent surplus of 80%. Therefore, CO_2 emission for 1 kWh shaft power for AVGAS with LCA is $600 * 1.8 = 1080$ g.

We applied the same ratio (1.8 times) for NO_x and hydrocarbons, which would probably also arise during LCA of AVGAS. On the other hand, CO and lead emissions are nearly exclusive for aviation piston engines and, therefore, we do not expect their increase in any part of AVGAS LCA. It is important to mention that the value of AVGAS LCA is only a rough estimate and shall be considered with cautiousness.

3.5. Electricity Emissions

Emissions that are emitted during electricity production depend on the primary source. The mix of electricity sources is different for each country; because of the important effect of foreign electricity trading and seasonal deflection in production from wind and solar sources, it is quite challenging to establish the precise volume of emissions, which were omitted for the production of 1 kWh of electric energy.

For the 28 countries in the EU, there was an estimated amount of CO_2 emissions in g per kWh of electricity in 2017, between 290 g and 550 g [39,40]. We use a lower value (149 g, computed in equation 7), which is mainly based on a different mix of electric energy sources. Because, until 2020, the shift in EU's 28 renewable energy sources was very significant, the CO_2 emission seem to be lower than the estimates from 2017.

As there is a long-time discussion about the real impact of renewable energy sources on the environment, we have also analyzed LCA for electricity production. LCA for electricity should represent a wider look at the estimated emissions, considering that even renewable sources of electricity are burdened by some environmental impacts. The volume of LCA emissions from electricity production is discussed later, as an important aspect for estimating more realistic emission production.

Electricity production mix, which was used for further computation, based on [41], for the first quarter of the year of 2020 is as follows:

- Nuclear 30%;
- Renewable 42%;
- Coal 12%;
- Gas 13%.

It is important to mention that this mix represents the best share of renewables in EU history. This was partially influenced by decreased energy consumption due to the COVID crisis. Under normal circumstances, the share of coal would likely be higher and, therefore, the electricity production would emit more emissions. Therefore, we may introduce the values mentioned in the next paragraph as valid for the near future, because the increasing percentage of renewables will negate the effect of increasing power consumption after the COVID crisis.

Estimation of CO_2 emissions, without LCA consideration, based on the CO_2 emission indexes by IPCC 2006 (in Table 2) and aforementioned Q1 2020 electricity production mix:

$$0.30 * 0 + 0.42 * 0 + 0.12 * 0.76 + 0.13 * 0.4 = 0.143 \text{ t } CO_2 \text{ per MWh produced,} \tag{7}$$

where the 0.4 value is the aggregated natural, heating, and biogas emission factor from Table 2.

Table 2. Emission factors CO_2 expressed in tons of CO_2 per MWh.

Fuel	IPCC 2006 Based on [42]	Additional LCA Emission Factor Based on [43]	Total Emission Factor Based on [44] with LCA	Total Emission Factor (Used Further in This Paper)
Coal	0.760	0.363–0.375	0.660–1.300	1.05
Natural Gas	0.483	0.24	0.38–1	0.780
Heating oil	0.268	0.306	0.53–0.9	0.730
Biogas	0.197	0.284	0.0085–0.13	0.6
Solar	0	0.04	0.012–0.19	0.1
Wind	0	0.01	0.003–0.041	0.015
Geothermal	0	0.05	-	-
Hydro	0	0.006	0.002–0.02	0.01
Nuclear	-	0.01	0.003–0.035	0.03

3.6. Emissions of Other Pollutants from Electricity

Concerning emissions from other pollutants, we applied the same principle as for CO_2. Because IPCC typically provides just the emission factor for CO_2, we used the emissions factors of other pollutants from different sources and gave them proportion based on the Q1 2020 energy mix. The SO and NO_x, HC emission factors are based on [45], and particulate matter (PM) emissions are based on [46]. The used values were always crosschecked to make sure that they were in magnitude (the same as at least one other source) [47,48].

The results are in Table 3 in the column: all-electric emissions per g/kWh. These results represent how many grams of pollutant are produced for 1 kWh of shaft power in the aircraft. Therefore, we increased production by 25.6% (Ltotal), which represents losses between electric production and real energy consumption at the shaft of the motor.

Table 3. Emission comparison.

In Gram per 1 kWh Shaft Power	AVGAS 100LL	AVGAS 100LL with LCA	All-Electric	All-Electric with LCA
CO_2	600	$600 \times 1.8 = 1080$	179	344
CH_4/HC	4.5	$4.5 \times 1.8 = 8.1$	5.4	10
NO	1.5	$1.5 \times 1.8 = 2.7$	0.8	1.536
SO			10	19
PM			1.25	2.4
Water Vapor	360	360		
CO	300	300		
lead	0.24	0.24		

As the emission of sulfur oxide is directly dependent on the used coal type and may vary by more than 50%, we used an average value. The estimation of PM emission is based on just one source [46] because we were not able to cross-check it with any other available source.

The real amount of emissions may vary significantly because, in the countries with a higher share of renewable sources (Figure 3) of energy, the emission of CO_2 per kWh will be lower and, therefore, the switch from gasoline to electricity may show more significant results.

Electricity production by source, 2019
(%)
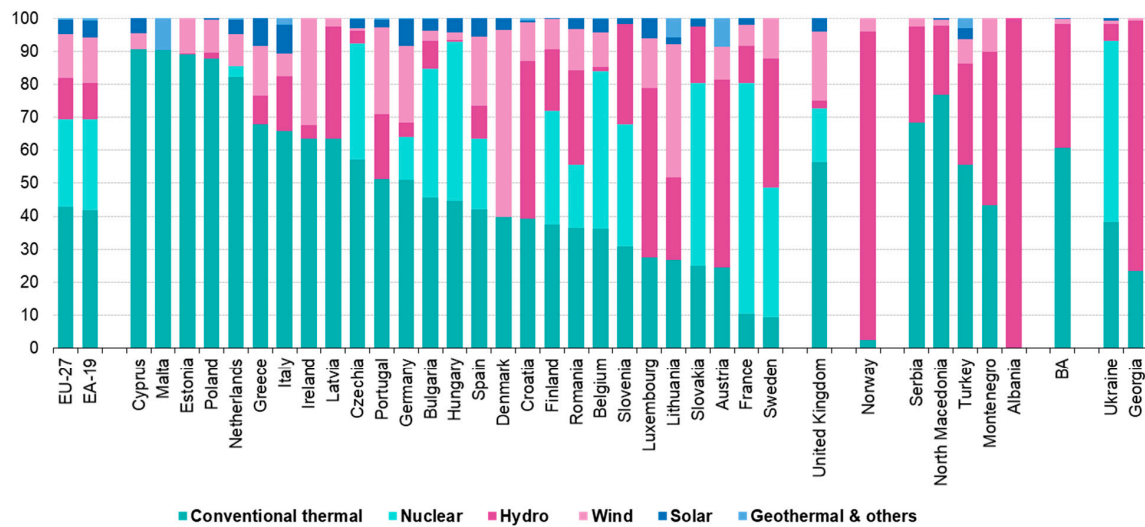
Source: Eurostat (online data codes: nrg_cb_em, nrg_cb_pem)

Figure 3. European Union (EU) electricity production mix [49].

For any potential user of an all-electric aircraft who would like to take into account the local specifics of energy production, for example, the usage of their own source of renewable energy, and therefore, estimate the difference of the environmental impact of switching from gasoline to electricity more precisely, we recommend the use of methodology established in [43], which focuses on the issue of local produced electricity.

3.7. LCA Emissions for Electricity

For a more complex estimation of the total environmental impact of different sources of electric energy on the environment, it is necessary to consider emissions from LCA. LCA emissions are emissions generated from the whole life cycle of an energy source; therefore, these are mainly influenced by the environmental impact of raw material processing, and construction of such an energy source, contrary to the conservative estimate (such as IPCC emission factors), the emission factor for renewable energy sources are not zero.

For the estimation of LCA, we used two main sources [43,44], which seem to be in order of magnitude in concordance. The value of total emissions (last column of Table 2) is IPCC emission factor, plus our best estimated average value of emission factors from [43,44].

LCA for nuclear power is based on [50], which found the nuclear LCA comparable to LCA of wind, but the LCA factor for nuclear energy production seems to vary between different studies (mainly because accidents and incidents in several studies were not included).

To establish CO_2 emissions from electricity production, with LCA taken into account, we used the same principle as formula (7) with emission factors from Table 2, column total emission factors.

$$0.30 * 0.03 + 0.42 * 0.04 + 0.12 * 1.05 + 0.13 * 0.75 = 0.2745 \text{ t } CO_2 \text{ per MWh produced,} \qquad (8)$$

where:

- Value 0.04 is average of LCA emission factor of hydro, solar, and wind;
- Value 0.75 is chosen as a combination of emission factors of heating gas and natural gas.

Results are in Table 3. Again, to consider increase of power production due to losses, we increased them by 25.6% (Ltotal). For the LCA emissions of other pollutants (SO, NO, PM, HC) in Table 3, we used

simplification. We computed the ratio between CO_2 emission with and without LCA, which is 1.92, and we multiplied the values from the Table 3 column, all-electric emissions, by this ratio.

3.8. Operational Limitations

The greatest limitation for all-electric aircrafts represent the energy density of batteries today. As shown in Figure 2, the mass of batteries, at today's energy density level, increases logarithmically with the distance. Such behavior leads to important limitation of effective range of an all-electric aircraft.

Figure 4 shows theoretical range of the all-electric aircraft (based on Formulas (5) and (6)), for different total battery mass (100 kg, 200 kg, 500 kg) depending on variable energy density of the battery. Difference in range, for batteries of the same energy density, is because of the logarithmic effect described in Figure 2. As shown in Figure 4, with twice the amount of batteries, the range will increase only about 70%. With five times more batteries, the range will increase only about 170%.
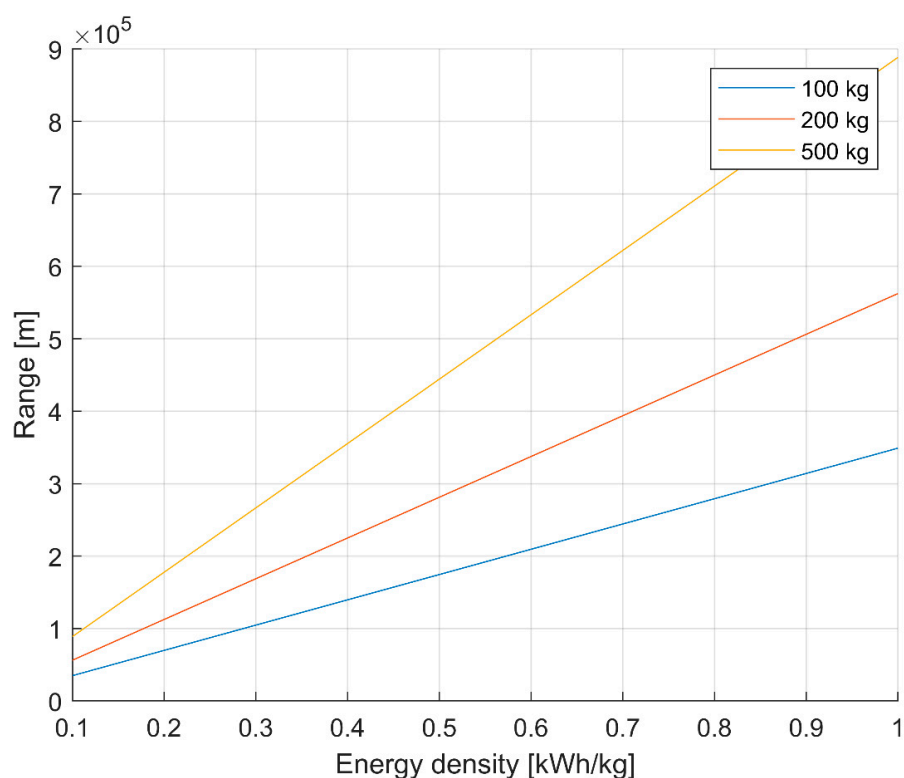

Figure 4. Energy density range influence.

3.9. Minimal Fuel Reserve

According to the International Civil Aviation Organization (ICAO) Annex II part two, for a flight conducted in accordance with day visual flight rules (VFR), a required fuel is enough fuel to reach destination, plus fuel for an additional 30 min of flight at normal cruising altitude and 45 min for VFR at night. For flights that are not under Annex 2 Part 2, for example, local training flights in the vicinity of an aerodrome, typically 10 min of flight time is the minimal required fuel backup.

There is a significant dependency between the battery output voltage, characteristics (Lbch, Lbrt, and Lbd) and state-of-charge (SOC) (Figure 5). For different types of batteries, the dimension of the nominal region varies, for example, in case of the most commonly used lithium-ion batteries, the state-of-charge should be always more than 10% to avoid a significant drop in battery voltage and the increase of Lbrt and Lbd.
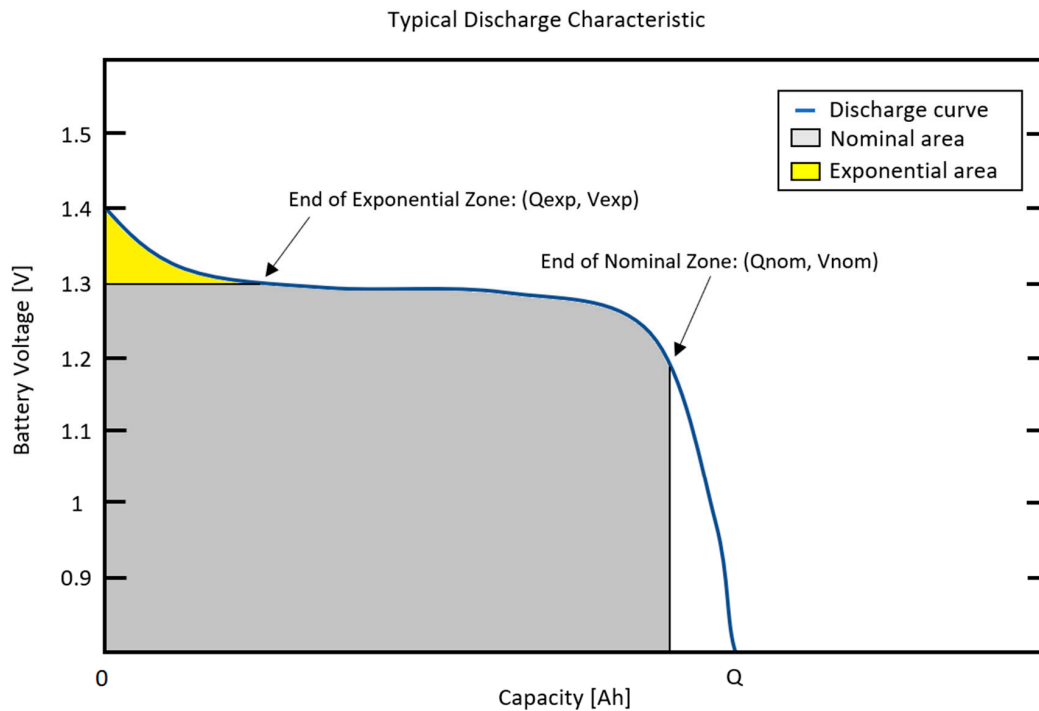
Typical Discharge Characteristic

Figure 5. Battery discharge voltage [51].

While Lwe and Lee remains stable, and can be measured directly for the given aircraft, and Lbch influences only the economy of the all-electric aircraft operation, the most significant parameters for estimating actually achievable shaft power are the variables Lbd and Lbrt. These two variables effectively influence the power output of the whole propeller system, while they change during the operation based on SOC and number of previous charging cycles. It will be very challenging to establish a suitable method to estimate the minimal fuel reserve of the flight with respect to these variables. From our point of view, this is the strongest safety obstacle regarding all-electric aircraft usage. To overcome this issue with batteries, either different types of batteries shall be used, or the flight manual of the aircraft shall not allow operating the aircraft under a strictly given SOC percentage—parallel to the final reserve fuel used in flight planning today—this limitation would reduce even more the already limited range of an all-electric aircraft.

Because of these aforementioned limitations of today batteries, it will always be required to fully charge the battery. Operation with only partially charged batteries would lead to increased Lbrt loss, which would lead to lower efficiency and, therefore, the range of the aircraft would significantly decrease. Full charging is time consuming and may limit the time during which the aircraft is operational. This issue can be partially solved by using replaceable batteries, which can be changed on the ground and, therefore, the in-air time can be increased, as there is no need for long recharging [52]. However, due to the high mass of batteries, such operation would require additional equipment, which is not guaranteed at every aerodrome. Moreover, using a portable charger may lead to increased loss of Lbch and, therefore, using more robust stationary charging stations may be advisable, but with limited infrastructure this decreases the usability of all-electric aircrafts.

Low temperatures are not an operational obstacle for lithium-ion (li-ion) batteries. Batteries are normally tested to operate between −40 °C and 50 °C. For charging, a temperature between 5 and 25 °C is typically recommended to minimalize losses.

3.10. Cabin Heating

For an all-electric aircraft, there is additional energy consumption for the heating system, because heat from the engine cannot be used. We based our estimates about heating on data from the automotive.

Electric cars typically use resistant heating, which has a power consumption from 0 W for +20 °C up to 3000 W for −20 °C. Based on this, and the fact that general aviation aircraft cabins are typically about half the size of a car interior, and often better insulated, we can presume that energy consumption should typically not overcome 500 W. This presumption is based on the fact that most general aviation aircrafts do not have anti-icing protection; this, they typically do not operate above zero isotherm. With such conditions, for one hour, flight in air temperature around 5 °C, the necessary battery mass would be less than 5 kg. With decreasing temperatures, the energy consumption for heating rises. Better efficiency is achievable with a heating system equipped with a heat pump, but such a system is more complex. Based on these estimates, we neglected the influence of heating in our calculations.

4. Discussion

4.1. Operational Costs Discussion

As for the assessment of operational costs, possible changes in maintenance costs have to be considered. It is presumed that the motor would require less maintenance work and, therefore, maintenance costs can be lower. However, the battery system would probably require much more attention compared to the fuel system today. At this time, it is not possible to estimate these values because there are no maintenance plans made specifically for an all-electric aircraft. After such materials are published by a regulatory body, it would be essential to incorporate them in the assessment of all-electric aircrafts.

4.2. Electricity Price

Comparison between the cost of 1 kWh shaft power from the piston engine (0.7 EUR per kWh) and all electric aircraft (0.144 EUR per kWh) shows nearly five times lower fuel costs in favor of electricity. On the other hand, there is additional electricity consumption due to increased mass of the aircraft because of the batteries. This will decrease the advantage of lower electricity prices. Details are shown in Figure 6.
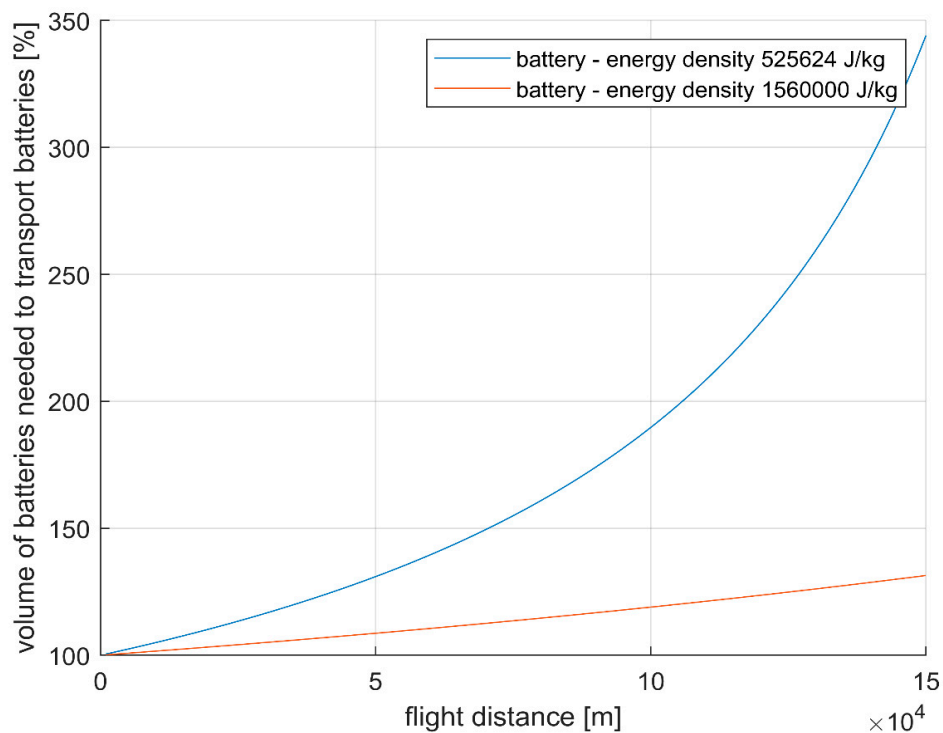

Figure 6. Additional battery mass.

Figure 6 shows the percentage of the whole mass of the aircraft (with batteries) required to transport the batteries. Percentage is a ratio between additional mass of batteries compared to the original mass for the flight distance. Due to additional fuel consumption caused by the increased mass of the aircraft, the advantage of cheaper electricity is partially neglected. It is another example of the crucial role of energy density for cost effectiveness of the all-electric flight.

4.3. Electricity Price Development

The average non-recoverable tax for electricity in the EU is 34%—which may be significant because of the aviation fuel tax exemption. Historically, based on the 1944 Chicago Agreement, aviation fuel is typically exempt from taxation. Based on article 13 of the Council Directive 2003/96/EC, "Member States shall exempt the following from taxation under the conditions which they shall lay down for ensuring the correct and straightforward application of such exemptions and of preventing any evasion, avoidance or abuse . . . energy products supplied for use as fuel for air navigation other than in private pleasure-flying." This means that, at this point, the fossil fuel is exempt from excise tax, but electricity for the same flight activity is not exempt because it does not fit under definition of energy product, which is tied to the combined nomenclature (CN) code of the energy source. The CN is the EU's eight-digit coding system, comprising of harmonized system codes with further EU subdivisions [53]; electricity does not have CN code attached.

Therefore, the future price for one kWh of electricity in the EU for use in aviation can decrease to €0.08 EUR per kWh, if electricity for navigation would be exempt from excise tax, and if the aircraft operator could reach the price for non-household users, which typically represents a yearly consumption between 500 MWh and 2000 MWh. It would make electricity nearly 8 times cheaper (with 20% Lbt loss) per kWh in comparison with 1 kWh produced from AVGAS.

In the distant future, there is potential for another electricity price drop. With higher energy consumption, the unit price could go even lower. For consumers who use large amounts of electric energy, such as railways or factories, the price of electric power can drop even more dramatically. The average price of 1 kWh on the energy stock market is about €0.04 EUR per kWh. With the connection fee about 10%, the price for one 1 kWh of electric energy for these consumers may decrease to €0.045 EUR per kWh, which is about 50% of today's non-household electricity price. However, this drop of electricity price would only be possible if the shift towards electricity would be massive in aviation in order to achieve very high-energy consumption, especially in airports with high volumes of traffic. Such a great decrease in electricity price drop would represent a significant opportunity for electricity usage in the distant future, but in the next 10 years, it would not be achievable, because it would require transition to electricity for a significant percentage of flights within the EU. We believe that the change in electricity taxation for aviation is in harmony with principles stated in [2–4], and that this step may positively influence the development of this area. Not only would such a step decrease the costs of fuel, but also, it would show that introduction of an all-electric aircraft is supported by the EU.

However, the drop of cost per 1 kWh for internal combustion engines is also possible. Today, there are versions of the most used general aviation engines that can use Jet A1 fuel or diesel fuel, which are very similar. The price of Jet A1 fuel is about 50 percent lower than the AVGAS price. Engines using Jet A1 fuel are typically heavier and have some operational limitations, but in general switching from AVGAS to Jet A1 would decrease the cost of 1 kWh to about €0.4 EUR, which would make electricity only three times cheaper in comparison to five times for AVGAS.

4.4. Environmental Impact Discussion

To estimate the environmental impact of the specific change of an aircraft fuel from AVGAS to all-electric, it is necessary to take into consideration information that is not available. Electricity production emissions are heavily dependent on energy production mix, for example, in the Czech Republic, where the energy mix is 57% coal, 37% nuclear, and 6% renewable. This would represent about 450 g of CO_2 per 1 kWh of aircraft shaft power. For such a scenario, the difference

between AVGAS and electricity CO_2 emissions is only 25%. With increased percentage of renewable sources of electric energy, the difference in CO_2 production level increases. This is true even for the situation when all-electric aircraft emissions, including LCA emissions and AVGAS, do not include LCA (because of the lack of suitable data). An all-electricity aircraft always has lower carbon impact, but the significance of the difference is subject to local conditions.

Based on [54], in 2015 there were 103,063 general aviation aircrafts registered by national aviation authorities in the EU. In the same year, there were about 6500 aircrafts used for commercial aviation in Europe. The number of aircrafts used for general aviation exceeds the commercial aviation aircrafts in, at least, a one to ten ratio. However, because of lower maximum take-off mass, and because general aviation aircrafts are operated less intensively, their share on aviation fuel consumption is minimal. Based on annual production of Jet A1, which is more than 100 times higher than production of AVGAS, we can estimate that switching to all-electric general aviation would not reduce the carbon emission footprint of aviation by more than few tenths of one percent. On the other hand, AVGAS greenhouse gas emissions represent about 1,500,000 tons of CO_2 annually.

The difference is more evident for emissions causing direct health issues. AVGAS is a source of CO, HC, and lead emissions. These gases mostly have local impact. The influence of these gases is most significant around the aerodrome, because of a combination of a higher volume of traffic in a small area, and a non-ideal working state of engines. As mentioned, leaded gas is prohibited for all other transportation usage, except for aviation. For at least 10 years, there have been initiatives to prohibit leaded gas in aviation. As for today, aviation is an exception, mostly because there is no alternative for leaded gas [55]. If an all-electric general aviation aircraft would offer similar usability, at least for part of the operation, this may dismantle the argument about there being no existing alternative. Therefore, the introduction of a viable all-electric aircraft may change the future development of the whole general aviation segment.

4.5. Model Example for Assessment of Operational Limitations

Let us assume a Virus 121-like aircraft. According to [25], to fulfill the minimal fuel reserve mandate, there is fuel reserve for 30 min of flight, which equals to 6 L of fuel. The same amount of energy would represent 91 kg of batteries. The 91 kg of batteries represents a sufficient minimal fuel reserve, in accordance with the ICAO Annex II, but only if the effect of the voltage drop, shown in Figure 5, is neglected.

For Virus SW 121, the difference between maximal take-off mass and dry aircraft mass without batteries, including the motor/engine mass difference mentioned earlier, is about 350 kg. With two people on board (160 kg), and a remaining 190 kg for batteries, with a necessary 91 kg of batteries for minimal fuel reserve, the rest of the batteries represent about 15 kWh of energy. This is equivalent to 4.5 kg of AVGAS fuel, which represents less than 30 min of cruise during the flight (depending on flight level, engine setting, atmosphere conditions) with cruise speed about 115 knots. Therefore, the real range of such an aircraft is about 60 nautical miles, plus 30 min minimal fuel reserve. Such a simple model neglects the additional energy necessary when changing the flight level. The purpose of the model is to point out that, without an increased energy density, the operation range would be very limited.

5. Conclusions

The assessment of the all-electric general aviation aircraft shows that all-electric aircrafts have several benefits in comparison with the piston engine. The direct cost of fuel is significant today and could be even more significant in the future, especially if some adjustment in taxation is made.

The environmental impact of the all-electric aircraft is also positive, but for a more detailed analysis, it would be necessary to estimate LCA emissions more precisely. However, from the comparison of real emissions, it is obvious that the main benefit of this transition is in lowering emissions endangering health. In particular, CO and lead emissions from aviation are taken into strong consideration today [55].

The problem is that these emissions are often not considered because, in calculations, when standard emission factors for Jet A1 are used instead of AVGAS, emissions of CO or lead are not considered (because Jet A1 fuel does not emit them).

Operational limitations are, at this point, mainly because of limited energy density of existing batteries. As shown in Figure 4, increasing energy density range limitation will decrease more significantly because of logarithmic nature of the dependency. The other operational issue is a proper adjustment of the minimal fuel reserve, because of the voltage drop when the battery is nearly depleted.

The all-electric aircraft has potential to become a viable option, and in the near future, it may become a significant trend in general aviation.

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