Conceptual Design of an Urban Air Mobility Solution

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Abstract

Urban Air Mobility (UAM) is the aircraft industry answer to the ever-increasing mobility needs in heavily populated cities, where citizens spend up to two hours a day in the traffic jam. Moving oneself from point A to B the fastest way possible, with the minimum environmental and economic impact is the prime goal. Aircraft capable of taking off anywhere and that occupies the smallest land area is a great solution candidate, hence VTOL aircraft are a great fit. Helicopters are the only vehicle that could address this issue if only they were not so noisy and expensive to operate, resulting in an unfeasible solution. Hydrogen is the energy of the future, meanwhile, electricity is in the present, attending the aircraft is to be commercialized in 2024. Nowadays, the greenest, cheapest and widest available source of energy is electricity which results in conceiving an all-electric aircraft granting zero carbon dioxide operation emissions, with expected lower cost of operation than helicopters or any other solution from General Aviation (GA) given the energy cost is lower. Consequently, the estimated pricing for passengers will drop and potentially increase the number of costumers. The current work conceptualizes an aircraft from a set of cost, environmental and aeroacoustics requirements.The resulting proposal is a lift-plus-cruise solution with a Maximum Take-Off Weight (MTOW) of 1434 kg with an estimated energy system of 217kWh, considering a mission profile of three trips of 67 km each at a cruising altitude of 500 meters.

Keywords: Urban Air Mobility, Air-taxi, Conceptual Design, Noise Estimation, Environmental Impact, Operational Cost

1. Introduction

Uber [1] set the goal to have a fleet of air-taxis in service by 2023 by publishing a white-paper, where it showed a worldwide demand for this service. Such publication set UAM into motion. January of 2020 was the turning point for the UAM industry as contracts amounting to 500M US$ [2] were established between car manufacturing, aircraft and mobility companies.

Based on Uber's beliefs [1], the present paper has the following goals present when designing an UAM solution:

- be market-ready by 2024 to meet the market needs and expectations predicted by Uber in 2016 [1];
- be an aircraft with nonexistent operational carbon dioxide emissions;
- achieve the lowest operational cost possible to allow reasonable pricing for customers and profit for companies;
- produce the lowest noise possible, at least quieter than helicopters, so that people can keep living their lives with the smallest environment disturbance.

The present document has 5 sections. Firstly, there is the current introduction, then section 2 explains the UAM market state by 2020, section 3 presents the conceptual design, section 4 presents noise and environmental impact and the estimation of the operational cost and section 5 concludes while pointing towards future work.

2. State of Art

Anyone developing a fixed-wing all-electric aircraft up to 19 passengers and a maximum takeoff weight of 19000 lbs (approx. 6818kg) needs to follow the Code of Federal Regulations CFR 14 Part 23 [3], which sets the ground rules for Airworthiness Standards which have already been updated to fit some changes in the industry. Fortunately, in May of 2020, according to Future Planet [4], a Cessna Caravan 208B - eCaravan - with the capacity to seat up to 9 passengers despite only carrying the pilot during the test flight became the biggest commercial plane ever to fly all-electric for 30 minutes straight having a fuel cost reduction of approximately 98% (from around 300 US dollars to a mere 6 US dollars).

According to the National Aeronautics and Space Administration (NASA) [5], any UAM solution should require the minimum additional Air Traffic Control (ATC) infrastructure; minimal changes to the Federal Aviation Administration (FAA) automation systems (at least to begin with); must meet the regulatory requirements for vehicle-level and system-level safety and security; be resilient to a wide range of disruptions (from weather and localized system failures to widespread disruptions); be possible to scale economically for high-demand operations with minimal fixed costs; support flexibility and decision making to the greatest extent possible.

Nevertheless, the current solution and definition of UAM only applies to helicopters which do not pose an elegant solution due to their numerous disadvantages: high noise, high fuel consumption and extremely high operational costs. A UAM solution may either be autonomous or not, hence the designation of Autonomous Air Vehicle (AAV). Due to evolution and the current

course of technology, it is plausible to believe that UAM solutions posing as air taxis will be autonomous in the long run, to increase system efficiency to the highest level possible, therefore AAV is pointed out as the future of UAM. According to Ehang [6], electric AAV's have higher safety standards led by Distributed Electric Propulsion (DEP) with multiple propellers, dispose of full automation to eliminate human errors, support 4G/5G network, have centralized command-and-control, are sold at reasonable vehicle price, eliminate pilot costs, have low repair and maintenance cost, have a small noise footprint, have zero operational emissions, are small in size, easy take-off and landing with better manoeuvrability and can carry both passengers and freight with a payload up to 200-600 kg.

The biggest market feasibility hurdles are well identified by Uber's experts [1]. They are the following certification process [7], battery state of the art, vehicle efficiency, vehicle performance and reliability, ATC ([8] and [9]), cost and affordability, safety, aircraft noise [8], motor, emissions, pilot training [10], vertiport/vertistop infrastructure in cities and the command-and-control platform.

2.1. Aircraft Inventory

The Vertical Flight Society (VFS) started to publicly gathering information for statistical purposes and to centralize all existing and relevant information, in 2016. VFS gathered information on 262 VTOL aircraft [11] (assessed in the 20th of January of 2020) and organized them under 5 categories: vectored thrust, wingless (a type of multicopter), hover bikes and personal flying devices, lift-plus-cruise and electric rotor-craft; however, only 94 out of the 262 aircraft pages had some relevant information. Some of these aircraft are only a proof of concept, meaning there was no intention to produce them at a large scale, and other aircraft projects became extinct due to lack of investment. Nevertheless, eVTOL (electric VTOL) is a growing industry and its industry is to be worth billions of US dollars in the long-term [12]. Therefore, the number of companies investing in the field is increasing and 2020 has been proof of it. There are several big automotive companies creating bonds with the aeronautical industry because the automotive industry already has decades of knowledge for mass-scale production, but lacks the aeronautical expertise to build a UAM solution for on-demand transportation whether for 2 or 20 passengers.

2.2. Current Associated Technology State and Future Prospects

2.2.1 Electric Propulsion Benefits and Penalties

As mentioned, the current paper aims to design an all-electric UAM solution, therefore understanding the benefits and penalties of the technologies being used is a must. According to Moore, the advantages of electric propulsion [13] are 6-times the motor power-to-weight ratio; 3-4 times the efficiency of conventional engines; scale-free efficiency and power-to-weight ratio; high efficiency from 30-100% power; extremely compact engines; high reliability; safety through redundancy; low cooling drag; production of 100% power for 30-120 seconds; continuously variable transmission; extremely quiet; no power lapse with altitude or hot day; 10-times lower energy costs; reduction of engine-out sizing penalty and zero vehicle operational emissions. On the other hand, the penalties of electric propulsion [13] are the energy storage weight; energy storage cost; certification and safety.

2.2.2 Li-ion Battery Technology

Reference [14] helps to understand the concept of State-of-Charge (SOC) for Li-ion batteries and explains that a battery may be considered empty for calculation purposes when SOC is between 10-20% meaning a Depth-of-Discharge (DOD) of 90-80%, respectively, in every use [14]. However, the design team may opt for a more conservative DOD of 60-70%. The state of the art, in 2020, for lithium-air batteries is as follows: a specific energy density of 240-260 Wh/kg, a specific power density of 1300 W/kg, a volumetric energy density of 550-600 Wh/L and a voltage of 3.6 V. Considering estimations of battery technology for 2024, the specific energy density used in this project is 300 Wh/kg. The choice of battery density highly influences the weight of batteries and, consequently, affects all weight distribution of the aircraft.

2.2.3 Overall Aircraft's Noise

Current VTOL vehicles most used as a UAM solution are helicopters and they come as loud as they get. According to Brown and Harris [15], the prime sources of noise in a helicopter, by decreasing order of importance, are blade slap, piston-engine exhaust noise, tail-rotor rotational noise, main-rotor vortex noise, main-rotor rotational noise, gearbox noise and turbine engine noise. NASA [16] sets its limits, under 50dB as "quiet" operations and higher than 50 dB as "non-quiet" due to NASA's "Societal Barriers focus groups which indicated low public acceptance of a large number of high-noise Air Taxi operation."

2.2.4 Overall Aircraft's Emissions

All-electric aircraft have zero operational-emissions [1], meaning zero carbon dioxide emissions when flying. All they have are emissions regarding their building, recharging, maintenance, disposal, recycling and reusing processes, which all are part of the life-cycle of aircraft. Though recharging related emissions may be brought to zero if electricity from clean sources is used for this purpose.

2.2.5 The Reality of Autonomous Vehicles

Autonomous vehicles are getting closer, the biggest barrier being people as they are concerned whether such vehicles are reliable enough. From the engineering perspective, it seems easier to have auto-piloted aircraft rather than land vehicles, as on-air there are no passers-by and no signals to read. Despite this, autonomous land vehicles seem to be ahead of aerial solutions,

as companies like Tesla are making huge efforts and advancements poking the industry at all levels. Despite the car industry having a grading system for autonomous passenger vehicles, the aircraft industry has not developed a similar scale yet.

C2-link and 5G are promising technologies and some believe the path towards success is the joint effort of both technologies [17]. Nevertheless, one must state that regulations need to be ever-updated and communities must be duly informed to build-up people's confidence so that technology can be implemented in commercial solutions.

3. Conceptual Design

The fundamental phases of the aircraft [18] designing process are, by order of doing, requirements, conceptual design, preliminary design, detail design and proof-of-concept aircraft construction and testing.

3.1. Aircraft Requirements

One of the purposes of the current paper is to develop a UAM solution, hence the aircraft must address several needs of the UAM market. The starting point is Uber [1] as they were one of the first companies to publicly set the impetus of the UAM industry. Several companies, such as Uber [1], Volocopter[19], Ehang [6] and HyPoint [20], have independently published white-papers on the UAM market, assessing market needs and prospecting about the future.

Requirements are project guidelines, thus some of them may seem more reachable than others. The requirements that follow are based on the literature review and are presented by order of importance:

1. Air taxi - as the main aircraft purpose [1];
2. At least 2-passenger aircraft, if possible a 4-passenger, with respective cargo up to 10 kg each;
3. All-electric aircraft - to have zero operational emissions [1];
4. Power-train efficiency of, at least, 92% [1];
5. Energy costs account for 15% of the baseline direct operating costs, a maximum of 20%;
6. Range of, at least, 200 km [1];
7. Cruising speed of, at least, 275 km/h [1];
8. L/D of 15 for a cruising speed of 275 km/h [1];
9. Possibility of serving 5 trips of 40 km or 2 trips of 80 km on a single battery charge;
10. Include a 10-minutes emergency energy storage - according to MIT research such a reserve was used for a battery specific energy of 200 Wh/kg [21] for aircraft posing as UAM solutions. A jet fuel reserve for GA has to be able to provide 30 min cruise-reserve for day-time and 45 min for night-time ([22] and [23]). Given that GA has almost zero engine redundancy and that electric DEP adds a lot of redundancy, then a 10-minutes reserve may be considered reasonable;
11. At least, 90 minutes endurance to perform the mission;
12. Battery specific energy of 300 Wh/kg, at the pack level [1];
13. Battery pack with, at least, 2000 life-cycles [1];
14. 80% maximum battery energy discharge limit [21];
15. Save, at least, 40% of time relative to the homologous ground-trip [1];
16. 3-minute riders loading and 2-minutes riders unloading, both considering riders cargo loading and unloading [1];
17. Fully Autonomous - to ease ATC, avoid fuel management errors, reduce the loss of control problems, have improved trajectory flight profiles, minimize any additional power required [1];
18. Use DEP technology - to increase propulsion redundancy [1] and reduce the risk of auto-rotation [1] as well as ease manoeuvrability;
19. 75-80 dB(A) at 50 ft or, equivalently, 62 dB L_{Amax} at 150 m distance [1] in hover; [1];
20. Do not increase more than 1dB in DNL - for the long-term annoyance, as it is the minimum variance for a human to detect [1];
21. A 100-times quieter than a helicopter [24];
22. Technology Readiness Level (TRL) of, at least 7, [25] for commercial availability in 2024;
23. 0.3 fatalities per 100 million passenger miles - 2-times better than a driving car and 4-times better than the current air-taxi solution, both values are referenced to 2016 [1];
24. Accomplish aircraft availability of, at least, 3500 hours/year;
25. A cost of 2.5 US$ per passenger-kilometer [6];
26. 20% of all flights are dead-flights.

3.2. The Trade-offs

Trade-offs are presented and explained in numerous textbooks, articles or websites, references [26] and [18] explain most of them. For example, for the same wing area, the increase of the Aspect Ratio (AR) decreases induced drag increasing, in turn, L/D and potentially reducing the energy needs. However, the mentioned increase of AR as disadvantages such as the increase of the root bending moment, correction of such negative effect implies adding-on structural weight. Assessing the wing position and lift configuration is essential.

3.3. Primary Conceptual values by assessing similar solutions

Using historical data is a common basis to design aircraft, however eVTOL industry is very recent and has not been on the market long enough to have historic data. The majority of current UAM solutions have not reached the market yet, hence few details are readily available for data compilation and analyses. Very few companies make their data public or provide it when

asked by email so that their competition does not get a hold of their data. Most of the data used for the following results were found at [11].

The presented summary results from extensive analyses of the collected data and is a key part of the decision-making process of setting reasonable initial concept values of the UAM solution being designed in the current paper:

- All-electric propulsion;
- 4-passenger of 80 kg each with cargo up to 10 kg each, hence a payload of 360 kg;
- Lift-plus-Cruise configuration;
- Fully-autonomous;
- Empty-to-MTOW ratio around 0.6;
- Payload-to-MTOW ratio around 0.25;
- One motor for each set of propellers;
- MTOW of 1410 kg;
- Range of 200 km;
- Cruise Speed of 290 km/h, rather than the 275 km/h presented in section 3.1;
- Endurance of 90 min;
- At least 40% faster than a ground-trip.

At this is stage is natural for the design team to have some sketches of the aircraft to be built, like figure 1, showcasing several possibilities for exterior and interior design.

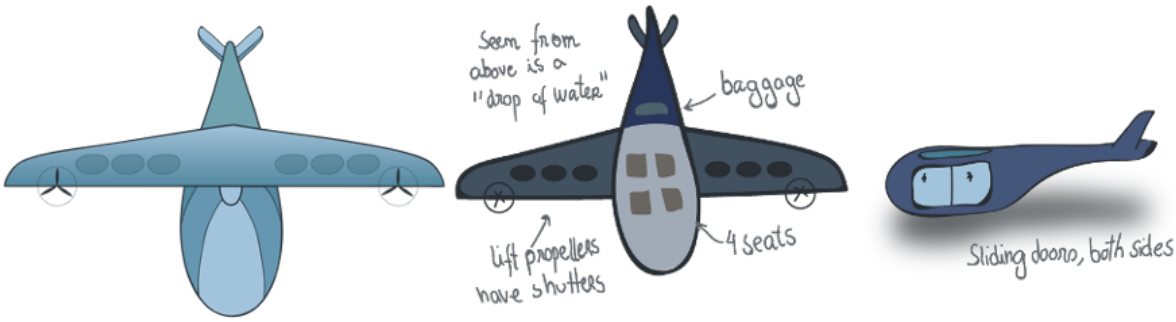

Figure 1: Iteration of the conceptual lift-plus-cruise configuration draw presented in the middle-figure. The autonomous aircraft has 6-lift rotors with shutters to be closed during cruise, reducing considerably the associated drag; the aircraft has 2-cruise rotors.

3.4. MTOW Estimation by Several Methods

After assessing current UAM market solutions one needs to start choosing aerodynamic values to estimate MTOW (in kg). A joint effort of 6 methods was used, as presented in table 1, to achieve the MTOW of 1434 kg.

Table 1: Presenting the results for the 6 methods used to estimate MTOW. The "Logarithmic Regression of Conventional Aircraft Data" method results from collected data in November of 2019 for conventional propulsion of twin-engine aircraft for 4 passengers.

Method	Result [kg]
Raymer [26]	1 423
Raymer Adapted [27]	1 432
Gudmundsson [18]	1 256
Logarithmic Regression of Conventional Aircraft	1 759
Nicolai and Carichner [28]	1 323
UAM selection from section 3.3	1 410
Average MTOW considering all the values above	1 434

Given the choice of lift-plus-cruise configuration, a design similar to the conventional GA would not come as shock given the extensive research and the years of perfecting such body form. Using the conventional GA body-frame still requires an aerodynamic study because using DEP combined with a lift-plus-cruise configuration is a synonym of having multiple sets of propellers in neutral mode during most of the aircraft mission profile which in turn will change the stream body of the aircraft. Also, using DEP will immensely change aircraft's control, therefore the designing team must consider it in their decisions.

Raymer [26] provides the estimate of the wetted-area ratio of 4, given the resemblance of the drawn UAM solution to the Cessna Skylane RG. The choice of a wetted-area ratio along with the AR produces a more reliable estimate of Lift-to-Drag (L/D) [26], which is highly dependent on the wingspan and the wetted area. Aspect Ratio (AR) value of 7.5 [26]. The span of 9 m was chosen considering the maximum space the aircraft might occupy when parked in an over-crowded city is equivalent to 3 car-parking spots. The wing area is then calculated to be 10.8 m^2.

Other aerodynamic values need to be given the first estimates. The zero-lift drag C_{D_0} is 0.0315 according to Gudmundsson [18] assuming the typical values for GA trainer. According to a formula by Glauert and Weissinger presented by Raymer [26] considering sweep leading edge angle inferior to 30°and any aspect-ratio, the calculated Oswald efficiency is 0.825. The propeller efficiency considered was 0.8, considering the loiter movement of a piston-prop engine of variable-pitch [26].

Raymer also provides the maximum L/D of 15 for cruise [26], which is retrieved from a graph using the wetted aspect ratio mentioned above and then the L/D for loiter of 13 considering Raymer formula for propulsion.

Given the ageing aircraft that made the statistical relations being used, Raymer suggests a decrease of 5% in the empty-to-MTOW ratio to be updated to more recent air-frame materials such as composite [26].

3.5. Constraint Analyses

The mission profile aids in assessing cruise altitude, range and power needs. The design team reduced the number of trips per mission from 5 to 3. Consequently, the following missions were designed, all at the same cruising speed of 290 km/h:

- Mission 1 - 3 trips of 67 km each, ranging 200 km, at 500 m of cruise altitude;
- Mission 2 - 2 trips of 100 km each, ranging 200 km, at 1000 m of cruise altitude;
- Mission 3 - 1 trip of 60 min, at 500 m of cruise altitude;
- Mission 4 - the total range of 200 km, split into 5 trips, at 500 m of cruise altitude.

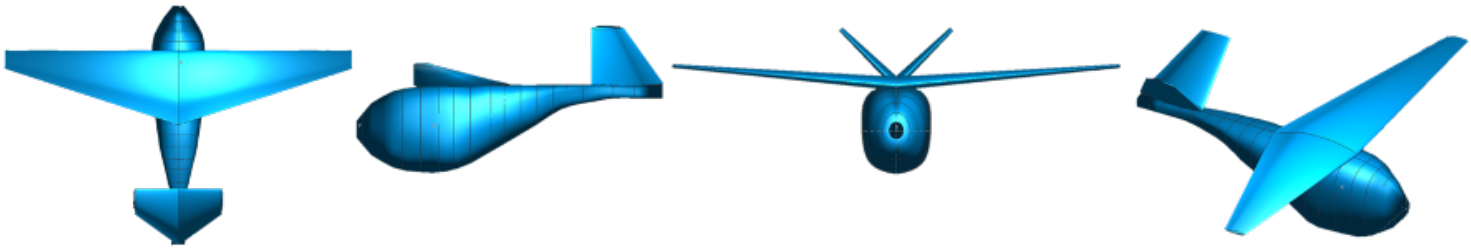

Figure 2: A computational model of the UAM solution being designed was obtained using xflr5 software. From left to right, the figure presents the top, side, front and iso aircraft views.

Each trip considered 3 min for boarding, 0.5 min for take-off, 0.5 min to transition from lift to cruise configuration, 0.3 min for horizontal acceleration, cruise time (14, 20, 60, 8 min from mission 1 to 4, respectively), 0.3 min for horizontal deceleration, 0.5 min to transition from cruise to lift configuration, 0.5 min for landing and 2 min for unloading. Power calculations using methods from Afonso et al. [29] resulted in the following power needs: 623 kW for hover Out of Ground Effect (OGE), 765 kW when climbing or landing and 109 kW for cruise at 500 m of altitude. Considering a battery discharge rate of 80%, a battery energy density of 300 Wh/kg and a 10 min cruise reserve, then the battery needs to sustain 217, 186, 199 and 283 kWh each mission 1, 2, 3 and 4, respectively. Mission 1 was chosen as the leading mission, because its energy needs are higher than mission 2 and 3 power needs, then an aircraft capable of mission 1 can also execute mission 2 and 3 worry free. Hence the following results are based on mission 1, except if mentioned otherwise.

The weight ratio distribution resulting from Mission 1, is as follows: 50% battery-to-MTOW, 25% payload-to-MTOW and 25% (empty without batteries)-to-MTOW, resulting in the operational-to-MTOW of 75%.

The electric engine choice was made considering 6 rotors for lift and OGE (on the wing) and 2 rotors for cruise (on the wing), resulting in 8 rotors each using an electric engine, hence 8 engines of the model MP240150 of the company Freerchobby are needed. Consequently, the total engine cost of 27 200 US$ and a weight of 128 kg.

A battery pack expecting to hold 2000 cycles (given each cycle allows the completion of one mission 1, meaning 3 trips) was designed according to the method [30] and used the cell Panasonic NCR18650GA as the starting point. Calculations assume a single charge range of 327 km according to the choice of mission 1 and a battery pack voltage of 500 V. The resulting battery package is made of 14 580 battery cells occupying around 0.256 m^3 and 722 kg, each cell costing 3.99 US$ (available at the LIION Wholesale online store) resulting in a battery pack cost of 58 175 US$, hence a cost of 269 US$ per kWh.

Aircraft measurements that result in the computational model shown in figure 2 were obtained following the methods presented by Gudmundsson [18] and Raymer [26] along with iterations from balancing trade-offs. The fuselage resembles a drop of water. The resulting aircraft has a wingspan of 9 m (occupying around 3 car parking spots) with a wing dihedral angle of 5° and a wing tip twist of 3° and a V-tail with 3 m of span with a dihedral angle of 45° without tip twist. The aircraft is 6.13 m long, 9.00 m wide and 2.72 m high. The passengers' cabin is 1.60 m long, 1.40 m wide and 1.76 in height. The cabin considers 4 passengers, 2 in the front and 2 in the back. When considering the nose of the aircraft the center of the referential, the high-wing starts at 1.14 m and the v-tail at 4.70 m.

The design team has chosen to use propellers with rotors as their efficiency has been widely studied and improved through time, its current value is 82.3% [29]. To convert power into the Thrust-to-MTOW [Newton/Newton] force ratio the designed team used the much used formula of a propeller engine. The rotors used have a Mach tip of 0.3 and a radius of 0.4 meters, following the same characteristics as Brown rotors [15]. The chosen propeller blade is the "Ultra Prop II" (from the company Ultraprops) made of solid carbon fiber composite costing 350 US$ each mounting set with a weight of 2.7 kg. Hence, the total propeller costs amounts to 2800 US$ and total weight of 21.6 kg, considering one set of blades per rotor. The lift rotors dispose shutters to be closed during cruise flight, reducing considerably the associated drag; such rotors can also be used for lateral stability.

The aircraft systems' weight distribution followed Raymer's method [26] and the results are presented in table 2 after they were optimised to ensure that the payload, batteries, engine and propellers weight was accurate. Nevertheless, Gudmundsson [18] formulas were assessed for comparison.

Table 2: Total weight distribution according to Raymer historic-based formulas [26] but with a correction factor to suit the weight ratios for mission 1.

Part of the Aircraft	[kg]	Part of the Aircraft	[kg]	Part of the Aircraft	[kg]
Batteries & Engine & Propellers	871.8	Avionics	43.3	Landing Gear	9.3
Payload	360.0	Wing	14.2	V-Tail	3.8
Electrical	63.8	Furnishings	11.5	Flight Controls	1.3
Fuselage	44.2	Air conditioning & Anti-ice	10.5	Hydraulics	0.3
Total [kg]					
1434.0					

The lateral stability was not deeply investigated as it is highly related to the rotor speed, as by changing the speed of each rotor independently some maneuvers may be induced or corrected. On the other hand, to assess longitudinal stability the following was considered: each passenger weights 80 kg and carries a cargo of 10 kg; passengers are divide on the x-axis (longitudinal) in groups of 2, hence, from no passengers to full capacity there are only 9 seat configurations (in reality, there is 2 seats in the front row and 2 seats in the back row); cargo is always carried inside the luggage cabin behind the passengers' cabin; batteries are divided into four packs all placed under the passengers' cabin; engines weights are placed in the wings and elevators and the landing gear is placed under the passengers' cabin. At last, the longitudinal investigation resulted in Static Margin (SM) range from 6.6% to 18.5%, when 2 passengers sit at the back and 2 at the front, respectively. Empty and MTOW flight SM's are 9.7% and 14.7% and should range from 5-15% regarding Mean Aerodynamic Chord (MAC), according to Vural [31], despite the aircraft still being manoeuvrable for SM up to 25%. The acceptable values of SM are still under discussion within the aircraft industry.

3.6. Experimenting with battery density of 400 Wh/kg

Moore and Fredericks [13] believe that a battery specific energy density of 400 Wh/kg is sufficient to enable meaningful results. Hence, the present section presents the comparison of results obtained when using such battery energy density and a 300 Wh/kg (the one used throughout the whole project). The resulting values are expected to be substantially better (from the previous section) except for the static margin, which the design team expects to be similar.

Mission power needs presented do not change because the battery density is not a variable in such equations. The battery density is only accounted for battery weight calculations. Thus, the choice of engines and propellers is also not influenced as it is based on both power needs and number of rotors for each mission stage.

Regarding the weight ratio, there is a decrease of 24% of battery-to-MTOW ratio comparing to ratio to the previously presented, reducing from 722 to 542 kg. considering the constant MTOW of 1434 kg, these results allow for a smaller battery pack, a higher empty-to-MTOW ratio and more realistic weight distribution. The aircraft dimensions would remain essentially the same at this project stage

Following the same methodology as before [30], the battery cost is reduced in 25% dropping from 58.2k US$ to 43.7k US$ if the single battery cell has a nominal voltage of 4.5 V and a minimum nominal capacity of 4.4 Ah. There is a decrease of 25% in the the number of battery cells used (from 14,580 to 10,940) which results in the same percentage of decrease of volume (from 0.256 to 0.192 m^3). To state that these batteries are nowhere close to reach the market, some literature points such availability after 2025, consequently using this battery energy density would not comply with the requirement of having the aircraft market ready by 2024.

Regarding the aircraft stability. The same study as explained in the previous section was performed and the results obtained reveal a horizontal translation of 6.9% to the left, meaning a decrease in stability. With the present analyses, the stability range is (-0.1%)-11.7% which is not totally within the preferred range of 5%-15% in accordance with Vural [31]. To better assess stability one may extensively specify weight positioning.

Environmental, aeroacoustics and operational costs analyses presented in chapter 4 do not see any change as none of them depends directly from the battery energy density as it explained in such chapter but rather from the mission profile energy needs.

4. Brief Aeroacoustic, Environmental and Cost Analyses

4.1. Acoustics Analyses

Noise estimations followed Brown and Harris [15] and Afonso et al. [29]. The model only considers two semi-empirical models: rotational (by Gutin [32] and Deming [33]) and vortex noise (by Schlegel et al.[34] and Marte and Kurtz [35]). These two contributions are summed up in a logarithmic scale.

The model has as major inputs the number of blades per rotor (two), the rotor radius of 0.4 m, the rotor solidity of 0.2 ([29], [15]), the Mach at the blade tip of 0.3 ([29], [15]), the thickness-to-chord ratio of 0.12 ([29], [15]), the number of rotors used for lift (six) and, for the rotational noise specially, estimations were made for OGE flight considering an observer at a distance of 250 ft, 500 ft and 1635 ft (or 500 m), the first two being from Uber [1] and section 3.1 and the third being the cruise altitude.

The resulting noise estimations using the aeroacoustics model mentioned were not as good as expected. Hence the performance of a sensibility analyses, which results are as follows: reducing hover OGE power needs by 100 kW, adding one lift rotor and increasing the radius in 0.05 m all have approximately the same positive effect of reducing noise by 1.0 dB SPL, 0.7 dB SPL and 1.0 dB SPL, respectively; using 3 blades rather than 2 blades per rotor causes a decrease of 5.5 dB SPL. Given the

high variation of noise due to the increase of the number of blades per rotor and that doing so does not influence any other field of the current project, the design team has decided to use a 3-blade rotor rather than a 2-blade rotor. Then, noise estimation of the aircraft is as follows:

- 80.6 dB SPL for an observer at 250 ft, being equivalent to standing next to an alarm clock [36];
- 74.6 dB SPL for an observer at 500 ft, being equivalent to standing next to a dishwasher [36];
- 64.3 dB SPL for an observer at 1635 ft, being equivalent to standing next an air conditioner [36].

The estimations show that though Uber [1] and project requirements (section 3.1) are not met, they are close to being achieved for an observer at 500 ft. At a distance of 250 ft, hearing impairment occurs if there is a permanent sound exposure much higher than 16 hours [37], on the other hand, for a distance of 500 ft or 1635 ft the noise is considered "moderate to quiet" [38] which does not cause any hearing impairment.

According to the Helicopter Association International (HAI), helicopter noise perception ranges from 87-78 dB when in heights from 500-1000 ft [39], which is the same as standing next to a working washing machine [37] to riding the subway or a motorcycle, respectively [37]. Comparing to those values, the range of decibels SPL of 74.6-68.6 obtained for the current solution, from the altitude range of 500-1000 ft respectively, is appealing and seems to be harmless to humans [40] when being used for frequent riders if the passengers show preventive behaviour.

4.2. Environmental Analyses

According to Afonso et al. [29], Methane and dinitrogen monoxide are also contributors to the greenhouse effect and are expressed as kg CO_2eq through characterization factors assessing their relative impact to climate change. The environmental impact estimation presented as follows is assessed using a metric for Global Warming Potential (GWP) of the Life Cycle Assessment (LCA), the kilogram of carbon dioxide equivalent per functional unit (kgCO_2eq), as stated by Afonso et al. [29]. The most extensively used metric is GWP, being mentioned in most of the LCA articles and papers, to address the carbon foot-printing [41]. Equation 1 follows the methodology presented by Afonso et.al [29] which computed the GWP through the "ReCiPe Midpoint/Endpoint (H) V1.11 / Europe Recipe H method with the support of LCA software (SimaPro) and the Eco Invent database". The production and End-Of-Life (EOL) of the battery emission constant values are in accordance to Zackrisson et al. [42].

$$\begin{aligned} Emissions_{total} &= Emission_{Production} + Emission_{Battery\ Use} + Emission_{EOL} \\ &= \frac{Energy_{battery}}{1000} * [Battery_{Production} + Electric_{mix} * N_{cycles} + Battery_{EOL}] \end{aligned} \tag{1}$$

The input considered an electric mix of 13[1] gCO_2eq/kWh [43], a battery production of 148480[2] gCO_2eq/kWh [42] and a battery EOL of 97 gCO_2eq/kWh [42] and the mission 1 power need of 217 kWh. Consequently, the results show a production and EOL emission of 5.633 tons CO_2eq. and a battery lifetime (2000 cycles) of 32.190 tons CO_2eq, summing up to a total of 37.82 tons CO_2eq for each battery pack used.

Such results generate the emission of 87 gCO_2eq/(kWh). In reality there are no operational emissions as the aircraft is fully electric, nevertheless the design team choose the presented approach of diluting the emissions. Hence one trip of mission 1 emits to the atmosphere around 6.3 kgCO_2eq. Considering mission 1 lasts for 63 min plus the 10-minute reserve, thus follows a pollutants emission of 15.5kg CO_2eq/h.

These pollutant emissions result 85% from the energy used to recharge batteries, hence this "operational emission" may be reduced to approximately zero if the batteries are charged with totally green electricity instead of electricity produced by transforming fossil fuel. In reality, there are no operational emissions given the aircraft is fully electric.

The widely used Cessna 172 Skyhawk, which is a 4-seat aircraft, is part of the GA family and it is estimated to emit around 75 kgCO_2/h [45]. The UAM solution presents a 79% decrease in CO_2eq when compared to Cessna 172 Skyhawk. Despite being theoretical, this result leads the reader to believe the current UAM solution being developed pollutes much less than the homologous solution presented by the conventional GA industry. Nevertheless, further assessment is needed to validate the presented data and confirm these estimations. Also, the industry needs further assessment of the life-cycle of Li-ion batteries because it is still not clear if the zero operational emissions allow to overcome or not their heavily polluting production and disposal processes.

4.3. Cost Analyses

There are several methods to estimate operational cost, each with their own benefits and disadvantages. The author decided to articulate several methods and showcase the results in table 3: Brown and Harris [15] consider the deadhead mission (mission without payload to relocate aircraft), Gudmundsson [18] is made for conventional GA and Ploetner et al. [46] is electric-powered focused. The costs considered are based on the heavily studied costs of GA, resulting in a method that considers the following costs:

$$C_{total} = C_{AP} + C_{Storage} + C_{Command\ Controller} + C_{Energy} + C_{Insurance} + C_{Overhaul} + C_{Investment} \tag{2}$$

[1]The method used considered the electricity mix of 13 gCO_2eq/kWh [43] from Sweden in 2016, which may be considered a highly optimistic value considering the European average of 296 gCO_2eq/kWh [43] by 2016. Nevertheless, the aircraft is due to 2024, hence the global European average is expected to dramatically decrease given all the investments being made into greener sources of energy.

[2]Resulting from an average of the values presented by Zackrisson et al. [44].

Energy costs are of major importance and are highly related with power needs. Charging times used for energy cost calculations considered Tesla V3 Supercharger, commercially available since 2019, because it provides a peak power rate of 250 kW per car [47] resulting in the charging times presented.

Follows an enlightenment to better understand the missions considered for cost estimation:

- Mission 1 - Considering MTOW of 1434 kg and a mission energy need of 217 kWh, then follows a 63-minute mission split into 3 trips, each with 67 km. The battery charging time for Mission 1 is 58 minutes. This represents a charging-to-flight time ratio of 82%, therefore, for every minute of flight the aircraft has to stop 50 seconds to charge.
- Mission Deadhead - Without any payload and zero time for boarding and unloading and a mission energy need of 118 kWh, then follows a 28-minute mission split into 3 trips, each with 33 km. The battery charging time for Mission Deadhead is 28 minutes. This represents a charging-to-flight time ratio of 100%, therefore, for every minute of flight the aircraft has to stop one minute to charge.

The daily flight window considered is from midnight to 7 a.m. considering that in such time window the aircraft does not fly for 1.7 hours because there are no clientele, hence the model does not consider the case of the maximum daily operations possible. Regardless of the number of missions to be performed each day of the week, two of them are always deadhead missions. Also, from Friday to Sunday there is one more mission than from Monday to Thursday, as there is usually more Uber rides during the weekends. The yearlong operation is possible because the aircraft is autonomous, thus, the cost model only accounts for 3 weeks a year of non-operation for maintenance purposes. Consequently, the yearly operation of 2652 hours.

With the hours of aircraft usage and the charging and mission times explained above, it is possible to estimate the the cost of all the energy being used to charge the aircraft using equation 3 that considers the different energy needs of mission 1 and deadhead mission. Using the average price of electricity [48] 0.13 $/kWh, a charging-to-flight hours ratio of 84% (equivalent to 2233 yearly hours of charging) then follows an yearly energy cost of 73 642 US$.

$$\frac{C_{Energy}}{year} = \frac{\$}{kWh}\frac{Weeks}{year}\Big[(Days * Number_{Mission_1})_{Friday\ to\ Sunday}\, Energy_{Mission_1} \tag{3}$$

$$+ (Days * Number_{Mission_1})_{Monday\ to\ Thursday}\, Energy_{Mission_1} \tag{4}$$

$$+ (Days * Number_{Mission_{Deadhead}})_{Weekly}\, Energy_{Mission_{Deadhead}}\Big] \tag{5}$$

The acquisition price of the aircraft was calculated using the empty weight cost approximation of 772 $/kg [15], given the empty weight of the current project being 1 074 kg then the overall cost of the aircraft is estimated to be 828 686 US$. The designing team considered the payment of the aircraft in 10 years with an interest rate of 7,5% [49] to estimate the acquisition investment cost of 120 728 US$. The acquisition price of the aircraft is around 2,8 times the highest expected value by Uber [1].

Gudmundsson [18] only insures 1.5% of the aircraft, such value is for GA commonly used aircraft. Given the higher risk associated to the implementation of new technologies, this percentage should be higher, the author decided upon 2.5% and used the formulation of Gudmundsson [18] as follows in equation 6. Such equation considers the fixed price of 500 US$ to begin with. In the end, the yearly insurance cost of each aircraft amounts to 21 217 $.

$$C_{Insurance} = 500 + 0.025 * C_{Acquisition} \tag{6}$$

Following the method presented by Gudmundsson [18] the cost of 179 158 US$ AP (Airframe and Powerplant) can be estimated using equation 7. The cost of a battery pack is 58 175 US$ as explained in section 3.5 where is stated that each battery cycle suits the needs of mission 1. For redundancy purposes, the calculation of AP costs considered that the completion of a deadhead mission uses a full cycle as well. Both the maintenance man-hours per flight hour (MF) considered of 0.6, though the author believes it is conservative, and the hourly rate for a certified AP mechanic of 60 US$/h are in accordance to Brown and Harris [15]

$$C_{AP} = MF * \frac{Man\ \$}{h}\frac{hours\ of\ flight}{year} + \frac{Missions_{yearly}}{Battery\ Life\ Cycle}\frac{\$}{Battery\ Pack} \tag{7}$$

The estimation of a command and controller pilot cost to be sat at the vertiport controlling 8 aircraft, according to Brown and Harris [15], was done following equation 8 and amounts to 23 204 US$.

$$\begin{aligned}\frac{C_{Command+Controller}}{year} =& \frac{Man_{hour\ \$}}{kWh}\frac{Weeks}{year}\Big[(Days * Number_{Mission_1})_{Friday\ to\ Sunday}\, Hour_{Mission_1} \\ &+ (Days * Number_{Mission_1})_{Monday\ to\ Thursday}\, Hour_{Mission_1} \\ &+ (Days * Number_{Mission_{Deadhead}})_{Weekly}\, Hour_{Mission_{Deadhead}}\Big]\end{aligned} \tag{8}$$

Storage costs consider 86 000 US$ yearly for a place in a vertiport, according to Uber [1], including lease fees, maintenance, security personnel and support. The overhaul yearly cost of 90 000 US$ considered is in accordance with Uber [1].

Finally, all the costs are summarized in table 3 where it is showcased the operational hourly cost of 224 US$. To note that for each minute of flight the aircraft needs to charge for 50 seconds, representing an overall flight-to-charge hourly ratio of 84%. Energy accounts for 12% being lower than value of 15% set in the requirements in section 3.1. The cost of AP is high because the aircraft needs 1.4 battery pack renovation each year, meaning having to pay for an entire pack at least once a year. AP, energy and command controller are highly dependant hours of operation a year, therefore, if increasing or decreasing the hours of operation these costs will also increase or decrease, respectively.

Table 3: Subtotals of the yearly costs considered as well as overall charging to flight time ratio and hourly operational cost.

	Acquisition Airplane Value	$ 828 686	
Yearly Cost Breakdown	Cost of Airframe and Powerplant (AP)	$ 179 594	30%
	Cost of Airplane Acquisition Investment	$ 120 728	20%
	Cost of Overhaul	$ 90 000	15%
	Cost of Storage	$ 86 000	14%
	Cost of Energy	$ 73 677	12%
	Cost of Command Controller	$ 23 204	4%
	Cost of Insurance	$ 21 217	4%
	Total Yearly Cost	$ 594 420	100%
	Yearly Operating Hours	2652	
	Hourly Operational Cost	$ 224	

Section 3.5 presented the battery design to suit mission 1 needs, given mission 1 and 2 could be achieved as well as. Hence, a 21-minutes 67 km trip of mission 1 costs 79 US$, with an equivalent cost of 1.18 $/km and the higher the range the lower the price. The 28-minutes 100 km trip of mission 2 costs 105 US$ with an equivalent cost of 1.05 $/km and a 68-minutes 290 km of mission 3 costs 253 US$ with an equivalent cost of 0.87 $/km This results from the fact that mission 2 and 3 have higher range due to lower number of trips.

There was an utter care in the formulation of the problem and values considered in the model. Considering the cost of 224 US$/hour the base value of the following results are a comparison to such case:

- using the maintenance man-hour ratio of 3.5 commonly used for helicopters [50], then the operational costs is 398 US$/hour, representing an increase of 78%;
- using the maintenance man-hour ratio of 0.2, resulting from Gudmundsson [18], then the operational costs is 200 US$/hour, representing a decrease of 11%;
- removing the 1.7 hours daily ban, explained above, the operation costs are reduced to 211 US$/hour, representing a decrease of 6%;
- keeping operation 24h/day, the operation cost is 177 US$/hour, representing a decrease of 21%;
- a piloted version of the aircraft would make the costs increase by 27%.

Comparing the results to Uber desired estimated pricing for initial operation in San Francisco, Sao Paulo and New Dehli [1], though Uber does not clearly defines "initial" operation window, there is a profit margin of 25% for all cities. Uber desires to operate UAM vehicles by 2023 [1] and the current solution would only be made available in 2024 therefore it may not included in the initial period of operation.

5. Concluding Remarks

After conducting several extensive and thorough research and analyses of the UAM market, constraints, stability, acoustics, environment and costs the resulting proposal is a lift-plus-cruise solution with MTOW of 1434 kg with an overall emission of the aircraft of 87 gCO_2eq/(kWh) and producing 74.6 dB SPL for an observer standing 500 ft apart from the aircraft.

All in all, the overall results point to solutions like the one proposed by the current document as the way forward. Nevertheless, there are some points to consider:

- the batteries-to-MTOW ratio is much higher than initially estimated resulting in inaccurate weight distribution;
- the all-electric aircraft designed has OGE and climb energy needs are 5.7-times and 7.0-times higher than cruise energy needs, respectively. Therefore, hybrid aircraft, using batteries for OGE and climb and conventional engines for the cruise, are also to be considered by the industry;
- noise and environmental estimations are theoretical and use helicopter related historical data;
- a fully autonomous aircraft presents a low TRL, hence it would need to be adapted to be initially piloted if to be sold in 2024 and the operational costs would increase 27% due to the cost of pilot;
- and the battery density of 400 Wh/kg provides better overall results, as expected.

References

[1] J. Holden and N. Goel, "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," 10 2016. [Online]. Available: http://inrix.com/scorecard/

[2] "UAM Insight: 23 January 2020: $1B Investment in UAM Already in 2020 AirInsight," accessed: 2020-01-31. [Online]. Available: https://rb.gy/kzxw6p

[3] F. Colucci, "Turning Volts to VTOL," *Vertiflite*, p. 4, 1 2018.

[4] C. Baraniuk, "The largest electric plane ever to fly," accessed: 2020-06-18. [Online]. Available: https://rb.gy/qd2tgr

[5] D. P. Thipphavong and et al., "Urban Air Mobility Airspace Integration Concepts and Considerations," in *2018 Aviation Technology, Integration, and Operations Conference*, Atlanta, Georgia, 6 2018.

[6] X. Zhang, "The Future of Transportation: White Paper on Urban Air Mobility Systems by EHang," 12 2020.

[7] "Electric planes are the future of aviation, but they haven't taken off - Business Insider," accessed: 2020-07-28. [Online]. Available: https://rb.gy/i3ndin

[8] "Low-cost helicopters, a growing transport segment in Sao Paulo — Business — English edition — Agencia EFE," accessed: 2020-08-09. [Online]. Available: https://bit.ly/3oeVwG8

[9] "São Paulo: the world's biggest helicopter fleet Latin America Bureau," accessed: 2020-03-17. [Online]. Available: https://rb.gy/skkcjq

[10] J. Wood, "Top 10 causes of fatal GA accidents," 6 2019, accessed: 2020-03-30. [Online]. Available: https://rb.gy/yi65f6

[11] "eVTOL Aircraft Directory," accessed: 2020-09-09. [Online]. Available: https://evtol.news/aircraft

[12] A. Sinkevicius and et al., "Flying Cars: Investment Implications of Autonomous Urban Air Mobility," p. 85, 12 2018.

[13] M. D. Moore, "Misconceptions of Electric Aircraft and their Emerging Aviation Markets," in *52nd Aerospace Sciences Meeting*, National Harbor, Maryland, 1 2014.

[14] "Module 6 - Battery - Drona Aviation," accessed: 2020-09-09. [Online]. Available: https://bit.ly/3klckJ0

[15] A. Brown and W. Harris, "A Vehicle Design and Optimization Model for On-Demand Aviation," in *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Kissimmee, Florida, 1 2018.

[16] Booz, Allen, and Hamilton, "UAM Market Study - Technical Out Brief," 10 2018, accessed: 2020-08-13. [Online]. Available: https://rb.gy/tazjcj

[17] N. Hosseini and et al., "UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems," p. 10, 2019.

[18] S. Gudmundsson, *General Aviation Aircraft Design: Applied Methods and Procedures*, 2014.

[19] "Volocopter publishes white paper on urban air mobility," accessed: 2020-03-01. [Online]. Available: https://rb.gy/wicyh8

[20] A. Ivanenko, "HyPoint Technical White Paper," 4 2020.

[21] C. B. Courtin and R. J. Hansman, "MODEL DEVELOPMENT FOR A COMPARISON OF VTOL AND STOL ELECTRIC AIRCRAFT USING GEOMETRIC PROGRAMMING," 2019.

[22] FAA, "CFR - Visual Flight Rules," 2012.

[23] "Federal Aviation Regulation Sec. 23.25 - Weight limits." accessed: 2020-08-31. [Online]. Available: https://rb.gy/d30bac

[24] A. J. Hawkins, "Kitty Hawk says its third electric aircraft has a 100-mile range," 10 2019, accessed: 2020-04-1. [Online]. Available: https://bit.ly/35jxRf3

[25] "Technology Readiness Level — NASA," accessed: 2020-08-27. [Online]. Available: https://go.nasa.gov/37AZByi

[26] D. P. Raymer and American Institute of Aeronautics and Astronautics., *Aircraft design : a conceptual approach.* AIAA, 1989.

[27] D. Raymer, *Aircraft Design: A Conceptual Approach, Sixth Edition and RDSwin Student SET.* American Institute of Aeronautics and Astronautics, Inc., 1 2019.

[28] L. M. Nicolai and G. E. Carichner, *Fundamentals of Aircraft and Airship Design.* American Institute of Aeronautics and Astronautics, 1 2010.

[29] F. Afonso, A. Ferreira, I. Ribeiro, F. Lau, and A. Suleman, "On the design of environmentally sustainable aircraft for urban air mobility," 2020.

[30] R. Schröder and et al., "Comparatively Assessing different Shapes of Lithium-ion Battery Cells," *Procedia Manufacturing*, vol. 8, pp. 104–111, 2017.

[31] "STATIC PITCH STABILITY of an AIRPLANE," accessed: 2020-09-01. [Online]. Available: https://bit.ly/3jfao3r

[32] L. Gutin, "On the sound field of a rotating propeller," NACA, Tech. Rep., 10 1948.

[33] A. F. Deming, "Propeller rotation noise due to torque and thrust," NACA, Tech. Rep., 1 1940.

[34] R. Schlegel and et al., "Helicopter rotor noise generation and propagation," US Army Aviation Material Laboratories, Fort Eustis, VA, USA, Tech. Rep., 10 1966.

[35] J. E. Marte and D. W. Kurtz, "A review of aerodynamic noise from propellers, rotors, and lift fans," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, Tech. Rep., 1 1970.

[36] Chris, "Levels Of Noise In Decibels (dB) Level Comparison Chart," accessed: 2020-10-12. [Online]. Available: https://bit.ly/37xU7ED

[37] "Decibels Explained — TLC Electrical," accessed: 2020-09-21. [Online]. Available: https://bit.ly/3ohdRlN

[38] H. Xu, "Ad Noise Prediction of a NACA 0015 Airfoil with Gurney Flap A study based on Time-Resolved Particle Image Velocimetry," 1 2015.

[39] "Helicopter Noise," accessed: 2020-09-19. [Online]. Available: https://bit.ly/3kniDvY

[40] "Human Auditory Range," accessed: 2020-09-28. [Online]. Available: http://www.cochlea.org/en/hear/human-auditory-range

[41] N. Jungbluth and C. Meili, "Recommendations for calculation of the global warming potential of aviation including the radiative forcing index," *The International Journal of Life Cycle Assessment*, vol. 24, pp. 401–411, 2019.

[42] M. Zackrisson and et al., "Life cycle assessment of lithium-air battery cells," *Journal of Cleaner Production*, pp. 299–311, 6 2016.

[43] "Overview of electricity production and use in Europe — European Environment Agency," accessed: 2020-09-28. [Online]. Available: https://bit.ly/3mctBoC

[44] M. Zackrisson and et al., "Life cycle assessment of lithium-air battery cells," *Journal of Cleaner Production*, vol. 135, pp. 436–443, 6 2016.

[45] "cessna 172 — Communicate Science," accessed: 2020-09-19. [Online]. Available: https://bit.ly/31vLNBx

[46] K. O. Ploetner and et al., "Operating cost estimation for electric-powered transport aircraft," in *2013 Aviation Technology, Integration, and Operations Conference.*

[47] "Introducing V3 Supercharging — Tesla," accessed: 2020-15-09. [Online]. Available: https://bit.ly/2HlhLcu

[48] "Electricity Rates by State (Updated April 2020) – Electric Choice," accessed: 2020-16-09. [Online]. Available: https://rb.gy/mx9xcf

[49] "Sample Aircraft Loan Rates - Aviation Finance — AOPA," accessed: 2020-09-15. [Online]. Available: https://rb.gy/vhayf2

[50] "Rotary Aircraft," accessed: 2020-09-16. [Online]. Available: https://bit.ly/3dN9ZnP