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Life Cycle Engineering Modelling Framework for batteries powering electric aircrafts – the contribution of eVTOLs towards a more sustainable urban mobility

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Abstract

The aviation industry is increasingly facing the challenge posed by climate change. Alongside the aviation sector, advances in aircraft design and electric propulsion towards sustainability have also emerged in new segments of transportation, the urban air mobility, which has arisen to address the road traffic congestion challenges particularly faced in megacities. Within this new mode of mobility, electric vertical takeoff and landing aircrafts (eVTOLs) have gained interest as a solution for on-demand services, including passenger, cargo transportation, as well as rescue and air ambulances. In this regard, batteries are seen as one of the essential technologies towards decarbonizing the mobility sector. Even though studies have indicated the potential of eVTOLs to enable longer travel distances with significant time savings in comparison with battery electric vehicles (BEVs), the variability in terms of spatial, temporal and technological aspects needs to be addressed in order to assess in how far battery-powered eVTOLs will in fact contribute to a more sustainable urban mobility. Based on a modelling framework of the Life Cycle Engineering (LCE) of future aircraft technologies, this paper investigates the factors contributing to the variability of the environmental assessment results, revealing the inherent complexities of modelling emerging technologies. By simulating different scenarios for the battery operation in eVTOLs and BEVs around the world, a case study demostrates the applicability of the LCE framework in urban and regional application contexts.

Keywords: Life Cycle Engineering; aviation; eVTOLs

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1. Introduction

In a context of growing mobility demand and increasing pressure towards more efficient technologies and business models, strategies for improving the sustainability of the private road transportation sector have arisen. Battery electric vehicles (BEVs) are seen in this context as an essential technology towards decarbonizing the mobility sector. BEVs do not only not produce tailpipe emissions but also their power train efficiency is significantly higher than in internal combustion engine vehicles [1]. In this regard, traction battery systems are an essential technology as BEVs rely solely on these devices to store the energy required for a trip. In addition to passenger electric cars, new forms of mobility technologies ranging from micro-mobility (e.g. electric scooters, electric bikes) to long distances (e.g. ride-hailing and car sharing) have emerged. However, in order to overcome the limitation of congestion on roads, land-use constraints [2], and decrease

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commute times [3], urban air mobility (UAM) is recently attracting interest. Electric vertical takeoff and landing aircrafts (eVTOLs) are able to takeoff and land without the need of a runway and, combined with an efficient aerodynamic flight of an airplane, can bring significant time savings in comparison with ground vehicles [4]. However, in order to enable eVTOLs operation in urban areas, a distributed network of the so-called “vertiports” for takeoff and landing as well as charging infrastructure is needed [5].

Figure 1 illustrates two transportation options of going from point A to B: BEVs or eVTOLs. As travelling by car involves following a limited number of fixed routes, travellers can be exposed to long delays in case of a single interruption [5]. In contrast, by travelling with an eVTOL, as it travels toward the destination along the shortest path and without the limitation of congestion on roads, significant time savings can be expected. However, since eVTOLs need an infrastructure to operate, the variable distance and time spent for going from A to the closest vertiport in the city, as well as from the landing vertiport to B, would need to be computed. In contrast to eVTOLs, BEVs are subject to heavy traffic areas, which influences the energy consumption, given by the auxiliaries and traction. In eVTOLs, hover phases (takeoff and landing) correspond to the highest power requirement relative to the flight duration, followed by climb and cruise. Compared with BEVs, eVTOL batteries have significantly different operating profiles and hence very strict requirements (e.g. high specific energy and power, fast charging, long cycle life and safety) [6]. Given the many technological factors involved and the still scarce research on the topic, a direct comparison is rather challenging.

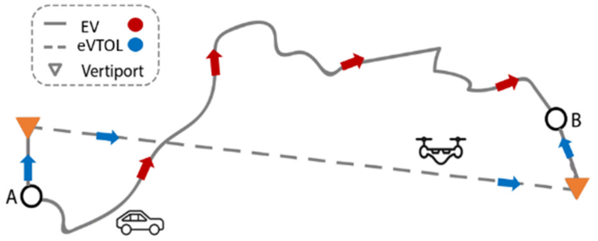

Figure 1. Concept for analysis of the potential of batteries powering eVTOLs in terms of time saving and reduced environmental footprint in comparison with ground vehicles.

Still, in order to investigate the real implications of new technologies, an analysis beyond the use stage is necessary. With the aim of avoiding the shifting of burdens between life cycle stages and impact categories, engineering strategies must be developed based on a life cycle perspective [7]. In this way, given the fact that the electrification of the powertrain brings a high variability in the environmental impacts, tools and methodologies are needed to handle the modelling of complex product systems such as electric aircrafts, highly dependent on external factors.

In this regard, an application of integrated computational life cycle engineering (IC-LCE) approach gains increasing relevance as it reduces considerably the high modelling effort from life cycle assessment (LCA) [8] by coupling engineering models and combining a large number of technologies under regional and temporal contexts [9, 10]. This allows to find the most sustainable design over a large number of product systems and parameters and to determine the main influencing factors on the environmental impact, studying different scenarios under which flying shows an advantage over driving.

Research studies have been conducted on the potential and attractiveness of different eVTOL designs for UAM [11–13]. Yang et al. [6] have studied the challenges and the different requirements of batteries powering eVTOLs and EVs. Aspects such as the need of fast charging in passenger-swapping gaps, and of long battery cycle life are addressed. With the purpose of investigating whether eVTOLs outperform internal combustion engine vehicles (ICEV) and EVs, Kasliwal et al. [2] assessed the use stage burdens in terms of primary energy and greenhouse gas (GHG) emissions. For trips shorter than 35 km, due to high energy intensive hover phase, eVTOLs do not show an advantage over ICEV and EV. Analysing beyond the operation phase, including the environmental impacts from vehicle production, André and Hajek [14] demonstrated that with 21% of hover share and maximum seat utilization, eVTOLs would lead to higher environmental impact in comparison with EVs ranging from 160-80 gCO2e/km to 58g gCO2e/km, respectively due to the different electricity mixes considered in their study.

By providing a modelling framework for the LCE of batteries powering eVTOLs, this paper aims at studying their potential to reduce the environmental impact of urban mobility based on the concept presented in Figure 1. Even though research has addressed some influencing factors on the environmental impacts of eVTOLs, the variability of LCA results still needs to be explored. Thus, the focus of this study lies on the case study analyzing environmental burdens of batteries powering these vehicles against BEVs, considering their production and operation in several geographic locations around the world, with different grid carbon intensities and weather conditions for a large number of urban routes.

2. Life cycle engineering of emerging aircraft technologies

An environmental assessment that supports the engineering of future aircraft concepts requires systematic methods and a substantial number of data, serving as basis for modelling the background and foreground systems of complex product systems, such as aircrafts. Modelling requires data for describing the air traffic system, the vehicle, the surrounding

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conditions, and all involved technologies throughout the entire life cycle. While the foreground data relates to the system under analysis (e.g. battery-related data from measurements, simulations, calculations, referring to materials, components, processes [9]), the background data relates to the definition of scenarios, including technology development, regional specific data, electricity mix and geographical data.

Thus, when modelling the environmental burdens of future aircraft technologies in UAM, external factors need to be considered as they can strongly influence the LCA results. Alongside with geographical aspects (e.g. ambient temperature as function of the climate zone, topology, electricity mix), temporal aspects (e.g. ambient temperature as function of the daytime and season) influence the environmental impact of battery-powered vehicles. As addressed in [15], seasonal and daily use patterns together with ambient temperature, varying throughout the day and the year, influence the energy consumption for heating and cooling. Hence, the knowledge on the regional conditions and use pattern (e.g. when and for how long it is used) plays a role when assessing the environmental performance of battery-powered vehicles.

In comparison with EVs, battery-powered eVTOLs present a higher influence on the environmental impacts from technological aspects, particularly because of the weight limitation for aircraft applications, resulting in the need for high specific energy battery technologies. However, in terms of geographical and temporal aspects, topology does not have an influence on the burdens from eVTOLs, in contrast to BEVs, whereas the regional conditions and electricity mix are influencing factors on the environmental performance of both BEVs and eVTOLs.

In this regard, given the high variability of LCA results, which depends on technological, geographical and temporal factors, an LCA-based approach that supports the robust design of emerging technologies is introduced by Cerdas et al. [9, 10] to the case of BEVs. Transferring to the field of aviation, Melo et al. [16] present a framework for the modelling and assessment of sustainability aspects of future aviation technologies. Based on this framework, its applicability in the UAM context is demostrated through a case study on batteries powering eVTOLs.

3. Methodology

Figure 2 illustrates the LCE concept applied in this study to the UAM field. A model-based assessment of environmental impacts is proposed, benchmarking battery powering eVTOLs with BEVs. This concept is based on the IC-LCE approach introduced in [9, 10], coupling models associated to the foreground and background systems, handling the high variability of the LCA results, as previously addressed in Chapter 2.

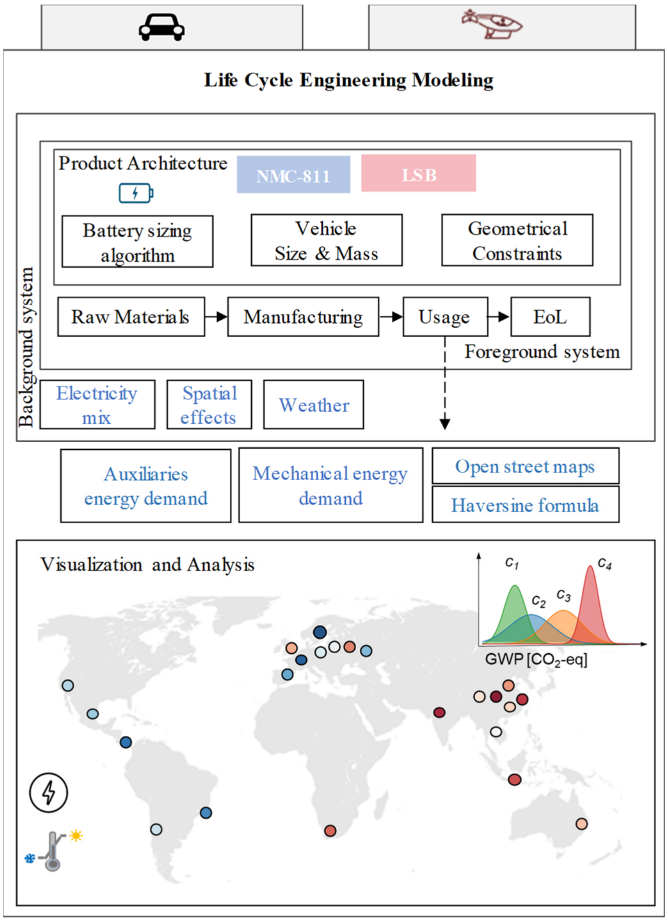


Figure 2. Life Cycle Engineering modelling approach applied to the field of urban air mobility.

The current anaylsis focuses on the battery system designed to power the vehicles. Given the findings related to the technical and environmental performance of the battery technologies assessed in [17] and [18], Nickel Manganese Cobalt Oxide (811-NMC) and Lithium-Sulfur (LSB) are the cell chemistries considered in this study. Each battery cell follows the geometry specifications of Samsung SDI-94. The state of the art specific energies (Wh/kg) at a cell level were retrieved from [17].

Firstly, in order to model the environmental impact of batteries powering eVTOLs, the power requirement for a given flight mission profile is calculated; hence the energy consumption per trip. The power requirement is modelled using a physics-based approach presented by Kasliwal et al. [2]. As described in [17], the flight mission profile consists of takeoff, climb, cruise, descent and landing, assuming 20% of battery's reserve capacity for emergencies.

The battery sizing algorithm follows the approach introduced in [17] to the case of eVTOLs. Since the power requirement is dependent on the aircraft takeoff mass, an initial battery capacity is estimated. The implemented model calculates the energy consumption over the flight period, verifying whether the battery's State of Charge (SoC) is below

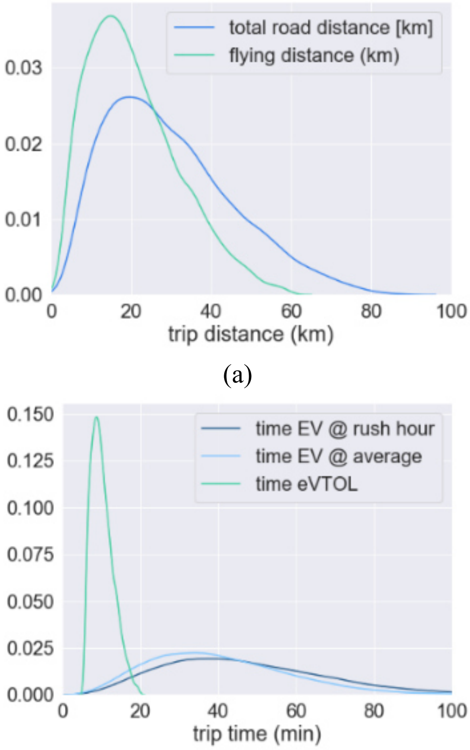
60% at the end of the mission (SoC_{end}), which corresponds to the aforementioned 20% of reserve for emergencies adding more 20% of reserve capacity for preserving battery's lifetime. Depending on the SoC_{end}, the model calculates the minimum capacity required to ensure a 40% of reserve at the end of the flight and a full hover power demanded by the electric motor. In this way, the size of the two battery chemistries analyzed are calculated for a maximum range of 100 km per charge.

Following the sizing of the battery system, the cradle-to-gate Global Warming Potential (GWP) impact of each battery cell chemistry produced is computed as described in [17], according to the findings from [9] and [19], assessing the environmental burdens for a given group of impact categories. Grid carbon intensities are taken from ecoinvent database and the total environmental impacts are calculated following a well-to-shaft analysis [14]. Additionally, in order to account for the lifetime aspect, which is associated with the maximum distance travelled before battery replacement, the number of life cycles are collected from the literature (NMC [14] and LSB [20]). A functional unit on a passenger-km displaced basis is chosen for analysis, addressing the influence of adding more passengers on the environmental burdens per km travelled.

As illustrated in Figure 2, the analysis includes batteries powering BEVs and eVTOLs in various cities around the world over a range of cruise distances, so that several routes starting from a certain location A to a location B were generated to build different context scenarios under which the vehicles operate. Ambient temperatures and electricity mixes are considered, which are regional influencing factors that play a role on the energy consumption in the use stage and on the environmental performance of BEVs. A total of 11305 routes in 24 different cities around the world were simulated using online services such as (https://openrouteservice.org/) and open street maps. A defined number of coordinates where randomly generated and placed within a bounding box in which a city is contained. The shortest path between two random points and other relevant information such as distance and average speed at a given time is then retrieved from online routing services. Cerdas [10] presents in detail the implemented models. In order to calculate the distance travelled with an eVTOL between locations, it is implemented the haversine formula.

4. Results and Discussion

From the generated routes, the benefit of shorter trip distances and time saving from travelling with eVTOLs can be demonstrated in Figure 3. From the illustrated probability distribution, the shifted curves show that shorter and faster trips are significantly more likely to occur by flying with eVTOLs. Despite the need of accessing or egressing the vertiports, which affects the total trip duration of eVTOLs also given the ground-based congestion, travel times with BEVs are significantly more affected by traffic congestion [3].



(a)

(b)

Figure 3. Probability distributions for trip distance (a) and trip time (b) for BEVs and eVTOLs.

Moreover, as addressed in Chapter 2, for the case of BEVs, the use of auxiliaries (heating or cooling) can lead to a high variability of LCA results under specific weather conditions. Figure 4 illustrates the variation of the total energy consumption for BEVs operating in the various cities under analysis, following the methodology implemented in [10].

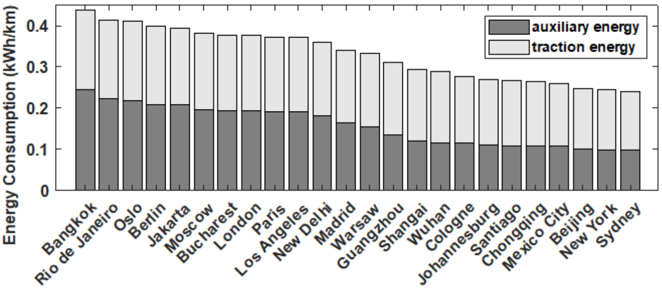


Figure 4. Average energy consumption (kWh/km) composed by auxiliary and traction energy for BEVs operating in 24 cities around the world.

Given the fact that the ambient temperature varies in function of the climate zone, as well as throughout the day and the year, the energy consumption for the auxilaries varies depending on the geographical and temporal aspects.

Further investigations are conducted on the variability of

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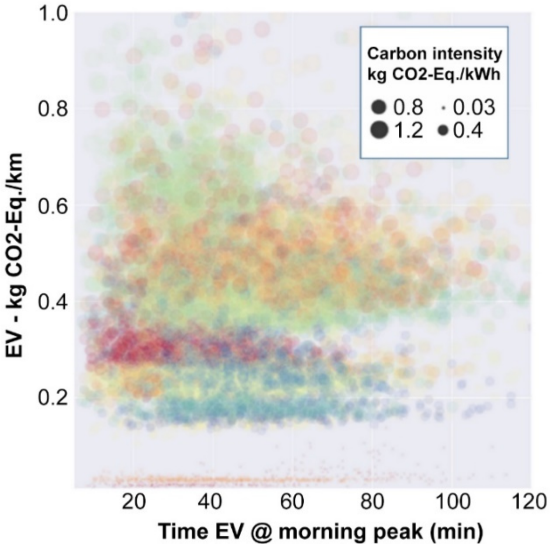
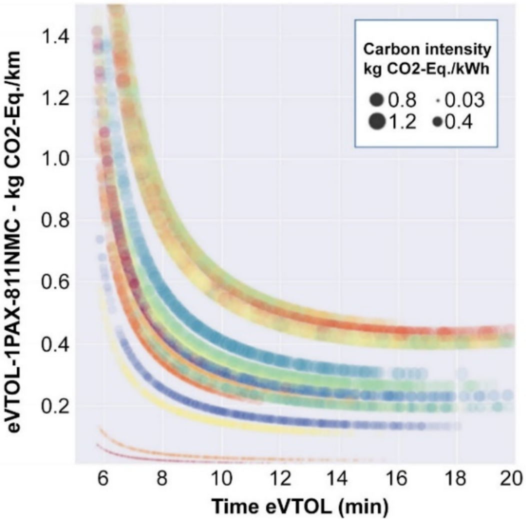
CO2-eq emissions for the large number of routes in the different geographic locations in which eVTOLs and BEVs operate. From the variability of results among the several simulated trips, Figure 5 (a) indicates the relevance of geographical and temporal aspects for BEVs; increasing the associated CO2-eq emissions per km-travelled as the carbon intensity (CO2-eq per kWh) increases (e.g. low impact for countries with cleaner grid carbon intensities). For eVTOLs, Figure 5 (b) shows the CO2-eq emissions per km-travelled considering 1 passenger (apart from the pilot) and 811-NMC technology over the duration of the flight.



(a)



(b)

Figure 5. Variability of GWP impact per unit of displacement (kg CO_2-eq/km) as a function of the trip time (a) BEV (b) eVTOL due to spatial aspects

It not only illustrates the influence of geographical aspects on the environmental impact, in terms of grid carbon intensity, but also the impact of amortizing the burden from the high energy intensive hover phase over the distance travelled (i.e. revealing the benefit of flying longer distances from an environmental perspective).

Alongside with geographical and temporal aspects, the impact of technology (e.g. weight, battery technology etc.) on the environmental burdens is assessed. From Figure 6, two aspects can be observed. First, the benefit of adding more passengers to the trip, redistributing the burdens. Second, the benefit of powering eVTOLs with higher specific energy battery chemistries (e.g. LSB). Thus, the lower CO2-eq emissions per passenger-km travelled are likely to occur for LSBs with a seat utilization of 4 (3 passengers + pilot).

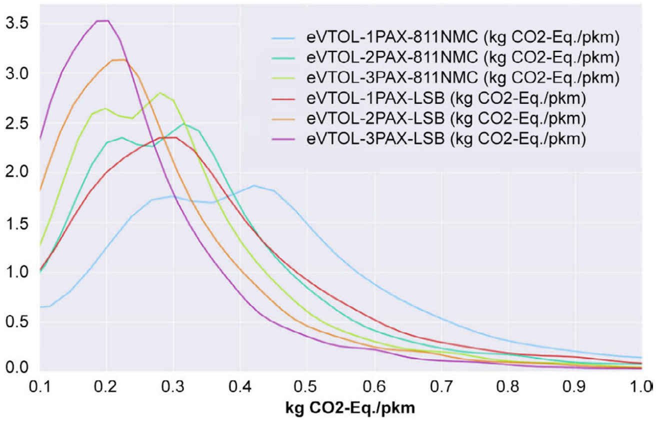


Figure 6. Probability distributions for CO2-eq emissions per passenger-km displaced (pkm).

Finally, by computing the CO2-eq emissions per km-travelled with respect to lifetime distance travelled for Germany (DE), China (CN) and Norway (NO), Figure 7 shows a lower impact for eVTOLs operating in Norway with LSB and 3 passengers. This results from a combination of lower grid carbon intensity with higher specific energy battery technology and a higher seat utilization. On the other hand, the highest environmental impact comes from NMC batteries powering eVTOLs with low occupancy in China, since most of its electricity comes from coal. Additionally, the amortization of the impacts from battery production over the battery's lifetime is revealed.

However, even though LSB are associated with lower environmental burdens, the shorter lifetime plays an important role on the feasibility of LSB against NMC, as it achieves its end of life (EoL) well before than NMC, having to be replaced. Most importantly, it is revealed a strong influence of the country of operation (i.e. the share of renewables on the electricity mix) on the environmental impact. Figure 7 also illustrates the 2020 regulation goal for road passenger cars (95g CO2-eq per km) and shows that a NMC battery operating in Norway with 2 passengers on-board would achieve this target before its replacement. Given ongoing improvements in battery lifetime, fast-charging ability and enhanced specific energy [6], a more viable scenario for eVTOLs can be expected in future.

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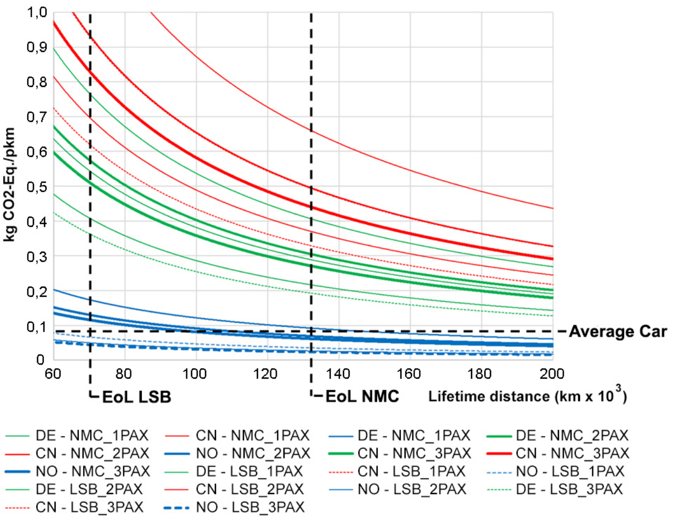

Figure 7. GHG emissions in kg CO2-eq/km over lifetime distance. The maximum distance achieved by LSB and NMC over time before replacement is indicated with vertical lines. “Average car” stands for a regulation target for passenger cars.

5. Conclusions and outlook

This paper introduced a modelling framework for the LCE of batteries powering future flying vehicles. Aiming to assess the potential of eVTOLs to reduce the environmental impact of urban mobility, a model-based assessment is conducted, comparing the environmental impacts from batteries powering eVTOLs with BEVs. A large number of routes in 24 cities around the world were simulated, building different scenarios for the operation of eVTOLs.

This modelling approach allows an integration of engineering models to rapidly compute the life cycle impacts for a range of technologies and contextual scenarios. By investigating the factors contributing to the high variability of LCA results, this paper discusses the high relevance of the weight, flying range, payload, and battery technology on the environmental impact of batteries for aircraft applications. Alongside with these technological aspects, the geographical aspects (i.e. electricity mix from the country of operation) play a role on assessing the sustainability of this new mode of transportation; as well as on determining how close current battery technologies for eVTOLs are to break even with the regulation goal for cars.

Future work should consider the whole aircraft, not only the battery system, and further investigate the influence of geographical and temporal aspects, in terms of the energy consumption, benchmarking with BEVs and other modes of transportation.

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