Energy and Emission Analysis of an Air-Taxi Service using Dynamic eVTOL System Models.

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Abstract

Electric Vertical Take-off and Landing (eVTOL) Vehicles, given their size and power requirements can serve as the perfect testbeds to study the feasibility of sustainable powerplants at scale with the arrival of air-taxi services. At Argonne National Laboratory, we have been developing a 6-degree of freedom eVTOL model, using Aeronomie to understand, predict, and eventually optimize the impact these aircraft will have on our current energy, emissions, and mobility infrastructure. This model can simulate the aircraft and powerplant dynamics for a thrust-vectoring eVTOL aircraft. In this paper we will analyze a hypothetical air-taxi service during the Los Angeles 2028 Olympics. Vertiports will be located at major stadiums around the city, which will be connected through eVTOL air-taxis. The paper discussed total energy use and emissions and estimate charging-turnaround time relationships for such a service.

Keywords: Urban Air Mobility, eVTOL, energy, emissions, aviation sustainability

1. Introduction

The dawn of Urban Air Mobility (UAM) represents a paradigm shift in the way we envision transportation within urban landscapes. These innovative aerial vehicles have captured the imagination of the aerospace industry, Silicon Valley investors, and automotive companies alike, igniting a fervor around their potential to reshape urban commuting. At the heart of this transformative movement is the pursuit of efficient, time-saving transportation solutions. As city populations burgeon and road congestion becomes increasingly untenable, the need for alternative modes of transit has become paramount. eVTOL aircraft, with their ability to take off and land vertically, promise to soar above the impediments of ground-level traffic, offering a swift and direct means of transportation within city limits. This novel concept has given rise to the term Urban Air Mobility, ushering in the prospect of a new era in urban transportation.

Furthermore, the advent of UAM may yield additional benefits by facilitating the connection of suburban and rural communities to urban centers, thereby fostering economic growth and development. Established aerospace entities like NASA[1], Airbus[2], Boeing (Wisk)[3], and Bell have made substantial investments in studying and designing the necessary aircraft and systems to support this novel form of travel. Additionally, a surge of interest has emanated from startups backed by affluent investors, aiming to design and manufacture eVTOL vehicles. Companies such as Joby[4], Lilium[5], Archer[6], Wisk[3], and Volocopter [7] are among the many startups striving to develop a viable vehicle for widespread adoption of UAM. The heightened interest and investment in UAM signify promising indications of its feasibility as a transformative mode of urban commuting.

The development of eVTOL aircraft not only addresses the urgent need for efficient urban transportation but also offers a unique opportunity to revolutionize the powertrains used in aviation. Electric propulsion systems have the potential to redefine the environmental impact of air travel, making it more sustainable and aligned with the global push for greener technologies. This intersection of innovation, urban mobility, and sustainable aviation holds promise for a future where cities are seamlessly connected through the skies, and the environmental footprint of air travel is significantly reduced. As we stand on the cusp of this aviation renaissance, the possibilities for a more sustainable and interconnected urban future beckon.

To meet the design and optimization challenges posed by the electric aviation market, Argonne

National Laboratory is developing Aeronomie [8], [9], a tool to simulate the entire aircraft over complete missions. There has been significant effort put into the development of higher-fidelity dynamic models of a vectored-thrust eVTOL aircraft based on the Joby S4 design. In this paper we will highlight the capabilities of our tool and model by analyzing an air-taxi service at the Los Angeles (LA) 2028 Olympics. First, we will analyze routes and vertiport locations based on event sites and existing airport infrastructure. Then, we will analyze time savings when compared to road transportation. Finally, we will simulate each mission segment and analyze and estimate the energy and GHG emissions for each route for different fleet size and operations. We will also investigate the power requirements for charging for this air-taxi service, while also highlighting the impact it has on turnaround times.

2. Electric Vertical Take-off and Landing (eVTOL) Aircraft Modeling

With the advancements in battery technology, it is finally feasible to develop aircraft which can achieve a range of 160-240 km/charge (100-150 mi/charge). These short-range aircraft, optimal for urban mobility commutes, will service very different missions than the typical fixed wing designs. These missions will consist of longer transient segments (frequent take-offs and landings), this big change in the operations will requires these segments of flight to be much more efficient. Another important consideration while designing these new shorter-range aircraft will be the ability to take-off and land vertically, especially important when operating in dense urban areas where airstrips are not practical. These considerations combined with new technological innovations have given rise to eVTOL aircraft. These aircraft combine the efficiency of vertical flight and forward flight by combining rotorcraft and fixed wing designs, allowing for vertical take-off, and using lift generated by the wing for forward flight. Many different designs iterations are being developed to achieve VTOL capabilities; these designs can broadly be classified as:

- Vectored Thrust: eVTOL design that utilizes thrust vectoring mechanism for both lift and cruise segments of flight.
- Lift and Cruise: separate thrusters contribute to the lift and cruise parts of the mission.
- Multicopter: these designs use multiple thrusters for lift and do not generate any lift through a wing.
- eRotorcraft: single rotor as a primary lifting surface, like a helicopter.

In this paper we will simulate the Joby S4 (Figure 2), a vectored thrust design being developed by Joby Aerospace. The S4 is a 6-rotor aircraft that consists of a wing, and a V-tail. All 6 of these rotor systems can be vectored to achieve vertical and forward flights. The choice of modeling the Joby S4 is made considering that it is the first eVTOL design to enter the certification stage. The Joby S4 prototypes have flown over 5,300 miles for flight tests, meanwhile Joby has received FAA part 135 air carrier certificate, which allows it to fly on-demand air taxi services [4]. Joby claims that the aircraft will be operational in 2025, making it the first eVTOL aircraft to enter commercial service [15].

To accurately model the dynamic and energy consumption of any aircraft it is pertinent to have good aerodynamic data that can be used to predict the performance. OpenVSP models (Figure 1) were created to calculate the aerodynamic drag for the Joby S4 [10] and a semi-empirical approach [11] was used to model the aerodynamic coefficients for the vee-tail design. The aerodynamic and geometric data gathered is then used to develop a non-linear 6 degrees of freedom dynamic model in Aeronomie.

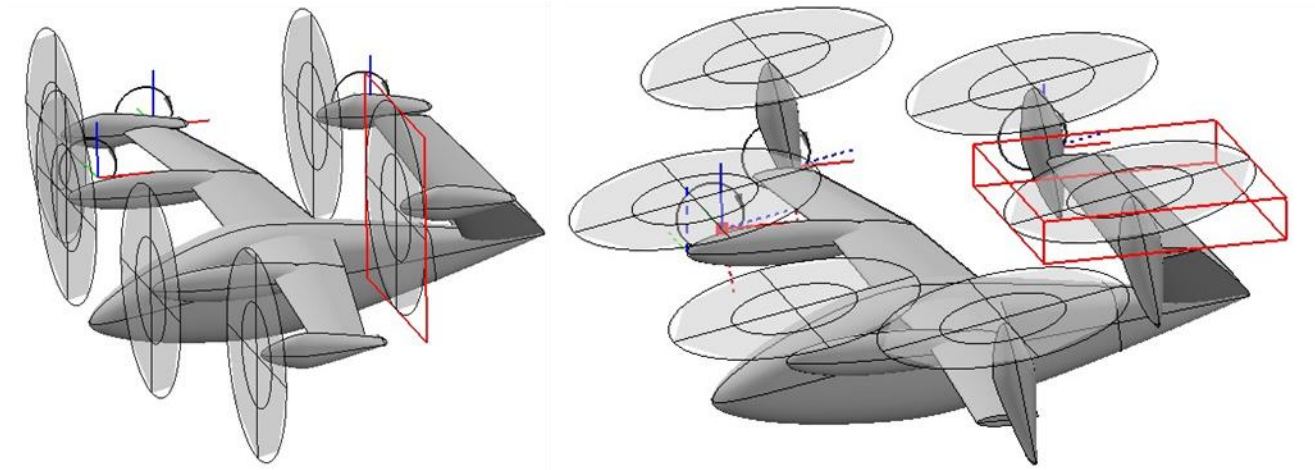


Figure 1. OpenVSP models of the Joby S4 in Forward and Vertical Flight Mode [10].

2.2 eVTOL models in Aeronomie

Aeronomie is built upon Autonomie, an established tool used for simulating road vehicle energy consumption. While Autonomie has been employed in the development of hybrid-electric and all-electric vehicles for over two decades, Aeronomie tailors its capabilities to aircraft-specific models and use cases. Both tools share the AMBER software framework, which streamlines simulation workflow management and provides reusable graphical user interface modules across various applications. The underlying modeling principle of AMBER is rooted in the effort-flow theory [12], where each system propagates effort forward and comprises feedback as flow. This framework simplifies energy calculations by representing them as the product of effort and flow. In the case of Aeronomie, its models encompass two main systems (Controls and Vehicle Dynamics) and three significant subsystems (Powerplant, Flight Dynamics, and Controls). This structure facilitates the seamless compilation of simulations, and the corresponding Figure 1 illustrates the framework, emphasizing its adaptability for easy reuse and replacement of specific subsystem models, enabling efficient parametric studies. The rotorcraft model formulation within Aeronomie is detailed by Badea et al.[13] and Heyerdahl et al. [14]. Their work demonstrates how Aeronomie serves as a valuable tool for comparing different systems, providing insights into their impact on the energy and performance of rotorcraft.

Aeronomie eVTOL models can simulate the powerplant and aircraft dynamics. Figure 3 shows an example of the nominal mission simulated using this model, the power required to achieve these maneuvers, without the diversion part, can be seen in Figure 4.

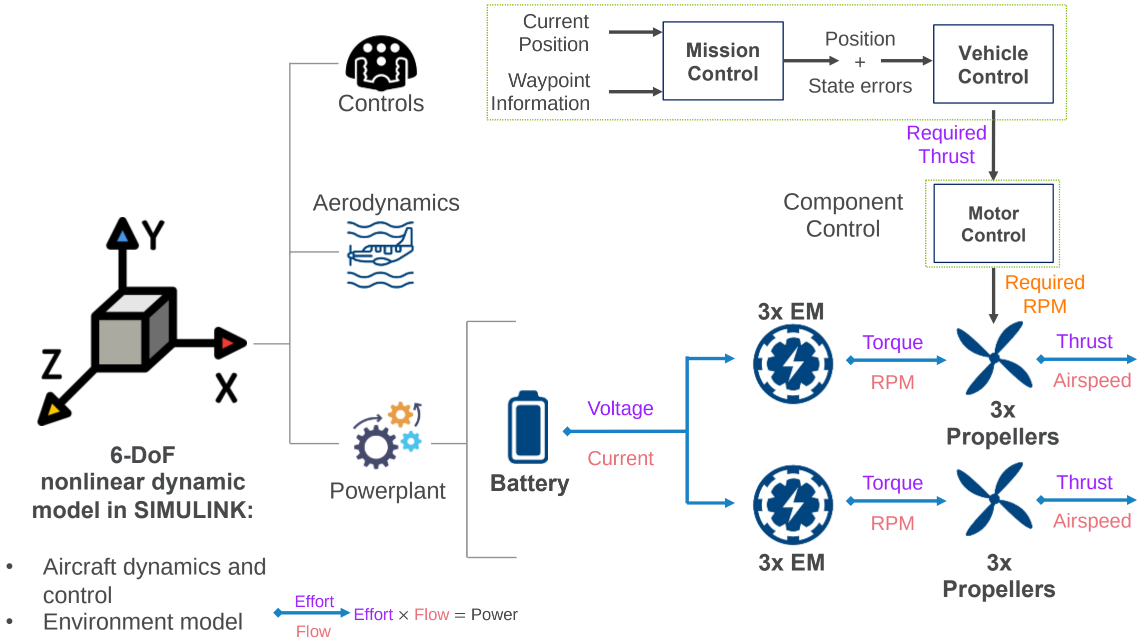


Figure 2. Aeronomie system structure for an eVTOL aircraft.

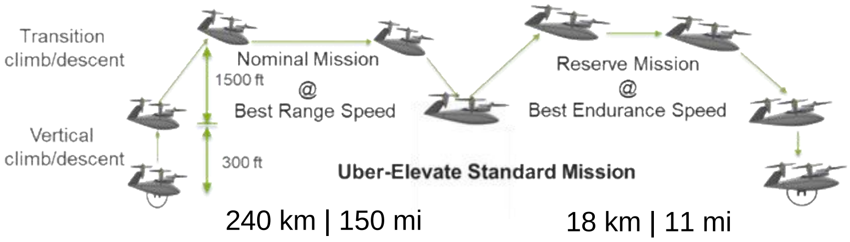


Figure 3. Nominal Mission consisting of a vertical climb and hover, and a forward flight segment consisting of a climb and 100-mile cruise.

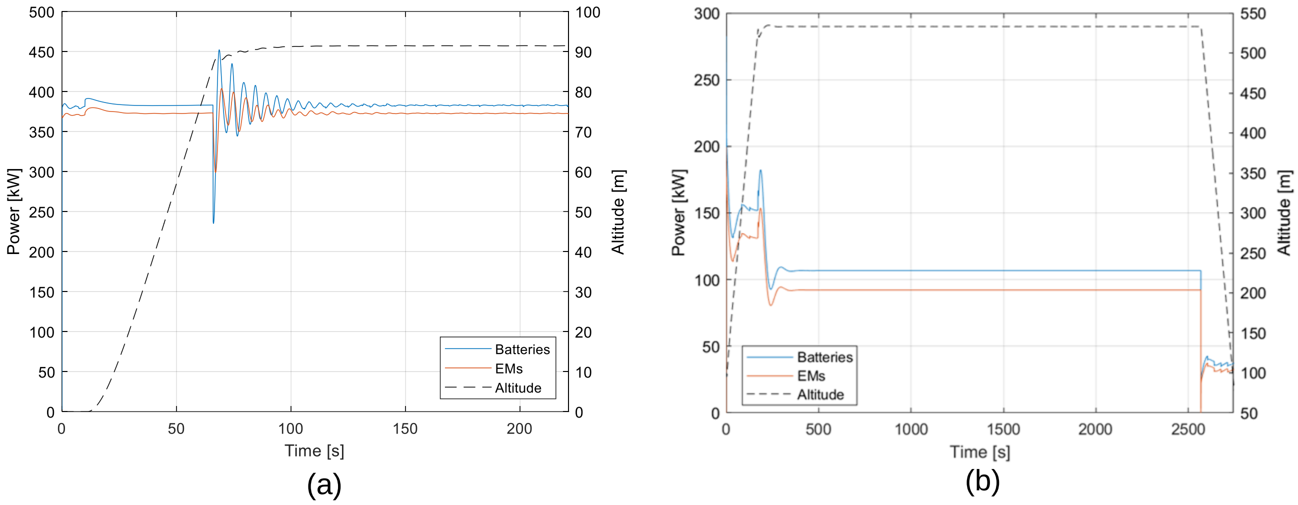


Figure 4. (a) Battery and Motor Power during the vertical flight segments of the nominal mission (b) Battery and Motor Power During the Forward-Flight Segment of the Nominal Mission for the Joby S4 Model. [11]

3. LA 2028 Air-Taxi Service

Volocopter [15] recently announced plans to start an air-taxi service during the Paris 2024 Olympics using their rotorcraft vehicle fleet. The surge of visitors during this event serves as an excellent test bed to highlight the potential of such a service to a global audience. Similarly, for this paper we will envision an air-taxi service that will focus on the Los Angeles 2028 Olympics. eVTOL manufacturers Joby and Archer expect the eVTOL market to be mature by then [16] and the FAA has also set the 2028 event as a goal date for certifying the safety of electric air taxis [17].

3.1 Vertiports and Operational Considerations

Using proposed urban development plans for the Olympic event [18], we identify the locations of major stadiums, which can be seen in Figure 5 along with the aerial distances and road networks used to travel from these venues to the airport (LAX) or downtown LA (LA memorial Coliseum). Each aerial route is highlighted with orange (from Airport) or with green (from Downtown). These vertiport locations offer direct connections with each of the venue to airport and downtown LA, which will form the basis of operations in this study. Table 1 consists of the aerial distance, road distance and drive times from LAX and Downtown locations to the Olympic venues.

In addition to the selection of vertiport locations there needs to be a discussion on the operational constraints around the LA airspace. We make some simplifying assumptions to develop this AAM service simulation using the FAA Advanced Air Mobility Implementation Plan [19], which include:

- eVTOL services have a ceiling altitude of 4,000ft.
- Only Visual Flight Range (VFR) operations (no bad-weather operations)
- Operations limited to Class B and Class C airspace, with different separations.
- All vertiport locations are at sea level.
- 300 ft minimum separation between inbound/outbound flights
- Nominal conditions: no wind, ISA conditions.

Table 1. Aerial distance, road distance, and drive times from LAX and Downtown locations to the Olympic venues.

	LAX	LA Memorial Coliseum	Dignity Health Sports Park	Drake Stadium	Long Beach Sports Arena	Valley Plaza Sports Complex
LAX	-	8.5|15|35	10|13|25	9.5|13.5|35	17.5|22|35	17.5|25|55
Coliseum	8.5|15|35	-	10|12|20	8.5|17.5|30	18|22|40	14|20|35

Aerial Distance (mi) | Road Distance (mi) | Time to Drive (min)

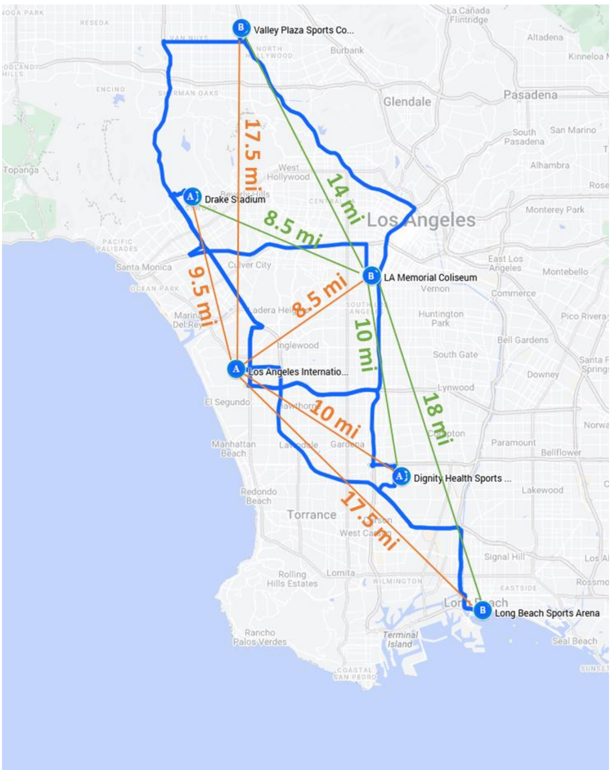


Figure 5. Locations, aerial distance, and road networks connecting different Olympic sites to the airport and downtown LA.

3.2 Routing

Using the operational assumptions and vertiport locations, we construct a route for this future AAM service.

Table 2 details the routes, aerial distance, and the outbound/inbound cruise altitudes that the Joby S4 will follow for this paper. As highlighted in the previous section, each inbound and outbound flight is separated by 300 ft, and the altitudes for each route are staggered from 1500ft to 4000 ft cruising altitude. This creates a safe operational environment to run an AAM service in a congested airspace without having to actively maintain separation between each route. Each of these routes will be simulated by the developed model to estimate the energy, power, and GHG for the flight. These flight parameters will then be used to analyze and compare the AAM service with other modes of ground transport, in addition to helicopter operations.

Table 2. Table showing the inbound and outbound distance and altitudes for LA AAM Olympic service.

Mission ID	Route	Air distance (mi)	Cruise Altitude outbound/inbound (ft)
1	LAX-Downtown	8.5	1500/1800
2	LAX-Drake	9.5	1800/2100

3	LAX-Dignity	10	2100/2400
4	LAX-Long Beach	17.5	3000/3300
5	LAX-Valley	17.6	3600/3900
6	Downtown-Drake	8.5	1300/1600
7	Downtown-Dignity	10	2500/2800
9	Downtown-Valley	14	3100/3400
8	Downtown-Long Beach	18	3700/4000

4. Results

Using the dynamic eVTOL models and the routing and operational details mentioned in the previous sections, we provide an overview of an AAM service. The motivation behind this study is to use the details of the vehicle to inform operations, including the time and GHG savings, and to predict the turnaround/charging times for these aircraft operating a service. First, we will use the dynamic models to create a power/energy profile for the aircraft. Second, we will use these aircraft level datasets to inform the total power and energy requirements of this service with various levels of operations and charging schedules.

4.1 eVTOL Performance

A standard Uber-Elevate UAM mission consists of taking-off vertically, climbing 300 ft., transitioning to fixed-wing flight while climbing to 1500 ft. and cruising at best range speed for 150 miles, then descending and landing. Additionally, there is a reserve mission which consist of a 10-mile extra cruise performed at the best endurance speed as seen in Figure 3.
Using the nominal mission as a standard, we can predict the power requirement for the aircraft for each part of the mission segments. Figure 6 provides an overview of the power required during an eVTOL mission for the battery and the motors, with respect to the altitude. It should be observed that cruising with the fixed-wing configuration is much more efficient (lower power requirements) than the vertical take-off and landing phases. In Table 3, we can find the corresponding energy and emission numbers for both a standard mission (without reserves) and a nominal mission, including energy/mi, energy/pax-mi, CO_2 emissions and life cycle GHG emission for the two missions. These power, energy, and emission values are used to calculate the requirements for an AAM service.

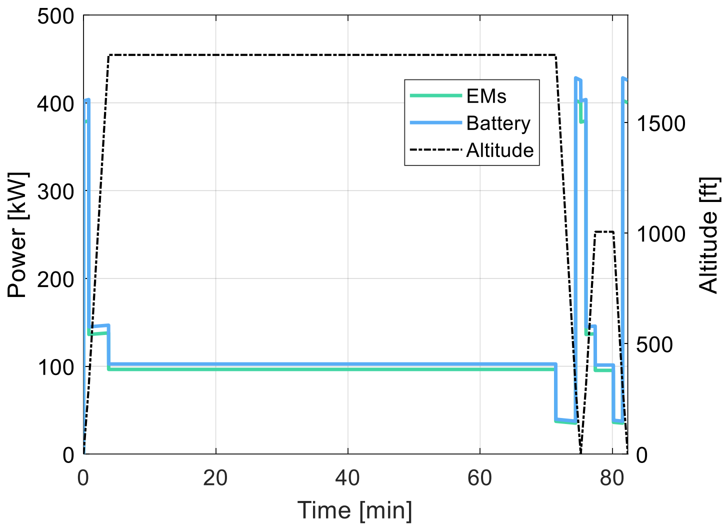


Figure 6. Power profile for the Uber-Elevate nominal mission for the Joby S4.

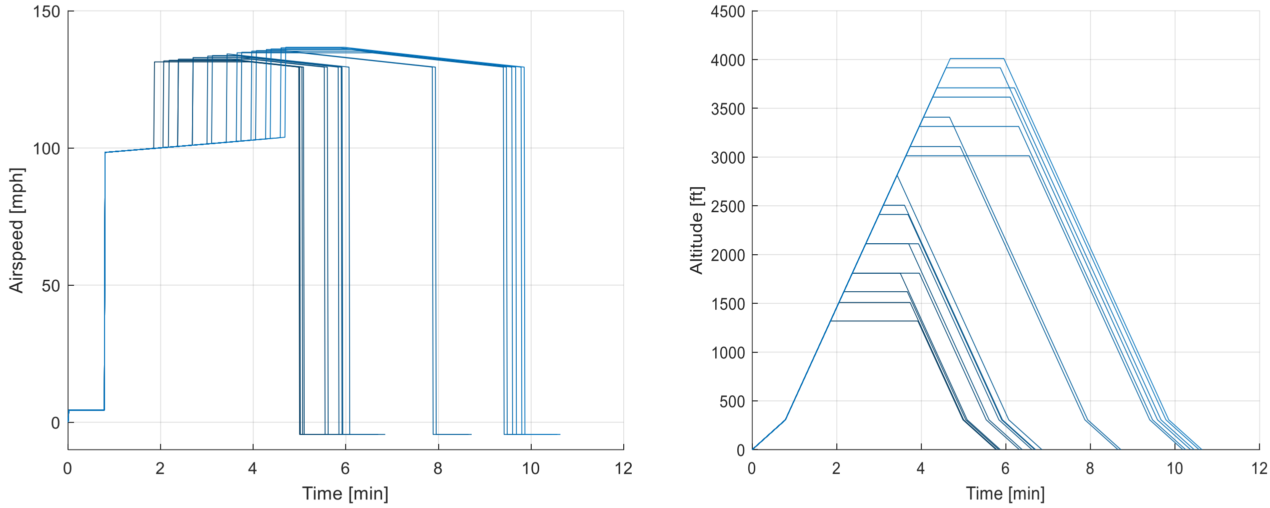
Table 3. Energy and Emission calculations for a standard and nominal mission.

	Standard mission	Nominal Mission
Consumed energy [kWh]	137.5	157.9
Energy/distance [kWh/mi]	0.855	0.916
Energy/pax-mi [kWh/pax-mi]	0.213	0.229
CO2 [kg/mi]	0.3763	0.3878
GHG [kgCO2e/mi]	0.4032	0.4155

4.2 AAM Service Energy Use and GHG emissions

In the previous sections we have discussed the modeling of an eVTOL aircraft, set up vertiports for an AAM service in LA, and set up routing and operational constraints of such a service. In this section, we will compile all those results together to analyze the energy and GHG use of air-taxi service in dense urban areas. Figure 7 highlights the speed and altitude profiles for all the different routes developed from

Table 2, where the cruise speeds of the aircraft is the best range speed, and there is a 300 ft. separation between inbound and outbound flight. Similarly, in Table 4 a compilation of time, distance, max. altitude, average speed, and energy can be seen for all the 18 different route combinations. The longer routes have higher average speeds and energy use, as expected however the differences are minimal. The longest routes use around 16% of the total energy onboard the Joby S4, which suggest multiple short-trips before needing to charge the battery. It should also be noted that longer routes with lower frequency of vertical take-offs and landing will use less energy, as the vertical segments of flight require almost 4x more power.



a. Cruise speed profiles for all routes　　b. Altitude profiles for all routes

Figure 7. Cruise and Altitude profiles for the AAM service.

Table 4. Details of each flight route including Total Distance, Max Altitude, Average Speed and Energy use.

Mission ID	Time [min]	Total Distance [mi]	Max Altitude [ft]	Average Speed [mph]	Energy Used [kWh]
1	5.8	8.5	1319	89.3	18.1
1R	5.8		1509	88.5	18.1
2	6.3	9.5	1810	90.7	19.1
2R	6.4		2111	89.6	19.2
3	6.6	10	2111	91.1	19.6
3R	6.7		2411	90.1	19.7
4	10.2	17.5	3013	103.3	25.8
4R	10.2		3314	102.7	25.9
5	10.4	17.7	3615	102.1	26.1
5R	10.4		3916	101.5	26.2
6	5.8	8.5	1620	88.2	18.2
6R	5.9		1810	87.5	18.3

7	6.7	10.2	2506	89.7	19.7
7R	6.8		2807	89.1	20
8	8.7	14	3108	97.4	23.1
8R	8.7		3409	96.6	23.2
9	10.6	18	3710	102.5	26.5
9R	10.6		4011	101.8	26.5

Using the total energy numbers, we can also calculate life cycle GHG emissions using GREET[20], [21] to analyze the environmental impact of an air-taxi service. Since the service is focused on LA, we use the electricity mix numbers from California (81 gCO2e/MJ). To calculate the total energy and compare it to existing modes of travel, we first calculate the average travel time by road using Google Maps [22], which can be seen in Figure 8. A significant time saving can be achieved by using eVTOL aircraft or helicopters when compared by our existing ground transportation, which is one the primary business cases for an air-taxi service operation. Using these travel time numbers as a reference and an average miles/gallon (mpg) value for different modes of transportation (car, shuttles, Airbus H-160 helicopter [23], eVTOL aircraft) with both electric and hybrid-electric powertrains, we can calculate the average GHG emissions for each mode using average occupancy numbers from U.S. DOT [24]. Please note that we use an average occupancy of 2 pax for the eVTOL with 4 pax capacity and a helicopter occupancy of 5 with a 10 pax capacity. These results observed in Table 5 and, highlight that public transportation is the most eco-friendly mode of transportation, and hybrid cars are still less polluting than an eVTOL aircraft.

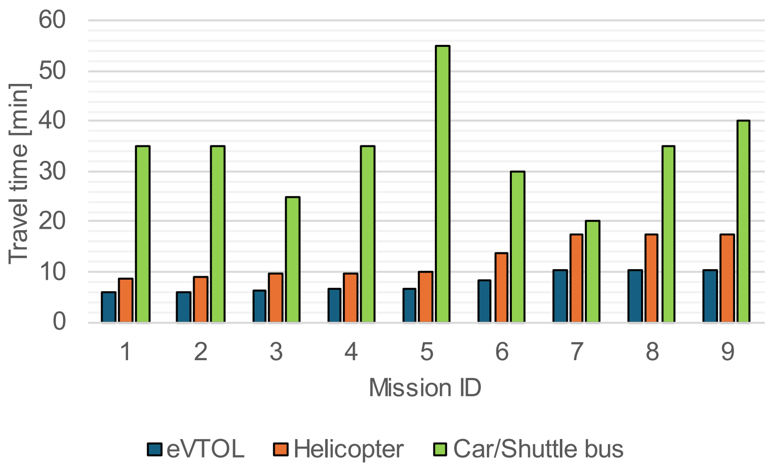


Figure 8. Travel time between for the routes using various modes of transportation.

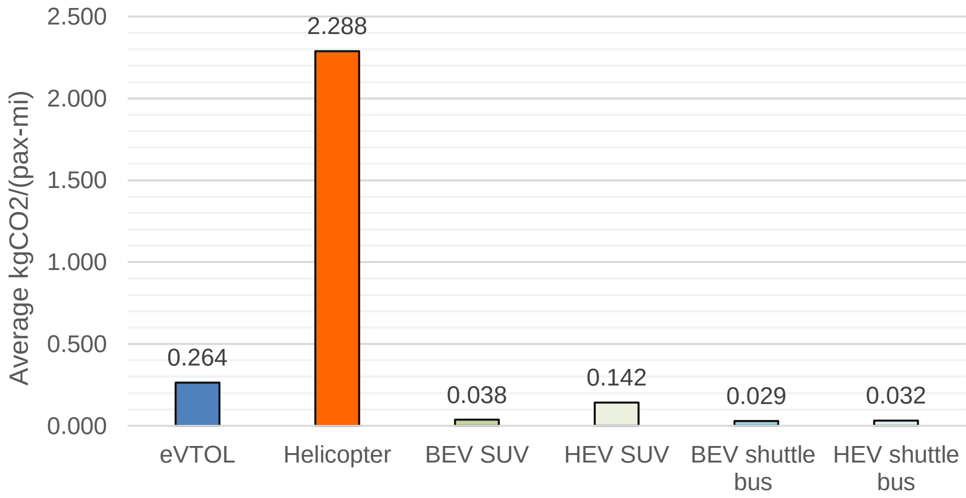


Figure 9 Graph of average CO_2 emissions for each mode of transportation on all the missions.

Table 5 Results for each transportation mode

	eVTOL	Helicopter	BEV SUV	HEV SUV	BEV shuttle bus	HEV shuttle bus
Avg. Pax capacity	2	5	1.7	1.7	13.9	13.9
Average mph	94.5	90.1	31.5	31.5	31.5	31.5
Average mi/kWh	0.6	-	4.6	-	0.7	-
Average mpg	-	0.9	-	45.1	-	24.6

Additionally, we also look at theoretical turnaround times expected to charge these eVTOL aircraft. Assuming a total battery energy capacity of 170 kWh and a state of discharge limited to 20%, using different levels of DC charging power we find that the charging time can vary between 30 mins-2hrs for charging powers of 72-240 kW. Therefore, for this air-taxi service the eVTOL aircraft can do a ~2.5 return trips before needing to be recharged, which will require an additional 30 mins with a 240-kW fast DC charger. These charging/turnaround times are expected to become shorter with the introduction of higher megawatt scale chargers [25] used in depots for buses and trucks, which can reduce the charging time to as low as 8 minutes.

5. Conclusions

This paper concludes that electric Vertical Take-off and Landing (eVTOL) vehicles have the potential to revolutionize urban transportation and contribute to a more sustainable aviation industry. The development of eVTOL aircraft presents an opportunity to optimize powertrains and make air travel more environmentally friendly. The study highlights the use of the Aeronomie tool developed by Argonne National Laboratory, which enables the simulation and analysis of eVTOL aircraft dynamics and energy consumption. Focusing on a hypothetical air-taxi service during the Los Angeles 2028 Olympics, the paper examines route planning, energy use, and emissions estimation. The modeling based on the Joby S4 design shows that cruising with the fixed-wing configuration is more efficient than vertical take-off and landing. Energy and emissions calculations indicate that eVTOL aircraft can provide time savings compared to ground transportation, but public transportation remains the most eco-friendly option. The study also explores charging requirements and estimated turnaround times for eVTOL aircraft, highlighting the potential for shorter charging times with advancements in charging infrastructure. Overall, the study demonstrates the feasibility and potential benefits of eVTOL aircraft in urban air mobility and sustainable aviation.

The initial success of an Advanced Air Mobility service will depend on its ability to save time with respect to ground transportation services. However, these time savings are highly dependent on the airspace regulations and congestion, which will require detailed guidance from the FAA to have a better understanding on AAM operations. Similar questions of service viability are centered around turnaround times for these aircraft, which depend on the charging and power infrastructure around vertiports. The AAM service described in this paper, which accounts for short (~20 mile) trips around dense urban areas provide the most viable starting platform to test the viability, safety, and operations. Using battery specific energy and powerplant efficiency numbers provided by the manufacturers, these eVTOL aircraft can do multiple round trips before requiring charging. The total GHG emissions are also in the same order of magnitude as a hybrid-electric SUV using 2022 California electric grid numbers.

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7. Copyright Statement

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