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ORIGINAL PAPER

The feasibility of electric air taxis: balancing time-savings and co_2 emissions - a joint case study of respective plans in Paris

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Abstract

This paper presents a comprehensive evaluation of the sustainability of Advanced Air Mobility (AAM) within urban and regional mobility infrastructure, utilizing Paris as a prominent case study. Driven by ambitious environmental targets, Paris aims to transform its transportation landscape into a cleaner, safer ecosystem. Collaborating with public and private stakeholders, the region has positioned AAM as a promising facet of future mobility, highlighted by the world's first scheduled commercial electric Vertical Take-Off and Landing (eVTOL) air taxi service during the 2024 Olympic Games. The study's main goal is to assess the energy consumption and CO_2 emissions of AAM aircraft across typical flight missions, encompassing urban and regional routes. A comparison is drawn between eVTOL performance and conventional modes, such as cars, public transport, and helicopters. However, it is important to note that only direct connections were considered for these time-savings, and boarding and de-boarding times as well as delays were not accounted for in the flight duration. On urban routes spanning 50 km, eVTOLs offer noteworthy time-savings of around 23 min compared to cars and 22 min compared to public transport. Moreover, concerning specific scenarios, eVTOLs demonstrate substantial time-savings for regional routes of 300 km—averaging 76 min compared to cars and 69 min compared to trains. Regarding CO_2 emissions, a contrast emerges between urban and regional contexts. Urban eVTOL operations are relatively less eco-friendly due to higher energy consumption, than electric cars. While multicopters consume 47% less CO_2 than traditional helicopters, they surpass petrol cars by 13%, diesel cars by 19%, and electric cars by up to 256%. In contrast, for regional travel, Lift-and-Cruise 1 eVTOLs consume 77% less CO_2 than average helicopters, 46% less than petrol cars, and 44% less than diesel cars, but emit 68% more than electric vehicles and 96% more than electric trains. In summary, while eVTOLs offer significant time-savings and CO_2 reductions on regional routes compared to traditional helicopters and fossil-fueled cars. However, it's essential to note that the comparison on urban routes compared to battery-powered vehicles and electric trains in terms of CO_2(eq) kg/person requires the eVTOL to produce higher emissions due to the higher energy requirement, which depends on the specific operating conditions. To harness AAM's full potential for Paris's sustainability goals, policymakers, manufacturers, and researchers should explore diverse configurations, account for real-world operations, and seamlessly integrate eVTOLs into the broader transportation framework. This approach can pave the way for less emission, and more efficient urban and regional transportation futures.

Keywords Advanced air mobility · Urban air mobility · Regional air mobility · Electric vertical take-off and landing vehicle (eVTOL) · Air taxi · Sustainability · Time-saving · Energy demand · CO_2 emission · Paris · France

List of symbols

A_r	Rotor area
BM	Battery mass
e_A	Specific energy density
E_B	Provided energy for the battery
E_C	Energy demand during cruise mode
E_G	Energy demand for ground vehicle
E_H	Energy demand during hover mode
E_{HC}	Energy demand during hover and cruise mode
e_{mix}	Energy mix
f_c	Fuel consumption
g	Acceleration due to gravity
h_v	Heat value

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s	Distance
t_C	Cruise time
t_H	Hover time
ε_C	Lift-to-drag ratio
η_C	Travel efficiency
η_H	Hovering efficiency
μ_A	Weight ratio of BM and Max. Take-off Weight
ρ	Air density
AAM	Advanced Air Mobility
GHG	Greenhouse gas
MTOW	Maximum take-off weight
PAX	Passenger
RAM	Regional Air Mobility
UAM	Urban Air Mobility

1 Introduction

Advanced Air Mobility (AAM) is an air transport system concept that integrates new, transformational aircraft designs, known as air taxis, and flight technologies into existing and modified airspace operations [1]. Electric Vertical Take-off and Landing (eVTOL) vehicles are the focus of this new transport technology. Considering the growing sustainability awareness of potential customers, eVTOL concepts are advertised to be especially free of emissions and contribute to the reduction of greenhouse gas (GHG) emissions, while quiet enough to operate in urban or regional environments without disturbing residents.

The Paris Climate Action Plan, launched in 2018, outlines a comprehensive strategy to reduce GHG emissions by improving energy efficiency from buildings, transportation, and waste management. Based on this, the municipality of Paris wants to be a carbon–neutral city, powered completely by renewable energy until 2050 [2].

Paris will host the Olympic Games 2024 and the world eagerly awaits the possibility of witnessing the first-ever commercial air taxi flight during this prestigious event [3]. This groundbreaking moment would not only enhance accessibility for travelers but also showcase the aviation industry's commitment to sustainability and time-saving convenience.

Additionally, Paris is building a new metro line that will provide a direct connection from the city to the airport by 2030 [4]. This crucial infrastructure improvement will greatly simplify the accessibility of citizens and tourists to the airport and introduce another convenient and time-efficient transportation option. Paris's clear focus is on innovative and sustainable transport solutions. [2]

However, are eVTOLs as sustainable in terms of time efficiency as assumed, especially additionally considering their energy demand? The deployment of AAM in Paris raises questions about its sustainability, particularly in terms of energy demand and resulting CO_2 emissions. According to the International Energy Agency, aviation is responsible for approximately 2.5% of global CO_2 emissions [5]. While eVTOL aircraft may offer a more sustainable alternative to traditional helicopters, their energy demand and carbon footprint during operation must still be considered in its assessment.

The Paris Region is home to 18.3% of the French population with around 12.3 million inhabitants and is a gateway to Europe and the world. It is easy to access with three international airports and seven TGV high-speed train stations that connect it to all of the world's major economic centers [6]. Paris Region accounts for 70% of French train traffic, with five million passengers traveling by train in France every day, including 3.5 million in the Paris Region. The Gare du Nord, one of the ten main train stations in Paris, is the busiest station in Europe, with over 200 million passengers per year [6]. In the Paris region, the average number of daily trips per person is 3.8, but this number hides strong disparities. Parisians themselves travel the most with an average of 4.3 trips per day, but cover the shortest distance by 12 km. Conversely, residents of the outer suburbs travel farther by 24 km. It is the working population who travels the most, with an average of 4.3 trips per day. However, the daily time budget for travel is the same regardless of location, at 1h30 per day. Even in the outer suburbs, some people only travel within their local area, which balances the time budgets of those who go to Paris [7].

1.1 Aim

In this paper, we address the question if eVTOLs can be a sustainable solution for urban or regional transportation in the Paris region. Specifically, the study will focus on the time-saving, but also on the energy demand and carbon footprint of eVTOL aircraft during operation by conducting a joint case study of respective plans for AAM in Paris. In this regard, there are two essential aspects which contribute to the success of the air taxi technology:

1) Do air taxis reduce commute travel time compared to conventional transportation solutions?
2) Do electric air taxis decrease the carbon footprint of travel compared to conventional transportation solutions?

1.2 Related work

As part of DLR's internal project, HorizonUAM, the focus lies on evaluating the potential and challenges presented by air taxis and Urban Air Mobility (UAM) concepts. A study conducted within this project utilizes a drone traffic scenario generator and 4D trajectory planning technology, tested within the urban landscape of Hamburg, Germany. Through a comparative analysis of travel times and distances, the research underscores a noteworthy 50% reduction in travel time and an impressive up to 16% decrease in route length for air taxis compared to conventional taxicabs. [8]

The ASSURED-UAM project, led by Łukasiewicz Research Network—Institute of Aviation, represents the acceptability, safety, and sustainability of UAM, thereby providing a valuable reference point. The analysis of energy efficiency parameters offers a framework for contrasting UAM passenger transportation with conventional ground-based methods. This approach draws from insights obtained from urban mobility evaluations, facilitating a comprehensive assessment of UAM's energy efficiency within the broader transportation landscape. Addressing environmental ramifications, discernible trends emerge. Notably, smaller aircraft with modest payloads exhibit lower carbon footprints, particularly during operations compared to larger aircrafts. The interplay between carbon emissions and a nation's electricity mix becomes evident, with a clear correlation between fossil fuel contribution and carbon footprint. Furthermore, nuanced insights emerge regarding aircraft specifications, operational concepts, and infrastructure, each influencing carbon footprints across different phases of an aircraft's lifecycle. [9]

In summary, the amalgamation of these studies underscores a comprehensive understanding of UAM's sustainability implications, as well as its potential energy efficiency benefits. These insights can be harnessed to critically evaluate electric air taxis' carbon emissions, particularly about traditional modes of transportation, such as helicopters, petrol, diesel, hybrid, electric cars, public transport, and electric trains. The collective research showcases the urgency and global significance of devising environmentally sound urban mobility solutions.

2 State of the art

The second chapter provides an overview of the latest concepts and advancements in the operation of AAM. This chapter also aims to offer a comprehensive understanding of the energy demand based on existing battery technologies used in eVTOLs, and the differences in CO_2 emissions among various traditional modes.

2.1 Advanced air mobility

AAM refers to the use of aircraft in urban and regional areas to address traffic congestion and enhance overall mobility [10]. With the advancements in technology and the integration of Artificial Intelligence, AAM is expected to become a reality in Europe within the next 3–5 years [11]. While the term encompasses a broader range of use cases, this paper primarily focuses on the passenger transport aspects of AAM. In this context, two main use cases for AAM are discussed: Urban Air Mobility (UAM) and Regional Air Mobility (RAM) as depicted in Fig. 1. Each of these scenarios presents a unique opportunity to revolutionize urban and regional transportation and offers fast, efficient, and environmentally friendly alternatives to conventional commuting methods.

Within the UAM scenario, eVTOL vehicles are designed to travel within a city, covering distances of about 50 km. This allows passengers to bypass long traffic jams and move swiftly to their destinations, contributing to smoother urban mobility.

On a larger scale, the RAM transport use case involves eVTOL vehicles traveling over distances of up to 300 km within highly urbanized areas. This holds the potential for valuable traffic relief and improved overall mobility in densely populated cities. Each of these use cases presents its own set of challenges and opportunities that require careful evaluation and consideration to realize the full potential of AAM [10].

2.2 Evtol types

There are currently over 900 VTOL concepts with a large variety of technological maturity and different configurations [12]. Most of these concepts are propelled by

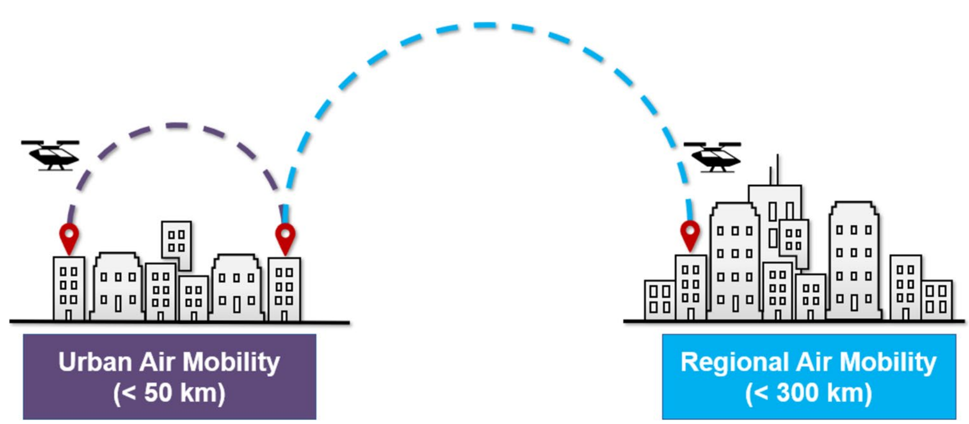


Fig. 1 AAM based on UAM and RAM

electric motors with energy supplied by battery systems [13]. Some of them use a hybrid-electric approach where combustion engines act as generators [14]. Essentially, the various concepts architectures can be differentiated by the use of a wing for highly efficient cruise flight or being wingless [15]. In Fig. 2, the four most common architectures of eVTOL are shown and compared against their forwarded and vertical lift.

The multicopter configuration has high hover lift efficiency and low disk loading due to its high number of rotors. This means that it can take off and land vertically, but is less efficient during horizontal flight than other types due to high power demand. [17]

Lift-and-cruise configurations have higher cruise efficiency and therefore able to fly longer distances compared to multicopters. This configuration can transit from vertical take-off to horizontal flight, allowing them to take advantage of both modes. [14]

Tilt-rotor or tilt-wing configurations have lower hover lift efficiency and higher disk loading than multicopter or lift-and-cruise models, resulting in higher power demand and lower efficiency. However, these models are better suited for longer distances due to their ability to fly faster and their longer range. [14, 17]

Vectored-thrust or fixed-wing configurations have low hover lift efficiency and high disk loading, meaning they are highly efficient in forward flight. However, they are less efficient in vertical take-off and landing than tilt-rotors or lift-and-cruise models. [13]

2.3 Lithium-ion battery

Batteries play a critical role in the operation of eVTOLs as they provide the power required for the electric motors to lift the aircraft off the ground and maintain flight. The state of the art in battery technology for eVTOLs is rapidly evolving, with research focused on increasing gravimetric energy density, reducing weight, and improving safety. Lithium-ion batteries are commonly employed in the current generation of eVTOL aircraft due to their high energy density and well-established performance characteristics [12]. This battery type has till today's state a gravimetric energy density between 150 and 350-Wh/kg on pack-level and proven reliability (See Fig. 3).

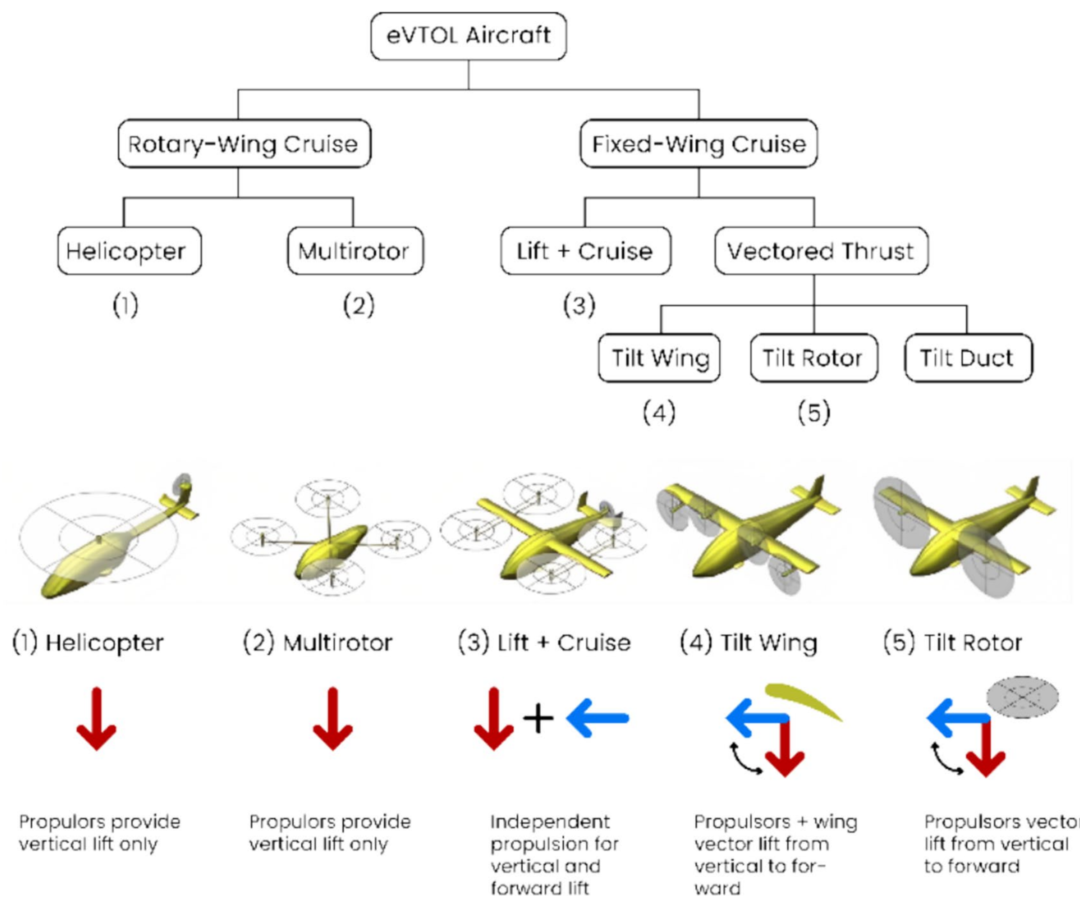


Fig. 2 eVTOL configurations [16]

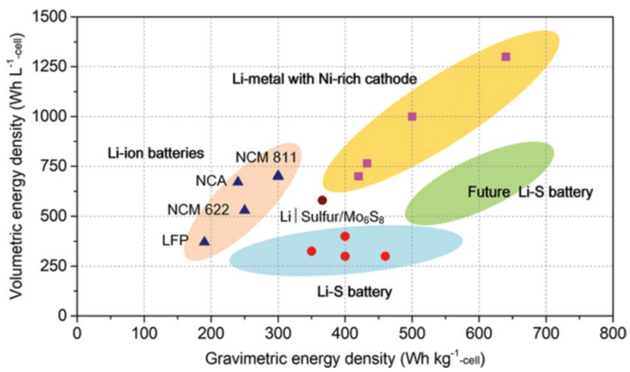


Fig. 3 Gravimetric & volumetric energy density of current battery development [18]

2.4 Energy demand of evtol

The energy demand of eVTOLs depends on various factors, such as their weight, design, propulsion system, and operational mode. Generally, eVTOLs require considerable amounts of energy for the phase during VTOL compared to the horizontal flight. [14] Additionally, it is the energy demand further affected by the duration of hovering, as well as weather conditions. Therefore, eVTOL manufacturers are continuously exploring ways to improve the efficiency of their vehicles through the use of lightweight materials, advanced propulsion systems, and optimized operational procedures. The energy demand of eVTOLs is a crucial factor in determining their commercial viability as it directly affects operating costs, range, and environmental impact. [19, 20]

To determine the power and the energy needed for the hovering flight of eVTOLs, it is necessary to calculate the thrust. [21] The climb and the descent phases are less significant regarding total flight time as the additional energy required for climbing is offset by the reduced energy needed during descent.The energy demand during hovering flight $\boldsymbol{E_H}$ is calculated as the product of the maximum take-off weight (MTOW), acceleration due to gravity (g), and the square root of the ratio of MTOW, gravity (g), air density (ρ), and rotor area ($\boldsymbol{A_r}$), divided by the hovering efficiency ($\boldsymbol{\eta_H}$), and multiplied by the time spent in hovering flight ($\boldsymbol{t_H}$) as described in [22]:

$$E_H = \text{MTOW} \cdot g\sqrt{\frac{\text{MTOW} \cdot g}{2\rho A_r}} \cdot \frac{1}{\eta_H} \cdot t_H. \quad (1)$$

Equation 2 determines the required power demand during cruise (E_C) flight for all types of eVTOL. The energy demand during cruise flight is calculated as the product of the maximum take-off weight (MTOW), acceleration due to gravity (g), the inverse of the Lift-to-drag ratio (ε_C), the real airspeed (v_{real}), the inverse of the hover efficiency (η_C), and the time spent in cruise flight (t_C) as in described in [22]:

$$E_C = \text{MTOW} \cdot \text{g} \cdot \frac{1}{\varepsilon_C} \cdot v_{real} \cdot \frac{1}{\eta_C} \cdot t_C. \quad (2)$$

The energy capacity (E_B) of the battery depends on the total mass of the battery pack (BM) and the effective gravimetric energy density on a pack level (e_A):

$$E_B = e_A \cdot \text{BM with } \mu_A = \frac{\text{BM}}{\text{MTOW}}. \quad (3)$$

2.5 Energy demand of ground vehicle

The energy demand for vehicles is a crucial factor in determining their environmental impact and overall efficiency. Petrol- and diesel-powered vehicles have long dominated the automotive landscape, primarily relying on their internal combustion engines to generate power. The energy demand for these vehicles is closely linked to their fuel consumption, measured in l/100 km.

In contrast, electric-powered vehicles, such as electric cars and trains, represent an eco-friendly alternative. The energy demand for these vehicles is measured in kilowatt-hours per 100 km (kWh/100 km). Electric vehicles rely on batteries to store electrical energy, which powers electric motors to drive the wheels. Their energy efficiency is considerably higher than traditional internal combustion engine vehicles as they convert a larger portion of the energy from the grid into actual propulsion (see Table 1).

Use Eq. 4 to determine the energy demand for all types of ground vehicles $\left(E_G\right)$, like cars, based on distance multiplied by heat value (h_v) and fuel consumption (f_c):

$$E_G = \frac{s}{100} * h_v * f_c. \quad (4)$$

2.6 Carbon dioxide equivalent / CO_2 (eq)

Based on Eurostat definition of carbon dioxide equivalent, CO_2 equivalent or CO_2 (eq) is a metric measure used to compare the emissions from various greenhouse gasses based

Table 1 Average European heat value and fuel consumption of ground vehicles [23–25]

Vehicle	Ø h_v [kWh/l]	Ø f_c	Energy consumption [kWh/km]
Petrol car	8.2	8.4 l/100 km	0.68
Diesel car	9.7	6.7 l/100 km	0.65
Electric car	–	15 kWh/100 km	0.15

on their global warming potential by converting amounts of other gasses to the equivalent amount of CO_2 with the same global warming potential. [26]

The carbon footprint of electric vehicles depends on the energy mix used to generate the electricity. If the electricity comes from renewable sources, such as wind or solar power, the carbon footprint of electric vehicles can be close to zero without considering the manufacture of batteries and the vehicle itself. The considerations of practical terms, certain emissions associated with the production, transportation, and installation of renewable energy infrastructure may be accounted for, thus affecting the total emissions over the life-cycle. However, if the electricity comes from power plants, such as coal-fired plants, the carbon footprint of electric ground vehicles remains substantial by around 50 g of CO_2 per km, which is still better than conventional vehicles. [25]

The CO_2 emissions depend on the energy demand and the energy source. Even fully electric UAM vehicles are not completely free of carbon emissions as the source of the electricity used to charge the batteries has an essential impact on the carbon footprint of the vehicle. [24]

Recent studies have shown that the primary energy demand and the CO_2 emissions of eVTOLs are notably lower than those of conventional aircraft. According to a report by Roland Berger, eVTOLs reduce CO_2 emissions by up to 50% compared to conventional helicopters [27]. Additionally, a study by the University of Michigan found that eVTOLs can reduce up to 40% of energy demand compared to ground-based electric cars [28]. These results demonstrate the potential for eVTOLs to improve sustainability.

The study by Carnegie Mellon University examines the energy demand and GHG emissions of a very small quadcopter drone used for last-mile deliveries. The model showed that an electric quadcopter drone transporting a package of 0.5 kg consumes 0.08 MJ/km and causes 70 g of CO_2 (eq) considering the electric energy mix in the United States. Comparisons with other vehicles show that drones can reduce energy consumption by 94% and 31% and GHG emissions by 84% and 29% per package delivered by replacing diesel trucks and electric vans, respectively [29].

Formula (5) describes the calculation of operational CO_2 emissions for UAM vehicles based on energy demand during hover and cruise mode $\left(E_{HC}\right)$ and energy mix (e_{mix}):

$$CO_2 \text{ emission} = E_{HC} * e_{mix}. \tag{5}$$

Table 2 provides a quick comparison of the average CO_2 emissions per passenger for different types of ground vehicles, ranging from traditional petrol and diesel cars to hybrid and electric vehicles, as well as public transportation, like bus, tram, and metro.

3 Research gap

Current research lacks quantifiable comparisons of CO_2 emissions and time-savings between eVTOLs and conventional transport modes like helicopters, cars, and public transportation due to insufficient data. This study aims to address this gap by collecting empirical data, performing a detailed comparative analysis on urban and regional routes, and considering the realistic energy demand during hover and cruise by different eVTOL configurations during a flight mission. Additionally, the European electricity mix will be utilized to ensure a valid comparison of different transport modes.

4 Methodology

This chapter describes the approach to determine the CO_2 emissions of helicopters and UAM vehicles for relevant routes in the context of the Paris 2024 Olympic Games.

4.1 Selected flight mission profile

To determine the energy demand of eVTOLs, the flight scenario is divided into two main phases, namely hover and cruise. The energy demand of the selected eVTOLs is evaluated by analyzing the calculated results based on the selected properties under optimal conditions as shown in Fig. 4.

The selected UAM mission profile includes 30-s hover phases for both take-off and landing and a cruise at 150 m altitude. The vehicle carries four passengers (including the pilot) and uses a battery with 250 Wh/kg energy density. The weather conditions is set by no headwind and an air temperature of 15 °C.

The energy demand calculations are performed using a calculation tool developed as part of prior research efforts. This tool, detailed in [31], enables the integration of equations and data to accurately determine the energy demand during hover and cruise phases based on realistic technical specifications of eVTOLs and mission profiles. The

Table 2 Selected European average CO_2 per PAX of ground vehicles [25, 30]

Vehicle	CO_2 (eq) / PAX [gr/km]
Petrol car	110
Diesel car	100
Hybrid car	65
Electric car	35
Public transportation	64
Electric train	36

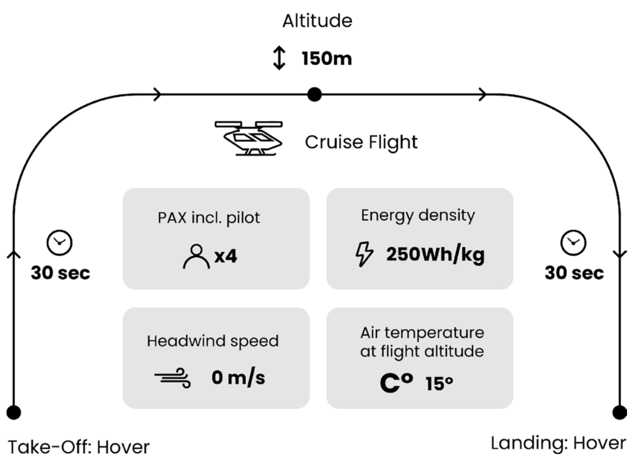


Fig. 4 UAM mission profile

development of this tool was outlined in a prior study, providing the framework for the generation of results within this current work.

4.2 Selected flight routes

In this paper, the starting point is the Place de la Concorde in the city center of Paris. According to the City of Paris, which provides real-time traffic updates through its website, traffic congestion is often high between 2 and 4 PM in the city center.

Using Google Maps, the average distance and the travel time of seven days are calculated to ensure a representative analysis (see also APPENDIX). This step is repeated for both the use cases UAM (max. 50 km) and RAM (max. 300 km).

All distances are determined under the assumption of a direct flight path without considering airspace structure, routing restrictions, and topography influence.

The map illustrates a set of UAM routes centered around Place de la Concorde in Paris, designed to enhance transportation during the Olympic Games 2024. These routes connect Place de la Concorde to 8 key locations, with distances ranging from 2 to 29 km (See Fig. 5).

The destinations include Charles de Gaulle Airport (29 km), a major international airport to the northeast, and Stade de France (7.5 km), the national stadium located in the northern suburbs. Other significant points include Gare du Nord (3.2 km) and Gare de Lyon (4.6 km), two of the busiest railway stations in Europe, positioned in the northern and southeastern parts of the city, respectively. Orly Airport (15 km), the second international airport, is located to the south of Paris. The iconic Eiffel Tower is also a destination, situated 1.9 km from the heart of the city. To the southwest lies the historic Palace of Versailles (16 km), while La Défense Arena (7.4 km), a large indoor arena in the business district of La Défense, is located to the west. Each route is depicted by a line emanating from Place de la Concorde to these destinations, highlighting the proposed UAM routes intended to facilitate quick and efficient transportation during the Olympic events (see Table 3).

The map illustrates a set of RAM routes designed to enhance connectivity between Place de la Concorde in Paris and 8 key cities across France. These routes, spanning distances from 69 to 240 km, aim to improve regional accessibility and transportation efficiency (see Fig. 6).

The destinations include Calais (240 km), situated to the north and known for its proximity to the English Channel and the Channel Tunnel. Lille (205 km), another northern city close to the Belgian border, is also connected. To the east, Reims (140 km) is included, a city renowned for its cathedral and champagne production. To the south of Paris, the routes extend to Orleans (103 km), a city with significant historical importance. Le Mans (185 km), famous for the 24 Hours of Le Mans car race, is located to the southwest. The northwest routes connect to Rouen (101 km), known for its medieval architecture, and Le Havre (179 km), a major port city on the northern coast. Additionally, Beauvais (69 km), located north of Paris and home to an airport serving budget airlines, is part of this network. These RAM routes highlight the strategic links between Paris and these regional hubs, facilitating quick and efficient travel across a broader geographic area (see Table 4).

4.3 Selected evtols

The initial stage of the investigation involves determining the characteristics of various eVTOL vehicles, drawing upon data derived from a previous study. These values serve as the foundation for the current analysis, with detailed information provided in the reference. In a previous study [31], the maximum realistic range of various eVTOL type configurations was assessed.

Table 5 presents several key performance parameters of the selected eVTOLs, which are essential for evaluating their overall efficiency and operational characteristics. Speed refers to the horizontal cruising velocity of the aircraft, representing its performance during level flight. Maximum Take-Off Weight (MTOW) denotes the maximum allowable weight for safe operation, including the aircraft's fuel, payload, and passengers. Battery Mass (BM) indicates the weight of the battery system installed in the eVTOL, which is a critical factor influencing range and energy consumption. Hover efficiency η_S measures depending on the eVTOL configuration how effectively the aircraft uses energy during vertical take-off and hovering. A higher hover efficiency means less energy is wasted when the aircraft is stationary or transitioning between vertical and horizontal flight. Cruise efficiency η_R indicates depending on the eVTOL

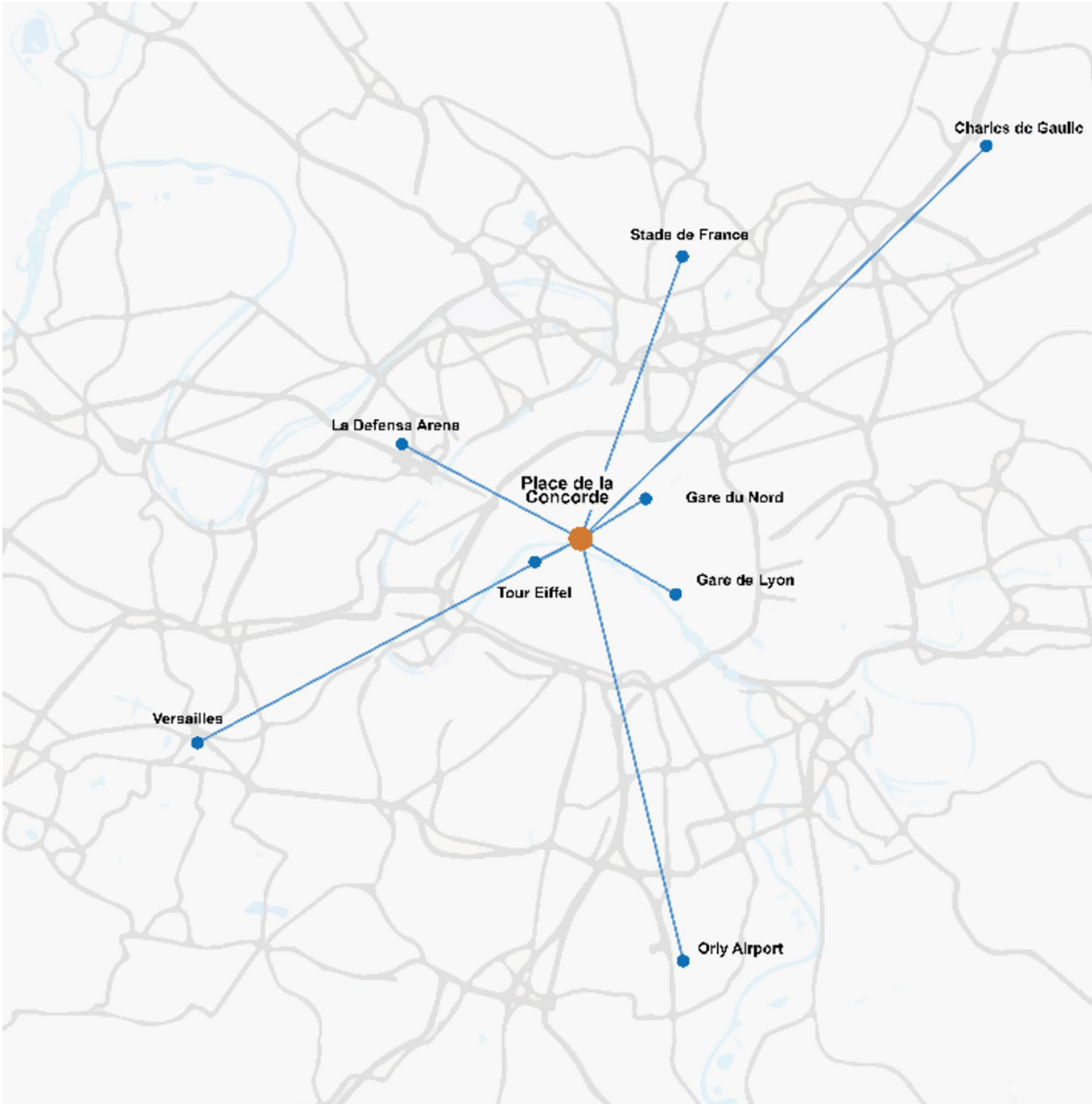


Fig. 5 UAM mission use case (< 50 km)

configuration how efficiently the aircraft uses energy during horizontal flight, with a higher value suggesting better performance in terms of fuel or energy consumption during cruise. The Lift/Drag-ratio ε_R is a measure of the aircraft's aerodynamic efficiency during cruising flight, with a higher ratio indicating that the aircraft generates more lift for less drag, contributing to better fuel economy and higher speeds.

These parameters are crucial for understanding the overall performance, range, and operational efficiency of a VTOL aircraft. It was found that certain eVTOL type configurations, due to current battery technology, are unable to achieve longer distances.

For the UAM use case with a range of up to 50 km, a multicopter is a suitable choice due to its inherent ability to TOL vertically, enabling operations within constrained urban spaces. The use of a multicopter configuration may offer advantages in terms of maneuverability and adaptability to urban environments. However, these alternative configurations might present challenges related to their maneuverability within densely populated urban areas. In

Table 3 Selected flight destinations on urban level

UAM (< 50 km)	
Destination	Flight range [km]
Eiffel tower	1,9
Gare du Nord	3,2
Gare de Lyon	4,6
La Défense Arena	7,4
Stade de France	7,5
Orly airport	15
Versailles	16
Charles de Gaulle airport	29

contrast, for the RAM scenario, a lift-and-cruise model is a better choice. These models TOL vertically, but can then transition into a more efficient cruise mode, allowing them to cover longer distances at higher speeds. This makes them more suitable for longer, regional flights that require higher speeds and greater efficiency.

4.4 Selected helicopters

A total of seven helicopters have been assessed for their CO_2 emissions per PAX*km during flight. The helicopters under investigation are detailed in Table 6. Except for the Robinson R44, which utilizes gasoline, all helicopters employ kerosene as fuel. For reference, the combustion of 1 gallon of kerosene emits 9.9 kg of CO_2, while the same quantity of gasoline emits 8.8 kg of CO_2 [32]. Helicopters' burn rate and cruise speed data can be found in their manuals. Furthermore, factors, such as run-up times, taxiing, route deviations during cruise, and approach and departure procedures, are not considered into the calculations.

4.5 Selected energy mix

CO_2 emissions generated by the operation of air taxis are closely related to the electricity mix of the country in which the operation takes place. The data collected serve as the basis for determining energy demand and CO_2 emissions. In this regard, the average energy demand of the chosen mode of transport and the emission factor of the electricity mix of the average consumption in Europe are considered. These data are combined with suitable calculation methods to determine the associated CO_2 emissions (see Table 7).

Based on the energy demand calculated, it is possible to calculate the CO_2 emissions during the operation for each use case. In this work, the European electricity mix was utilized for further consideration to establish a more globally realistic comparison, recognizing that while the use case is applied in Paris, the French electricity mix performs significantly more sustainable.

5 Results

This chapter presents the findings regarding time-savings and CO_2 emissions associated with eVTOLs, focusing on the selected routes and mission profiles within the context of Paris and France. As mentioned in Chapter 3.3, the analysis covered two representative eVTOL configurations: a multicopter for the UAM use case and a lift-and-cruise model for the RAM use case.

5.1 Time-saving

These findings are based solely on pure flight time and assume direct flight paths for selected urban destinations in Paris. Notably, boarding time has not been considered in this analysis. The reason for this omission is the lack of concrete security concepts and available data regarding boarding times. Consequently, this factor is out of scope in this current study. Given that there are no established on-demand options, passengers would first need to travel to one of the designated take-off locations, known as Vertiports, and pass through security checks. The theoretical time-savings, therefore, only reflect the direct flight route. Additionally, design and accessibility of Vertiports have not been concretely defined, which further complicates an accurate assessment of the total travel time. These uncertainties highlight the need for more comprehensive research and development of security procedures, boarding processes, and infrastructure to better understand and optimize the potential benefits of UAM in urban settings.

The results on urban level show that the average flight time using a multicopter is around 7 min which means a time-saving about 23 min compared to a car, while compared to public transportation, the average time-savings is 22 min (see Fig. 7).

On the regional level, the diagram below shows the average time-savings, while using a lift-and-cruise model, the average time-savings is approximately 76 min compared to a car, while compared to public transportation, the average time-savings is 69 min. These results were obtained considering only the pure flight time and assuming direct flight paths for the selected regional destinations in France departing from Paris. Again, no boarding time was considered (see Fig. 8).

5.2 CO_2 emission evtols vs. cars

In this section, the results of the study on the comparison of CO_2 emissions originating from the energy demand of

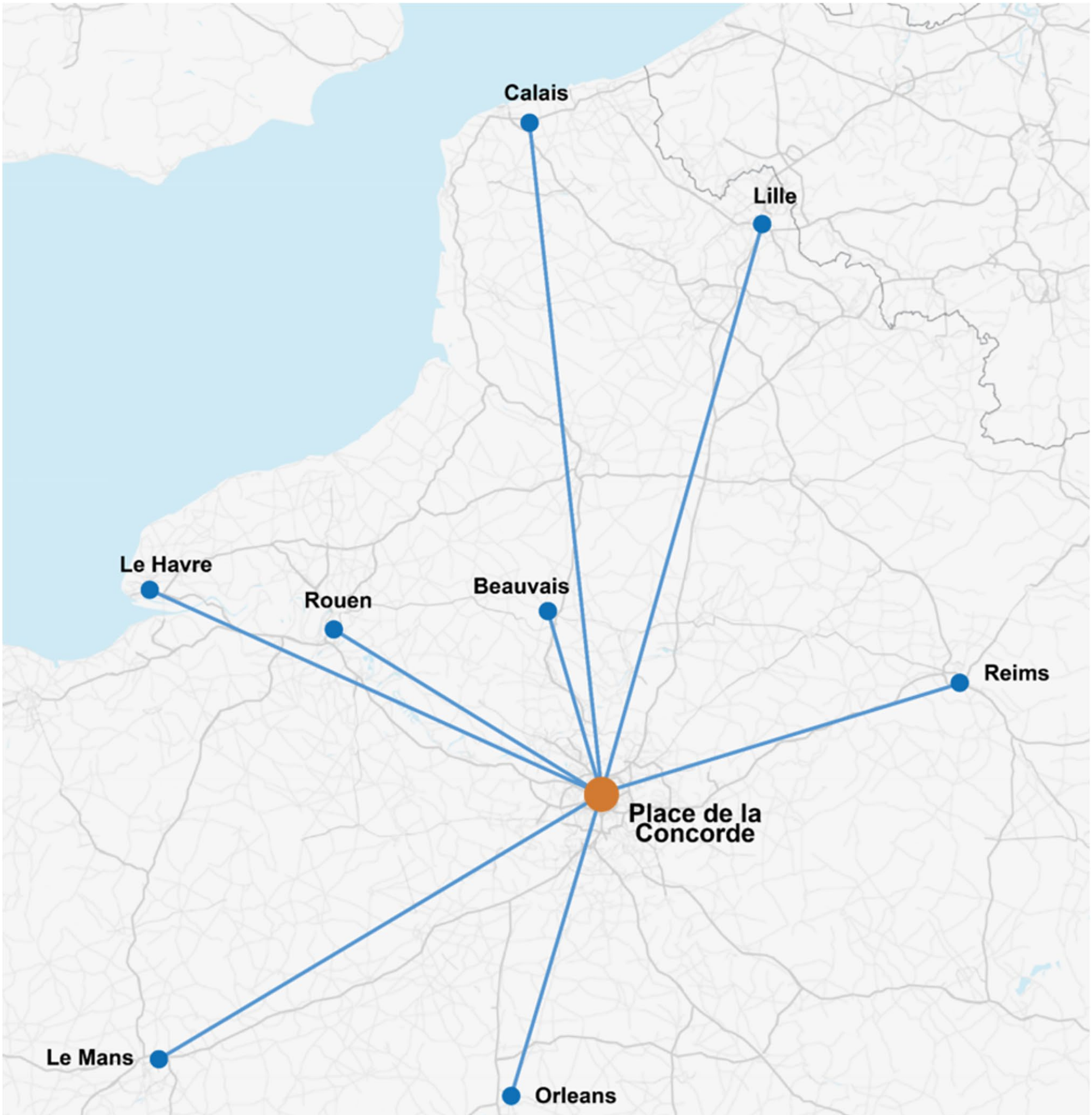


Fig. 6 RAM mission use case (< 300 km)

multicopter and conventional passenger cars (powered by petrol, diesel, hybrid, and electric) in the urban and regional setting are shown.

Fig. 19 (APPENDIX) shows the total CO_2 emission comparison between multicopter and conventional cars for the urban use case, based on the assumption of 2 passengers. The highest emission value of 4.19 kg CO_2 (eq) by a multicopter is recorded for the distance from Place de la Concorde to Charles de Gaulle Airport, covering a distance of 28.94 km. Comparatively, the electric car requires only 1.15 kg CO_2 (eq) for this distance, the hybrid car 2.14 kg CO_2 (eq), the diesel car 3.45 kg CO_2 (eq), and the petrol car 3.62 kg CO_2 (eq). Interestingly, on the shortest distance to the Eiffel Tower, spanning only 2.8 km, multicopter emit a relatively low CO_2 emission of 0.45 kg CO_2 (eq), suggesting their potential as a more environmentally harmful option for short-distance travel, compared to some conventional cars, such as a petrol car with 0.31 kg CO_2 (eq), diesel car with

Table 4 Selected flight destinations on regional level

RAM (< 300 km)	
Destination	Flight range [km]
Beauvais	69
Rouen	101
Orleans	103
Reims	140
Le Havre	179
Le Mans	185
Lille	205
Calais	240

Table 6 Helicopter type configurations

Helicopter Type	PAX seats	Cruise speed [km/h]
Bell 206	3	223
R44	3	200
R66	4	200
H120	4	223
H125	6	260
H135	7	253
H145	10	247

Table 7 Energy mix by different regions [33]

Area	Ø energy mix [g CO_2/kWh]
Sweden	13
France	57
Germany	508
Europe	226

0.29 kg CO_2 (eq), hybrid car with 0.18 kg CO_2 (eq) and electric car with 0.10 kg CO_2 (eq). The electric vehicle records the lowest CO_2 emission consumption for this route.

Fig. 20 illustrates the resulting percentage comparison of CO_2 emissions between multicopter and different types of cars per passenger concerning their respective total emissions. It is evident that for the aforementioned example of traveling from Place de la Concorde to Charles de Gaulle Airport, using an eVTOL for the flight route results in approximately 16% higher CO_2 equivalent emissions compared to the driving route with a petrol-powered car. When compared to a diesel-powered car, the eVTOL emits around 21% more CO_2, approximately 96% more than a hybrid vehicle, and a striking 364% more than an electric vehicle. Regarding the shortest distance to the Eiffel Tower, similar trends are observed: The eVTOL produces about 46% more CO_2 equivalent emissions than a gasoline car, roughly 53% more than a diesel car, approximately 247% more than a hybrid vehicle, and a significant 459% more emissions compared to an all-electric car.

Figure 9 shows on average across all 8 flight missions, a multicopter emits approximately 123% more CO_2 equivalent emissions compared to a car running on petrol, roughly 129% more than a car powered by diesel, approximately 209% more than a hybrid vehicle, and a staggering 388% more than an electric car.

Fig. 21 and 22 presents for the RAM use case the total and percentage CO_2 emission comparison of CO_2 emissions between the lift-and-cruise configuration and different car types at the regional level. The results reveal that the highest emission value of 16.82 kg CO_2 (eq) by the lift-and-cruise eVTOL is recorded for the distance from Place de la Concorde to Calais, covering a direct distance of 240.39 km. Comparatively, the electric car requires only 10.43 kg CO_2 (eq) for this distance, the hybrid car kg 19.37 CO_2 (eq), the diesel car 31.29 kg CO_2 (eq), and the car by petrol 32.78 kg CO_2 (eq). The shortest distance is between Paris and the city of Beauvais with a direct flight distance of 69.46 km. For this route, the CO_2 emission per passenger is calculated at 5.12 kg CO_2 (eq). Comparatively, the electric car requires only 3.40 kg CO_2 (eq) for

Table 5 eVTOL type configuration [31]

eVTOL type	Speed [km/h]	MTOW [kg]	BM [kg]	Hover efficiency η_S	Cruise efficiency η_R	Lift/drag ratio ε_R
Multicopter	100	900	180	0,70	0,50	4
Multicopter (coaxial)	100	600	100	0,55	0,48	4
Quadcopter	120	2200	800	0,55	0,40	2
Lift + cruise 1	180	800	200	0,70	0,50	9
Lift + cruise 2	180	1442	400	0,70	0,50	11
Vectored lift	300	3500	900	0,60	0,60	17
Tilt-rotor	320	1815	400	0,70	0,46	15

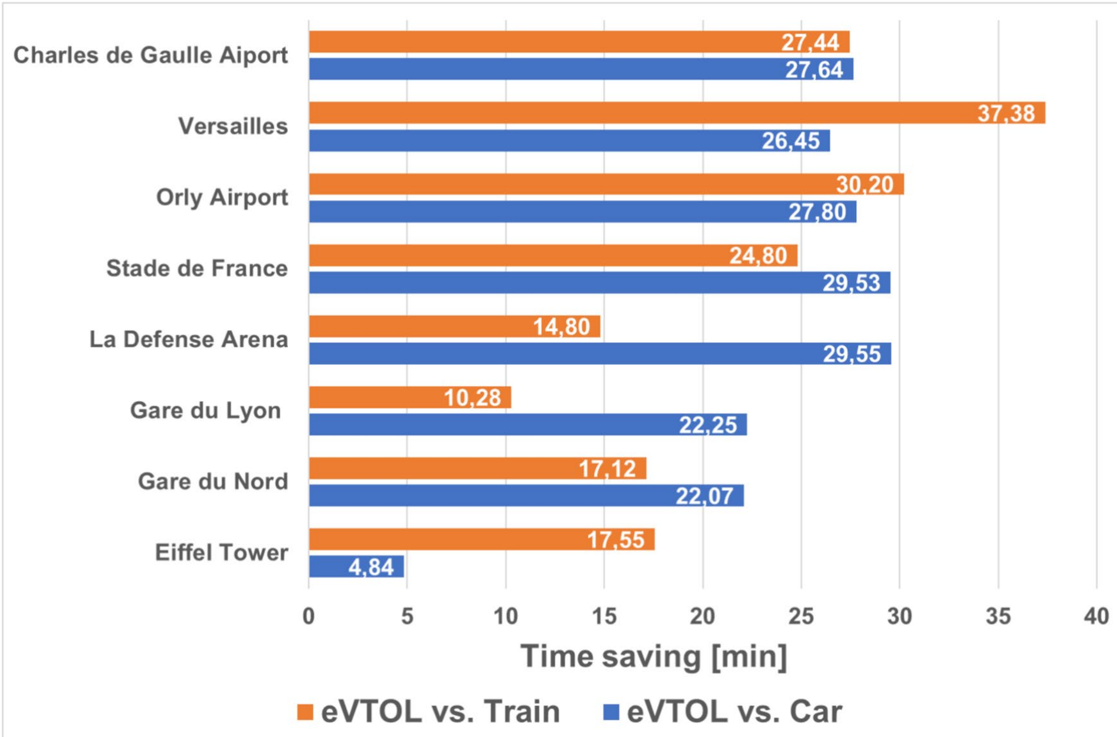
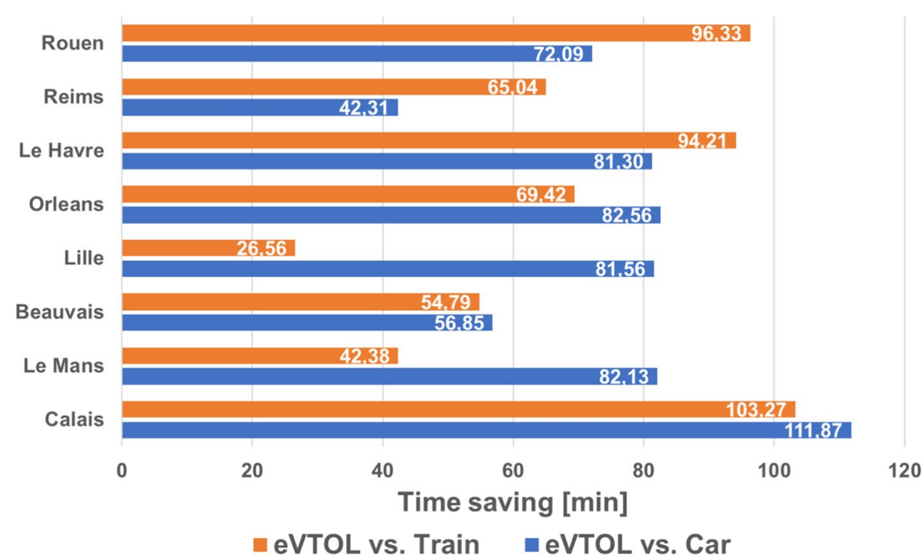


Fig. 7 UAM time-saving: eVTOL vs. car vs. train

Fig. 8 RAM time-saving: eVTOL vs. car vs. train



this distance, which accounts for 48% of the ratio. Compared to Car-Diesel, the eVTOL configuration consumes nearly 50% less CO_2 emissions. Moreover, it results in 19% fewer emissions than a hybrid car, however 51% more emissions than an electric car.

Figure 10 shows on average across the 8 selected regional flight routes, an eVTOL can save around 47% of CO_2 emissions compared to a petrol car, approximately 44% compared to a diesel car, and approximately 10% compared to a hybrid car. However, when compared to electric vehicles, eVTOL emissions are approximately 67% higher.

These findings indicate that, on the regional level, eVTOLs present notable advantages in reducing CO_2 emissions when compared to conventional petrol and diesel cars. Nevertheless, they still emit notably more CO_2 than electric vehicles on average for the 8 selected regional flight routes.

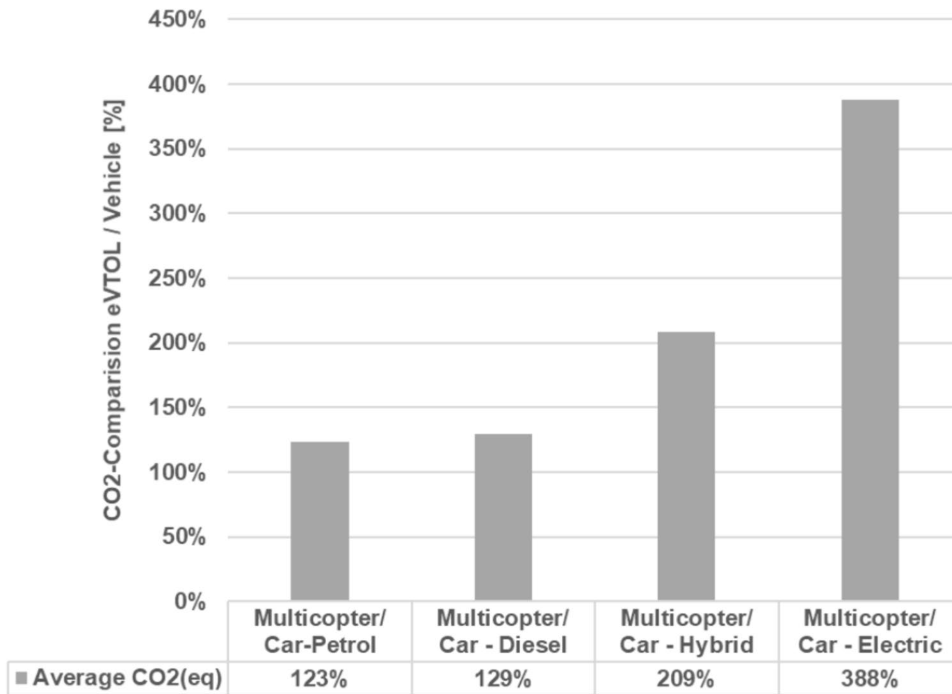


Fig. 9 Use Case: UAM—average percentage CO_2 emission comparison eVTOL vs. car

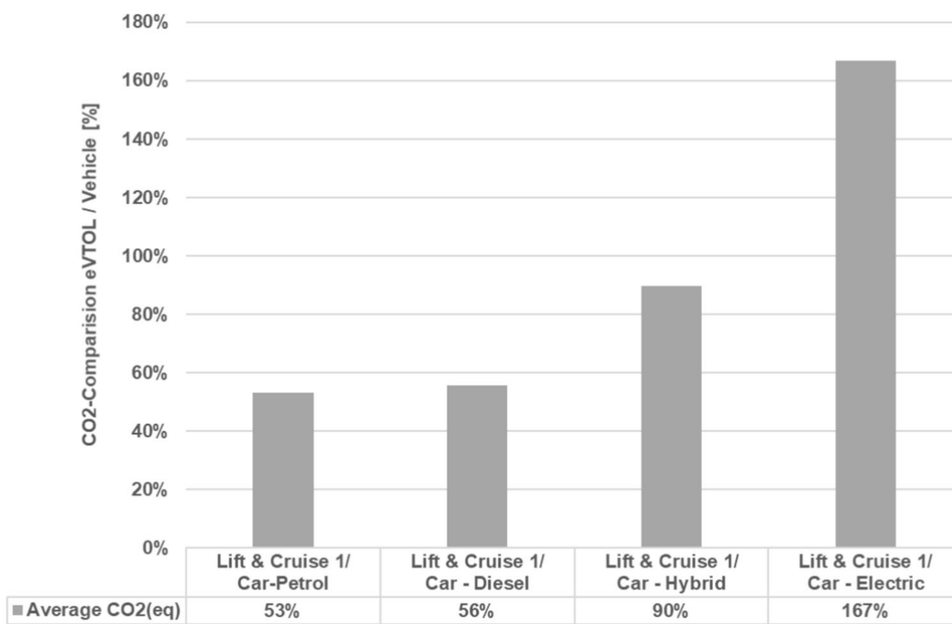


Fig. 10 Use Case: RAM—average percentage CO_2 emission comparison eVTOL vs. car

5.3 CO_2 emission evtol vs. train

In this section, the results of the study on the comparison of CO_2 emissions from energy demand between eVTOLs and public transportation on urban and regional levels are presented. Figure 11 shows the total CO_2 emissions per passenger at the urban level between multicopter eVTOLs and public transportation.

From the quantitative results, it is evident that the total CO_2 emissions generated by eVTOLs are crucially higher than those produced by public transportation.

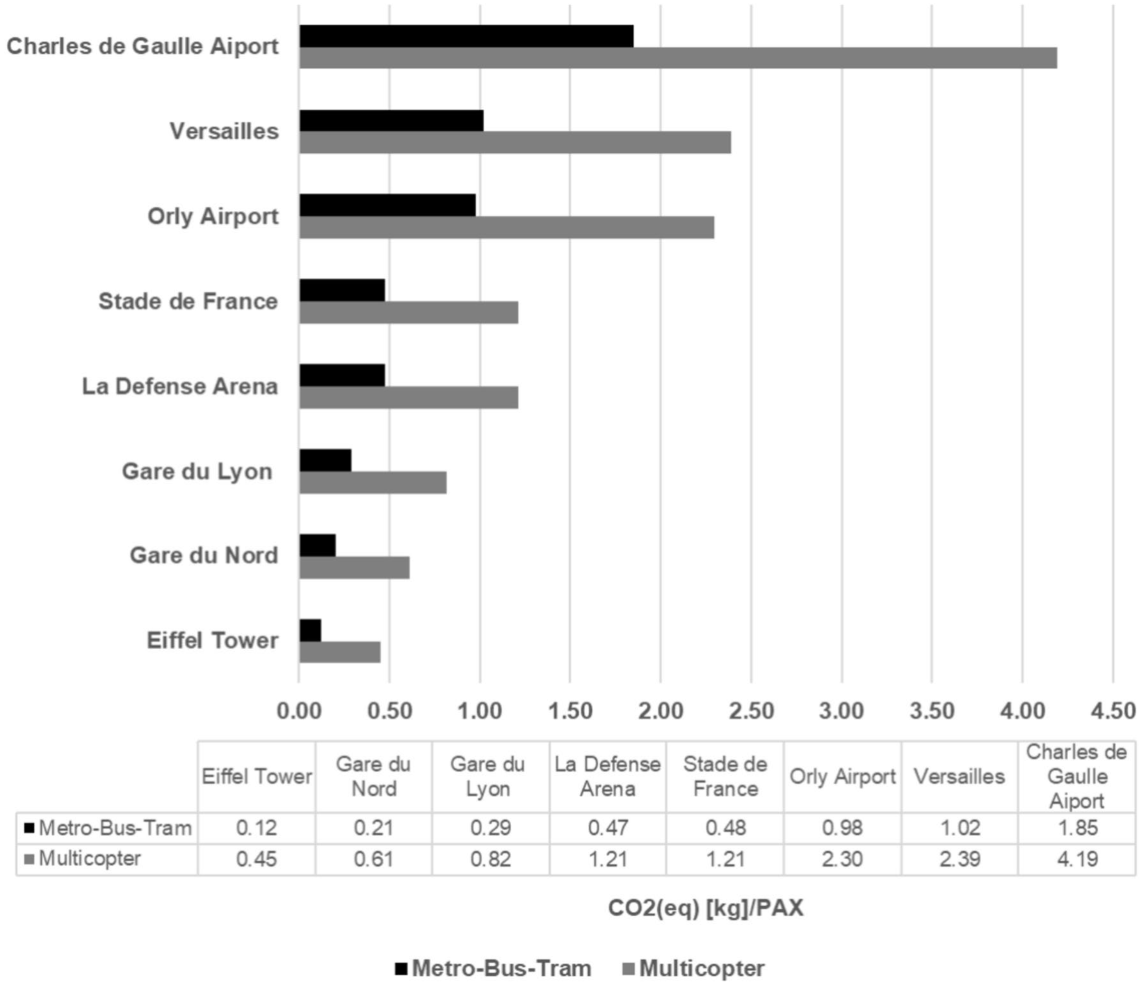


Fig. 11 Use Case: UAM—total CO_2 emission comparison multicopter vs. public transportation

Figure 12 presents a percentage comparison of CO_2 emissions between multicopter eVTOLs and public transportation.

The CO_2 emission results show that on the urban level, an eVTOL compared to public transportation exhibits crucial higher CO_2 emissions. It's worth clarifying that while multicopters primarily accommodate one passenger and one pilot, our calculations are based on the potential for autonomous flight, where two passengers can be transported in the long term. For the flight route from Place de la Concorde to Charles de Gaulle Airport, eVTOLs produce approximately 226% more CO_2 emissions. Similarly, for the route to the Eiffel Tower, eVTOLs generate nearly 362% more CO_2, equivalent to approximately 3.6 times higher emissions, which remains notably high. On average, across the selected urban routes for one passenger, a multicopter eVTOL produces about 2.6 times more CO_2 emissions compared to public transportation.

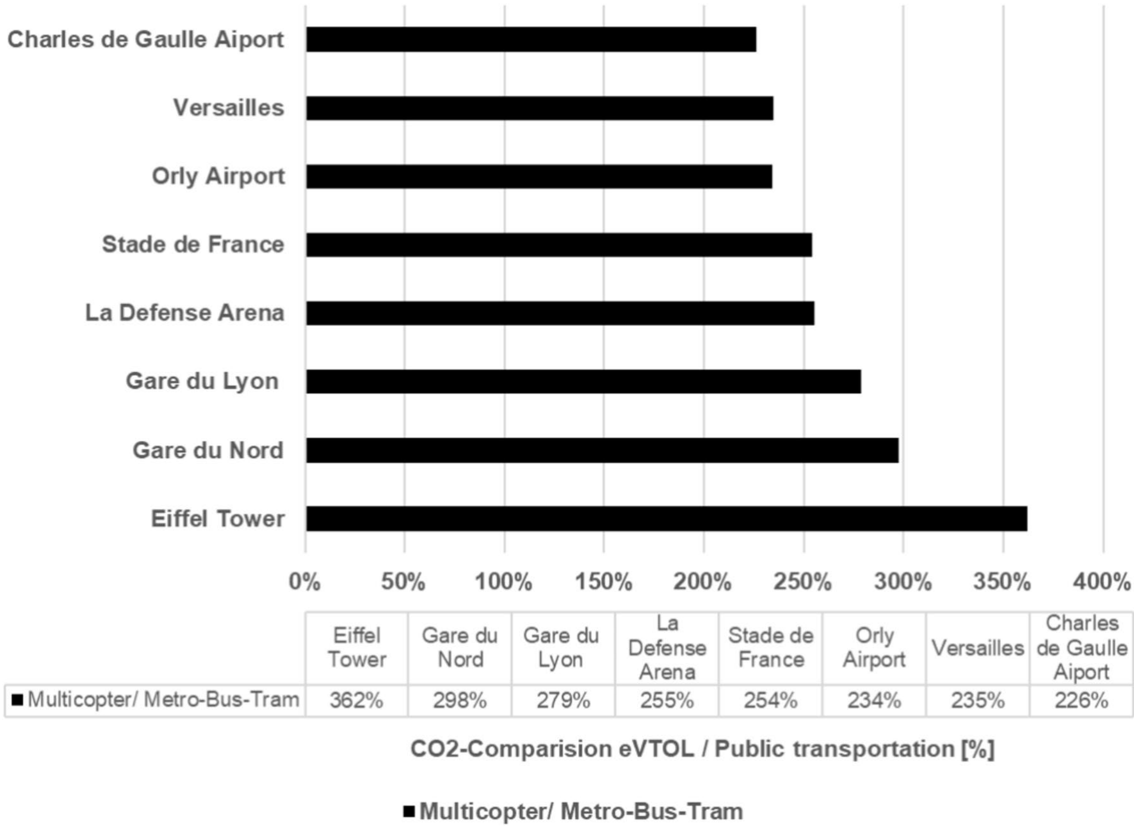
In the context of the regional use case, the comparison between lift-and-cruise eVTOLs and electric trains unequivocally demonstrates that eVTOLs emit notably more CO_2 than an electric train with 2 passengers (see Fig. 13).

Quantitatively, the eVTOL performs poorly with an average emissions level of approximately 197%, meaning it emits nearly 2 times more CO_2 than the electric train on regional routes (cf. Figure 14).

This difference in CO_2 emissions highlights the substantial environmental advantage of electric trains over lift-and-cruise eVTOLs for regional travel. Electric trains offer a much cleaner and greener alternative, essentially reducing CO_2 emissions and contributing to a more sustainable transportation system.

5.4 CO_2 emission evtol vs. helicopter

The results in Table 8 show the CO_2 emissions per km and passenger of all investigated helicopter types and eVTOL configurations. The flight mission with up to 300 km for



	Eiffel Tower	Gare du Nord	Gare du Lyon	La Defense Arena	Stade de France	Orly Airport	Versailles	Charles de Gaulle Aiport
Multicopter/ Metro-Bus-Tram	362%	298%	279%	255%	254%	234%	235%	226%

Fig. 12 Use Case: UAM—percentage CO_2 emission comparison multicopter vs. public transportation

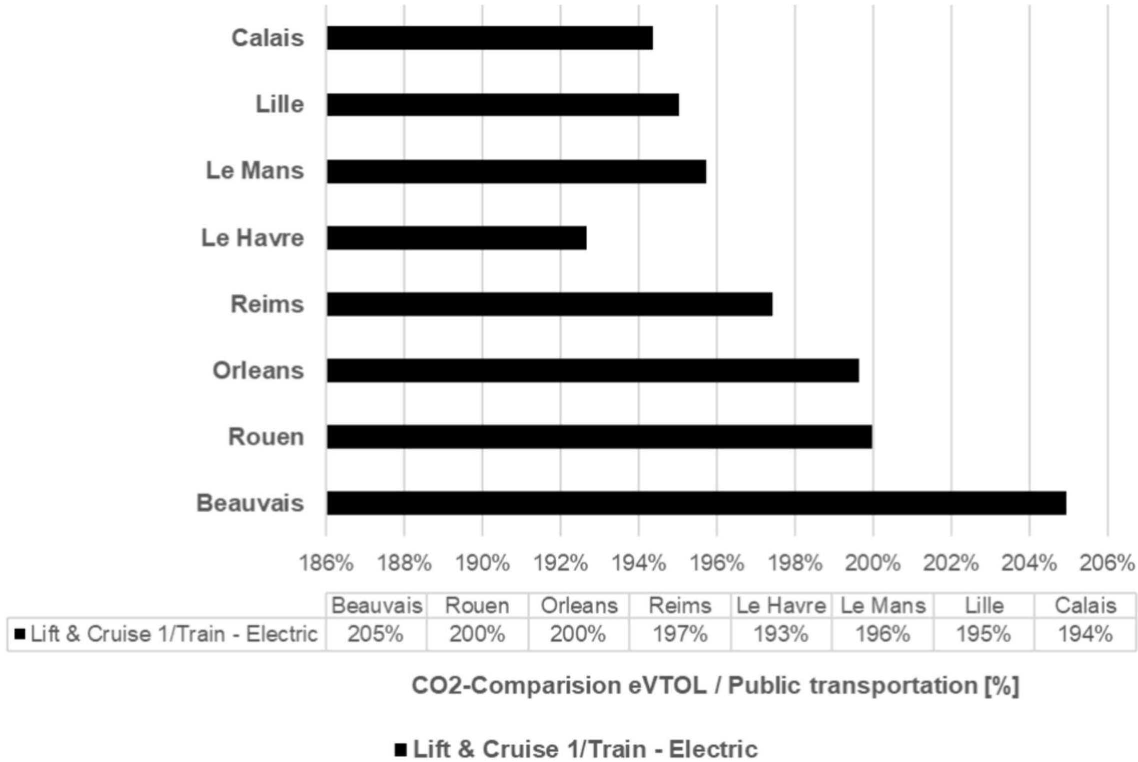
RAM was calculated using the energy demand for the cruise phase for, as described in Sect. 2.4. Using the formula (5), the CO_2 emissions were calculated, considering the European electricity mix, and then calculated CO_2 emission per passenger-km.

The lowest CO_2 emission for any helicopter is the R66 with 0.17 kg/passenger-km. Due to the turbine engine and the higher start-up fuel consumption, the R44 with a fuel consumption of 0.21 kg/km is used for subsequent investigations being more representative. The highest CO_2 emission for eVTOL configuration type is in this case the Quadcopter with 0.66 kg/km due to its MTOW and BM as shown in Table 5. In this study, the lowest CO_2 emissions are associated with the vectored thrust and tilt-rotor concepts, both at 0.05 kg/km. These results can be explained by the fact that the MTOW of the Quadcopter is very high, resulting in a high energy demand during the flight phase. Conversely, for the tilt-rotor concept, the high glide ratio and the low energy demand contribute to the low CO_2 emissions. This type can avoid the additional transition phase required by other eVTOL types.

Figure 15 illustrates the equivalent CO_2 emissions for a multicopter concept compared to the average emissions of seven selected helicopters for urban use cases. It is clear that the fuel consumption during run-up results in higher CO_2 emissions for the selected helicopters. For the shortest route from Place de la Concorde to the Eiffel Tower, the average emission from the helicopters is around 0.57 kg CO_2 (eq), resulting in a 12% reduction in CO_2 emissions with the multicopter. For the longest UAM distance to Charles de Gaulle Airport, the helicopters emit around 8.55 kg CO_2 (eq) per passenger on average, whereas the multicopter indicates a 51% potential reduction in CO_2 emissions.

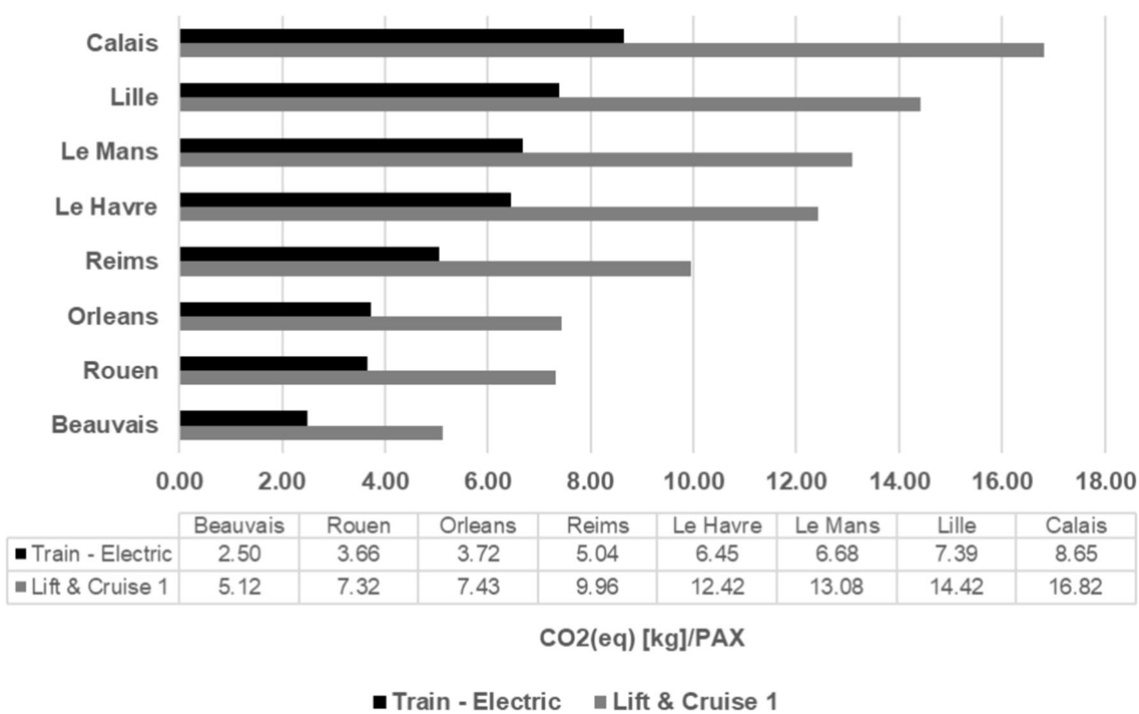
Figure 16 illustrates the equivalent CO_2 emissions for a lift-and-cruise concept compared to the average emissions of seven selected helicopters for regional use cases. For the shortest route from Place de la Concorde to the city of Beauvais, the average emission from the helicopters is around 20.91 kg CO_2 (eq), resulting in a 75% reduction in CO_2 emissions with the multicopter. For the longest RAM distance to Calais, the helicopters emit around 72.38 kg CO_2 (eq) per passenger on average, whereas the multicopter indicates a 77% potential reduction in CO_2 emissions.

All investigations do not consider the efficiency gains of the helicopter when cabin heating or defrosting is required. This will cost additional electric energy for the UAM concept, while the helicopter can use the engine heat exchanger.



	Beauvais	Rouen	Orleans	Reims	Le Havre	Le Mans	Lille	Calais
■ Lift & Cruise 1/Train - Electric	205%	200%	200%	197%	193%	196%	195%	194%

Fig. 13 Use Case: RAM—total CO_2 emission comparison lift-and-cruise vs. public transportation



	Beauvais	Rouen	Orleans	Reims	Le Havre	Le Mans	Lille	Calais
■ Train - Electric	2.50	3.66	3.72	5.04	6.45	6.68	7.39	8.65
■ Lift & Cruise 1	5.12	7.32	7.43	9.96	12.42	13.08	14.42	16.82

Fig. 14 Use Case: RAM—percentage CO_2 emission comparison lift-and-cruise vs. public transportation

Table 8 CO_2 emissions per PAX-km of different VTOL

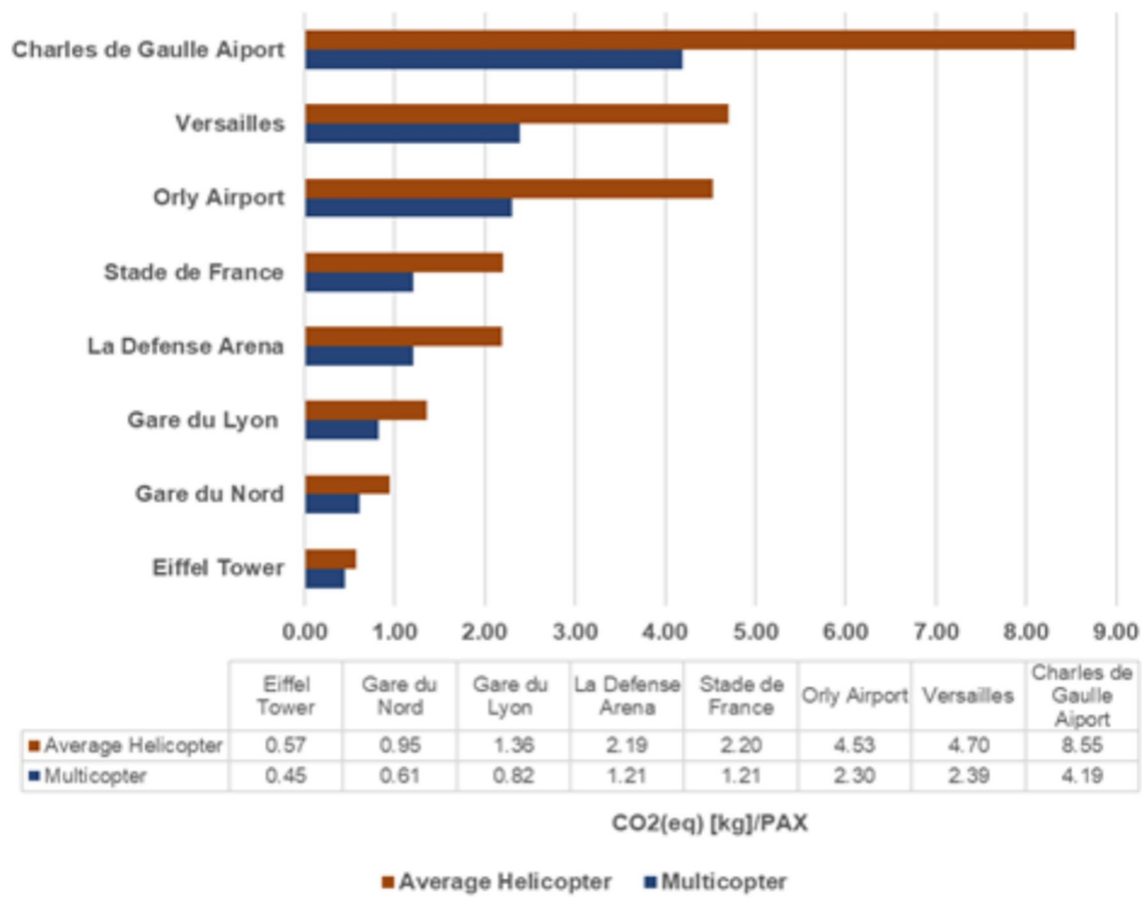
Helicopter	CO_2 eq [kg/PAX-km]	eVTOL	CO_2 eq [kg/PAX-km]
R44	0.21	Multicopter	0.14
R66	0.17	Multicopter	0.15
H120	0.31	Quadcopter	0.66
H125	0.27	Lift + cruise 1	0.06
H135	0.39	Lift + cruise 2	0.10
H145	0.35	Vectored lift	0.05
Bell 206	0.37	Tilt-rotor	0.05

6 Discussion

Several key elements will be discussed concerning the sustainability of air taxis. First, this paper acknowledges that while the analysis focused on time efficiency and CO_2 emissions of air taxis, sustainability encompasses various factors beyond these two aspects. Additional sustainable factors, such as noise pollution, land use for vertiports, or the overall infrastructure impact, should be considered to provide a comprehensive evaluation of the overall sustainability of air taxis.

Second, from the perspective of time-saving, it is needed to discuss the assessment of simplistic vertiport operations and crucial factors, such as boarding and de-boarding times. In real-world scenarios, the time taken for passengers to reach the vertiport from their location (door-to-vertiport time) and the time required for boarding and de-boarding procedures can essentially impact the overall travel time. Therefore, a thorough approach, encompassing the entire travel process from the passenger's point of origin to the final destination, is essential to provide a more accurate and realistic assessment of the time-saving potential of eVTOLs in urban and regional transportation settings.

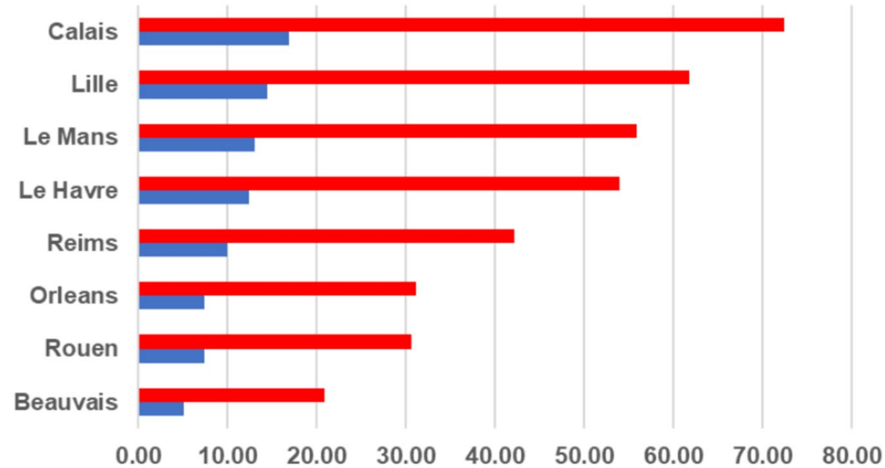
Third, this paper suggests that a more in-depth comparison of CO_2 emissions could be achieved through a detailed analysis of the entire Product Life Cycle, which would consider emissions across all stages of an air taxi's life, from manufacturing and operation to end-of-life disposal. This comprehensive approach would provide a more detailed



	Eiffel Tower	Gare du Nord	Gare du Lyon	La Defense Arena	Stade de France	Orly Airport	Versailles	Charles de Gaulle Aiport
Average Helicopter	0.57	0.95	1.36	2.19	2.20	4.53	4.70	8.55
Multicopter	0.45	0.61	0.82	1.21	1.21	2.30	2.39	4.19

Fig. 15 CO_2 emissions for UAM destinations multicopter vs. average helicopter

Fig. 16 CO_2 emissions for RAM destinations multicopter vs. average helicopter

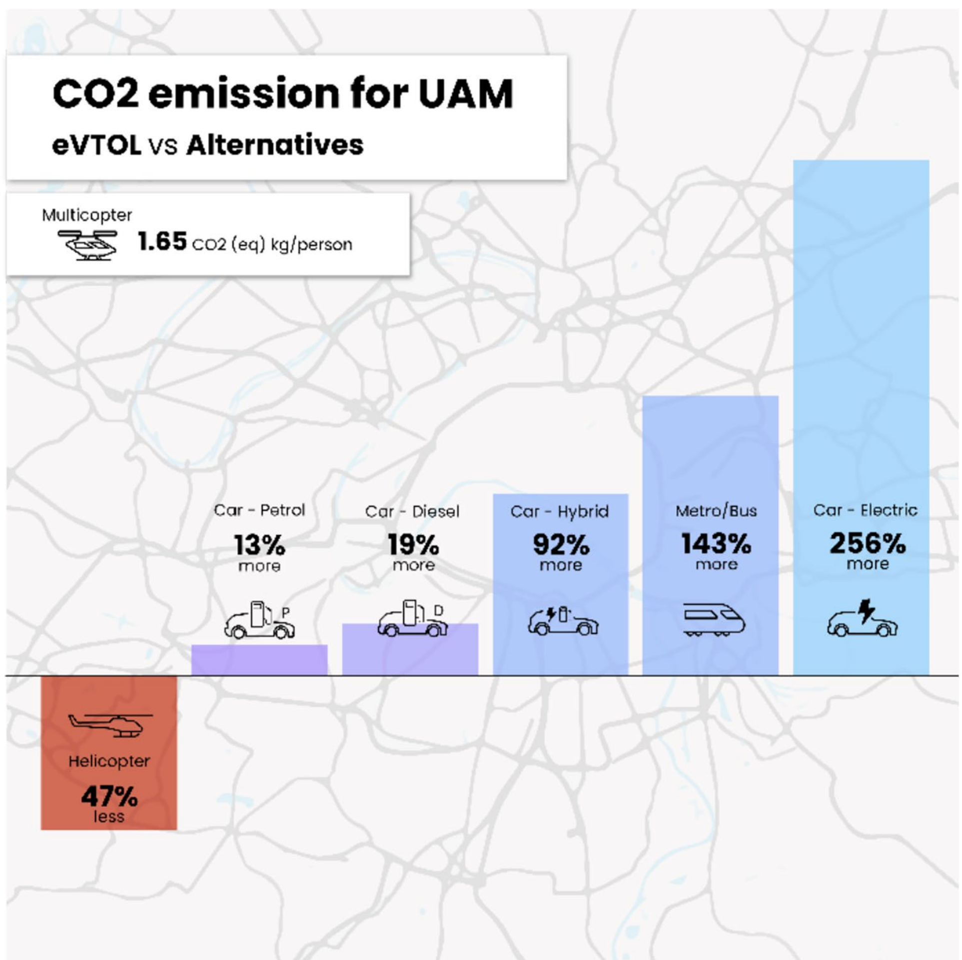


	Beauvais	Rouen	Orleans	Reims	Le Havre	Le Mans	Lille	Calais
Average Helicopter	20.91	30.63	31.11	42.17	53.92	55.89	61.82	72.38
Lift & Cruise 1	5.12	7.32	7.43	9.96	12.42	13.08	14.42	16.82

CO2(eq) [kg]/PAX

Average Helicopter Lift & Cruise 1

Fig. 17 CO_2 emissions comparison for UAM: multicopter vs. alternatives



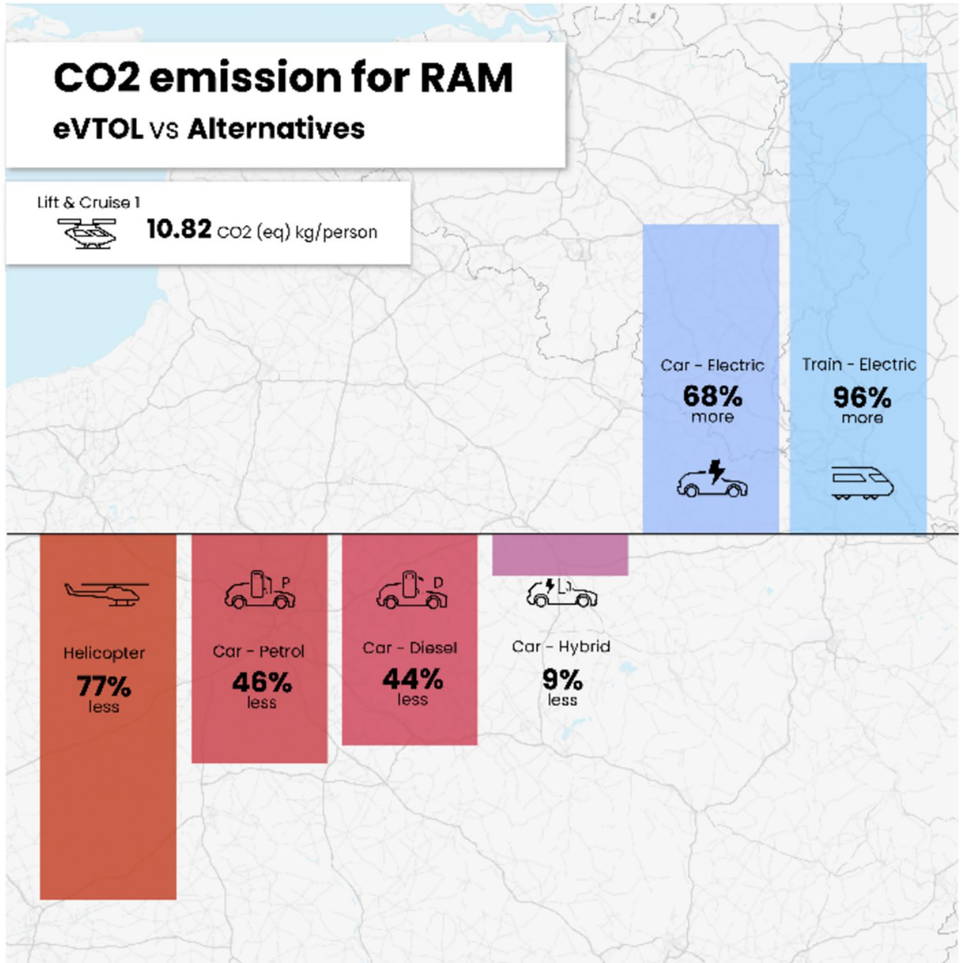


Fig. 18 CO_2 emissions comparison for RAM: lift-and-cruise vs. alternatives

understanding of the environmental impact of air taxis and aid in identifying areas for improvement.

Another crucial point raised is the limited scope of the analysis, which only considered multicopters and lift-and-cruise configuration. To provide a more holistic picture, this paper suggests including various configurations, such as tilt-rotors and vectored thrust, in the calculations and comparing their performance. Different flight models may exhibit varying energy efficiencies and emissions profiles, which could influence the overall sustainability assessment.

Additionally, an essential aspect to consider is that the energy demand of eVTOLs was only calculated for a simplified mission profile (cf. Figure 4) for two scenarios UAM and RAM, respectively. To obtain a more realistic representation, further calculations should account for various operating conditions, such as hover time, and flight altitudes. Also, redundancy, flight safety, and reliability were of no concerns for this investigation. The data show that these performance indicators have an essential impact on the fuel consumption of helicopters. Another factor that was not considered is winter operations capability or all-weather capability. It is anticipated that under these conditions, the energy demand will be considerably higher, consequently leading to increased CO_2 emissions.

Furthermore, this paper underscores the significance of tailoring CO_2 emission calculations to reflect the specific energy mix of the country in which the flight routes are situated. The choice to utilize the average European electricity mix in the analysis was driven by the aim to establish a broad foundation that aligns with the overarching integration of UAM into major urban areas across Europe. This approach facilitates a comprehensive understanding of the potential sustainability impact of UAM on a pan-European scale, guiding policy decisions and frameworks for UAM adoption in diverse metropolitan contexts. However, this paper recommends a more refined approach utilizing the distinct French electricity mix, boasting a lower CO_2 intensity of 58 gr/kWh, for flights conducted within France. This adaptable approach acknowledges the variance in energy sources between countries, ensuring the accuracy of sustainability data tailored to regional nuances. The dynamic nature of these energy sources also underscores the influence of contemporary political and environmental contexts.

These points emphasize the need for a broader analysis and more realistic operating conditions to obtain a comprehensive understanding of the sustainability and environmental impact of eVTOLs.

This paper brings attention to key considerations for a comprehensive evaluation of the sustainability of air taxis. It emphasizes the need to explore and include various sustainable factors beyond time efficiency and CO_2 emissions, conduct product lifecycle analysis, broaden the scope of flight models, and customize emission calculations based on the specific energy mix of the region. Addressing these points would lead to a more nuanced understanding of the environmental impact of air taxis and pave the way for promoting sustainable aviation solutions.

7 Conclusion

In this paper, timing saving and CO_2 emission by two eVTOL configurations for urban and regional transportation were evaluated. The analysis was compared to conventional transportation modes, such as cars, public transportation, and helicopters. In the realm of CO_2 emissions, the analysis uncovers a valuable divergence between urban and regional scenarios.

The key findings of CO_2 emissions by an eVTOL compared to conventional transportation modes during an urban flight are shown in the following Fig. 17:

Urban eVTOL operations are aiming to offer a greener and more efficient alternative to conventional transportation. However, due to their elevated energy consumption, they demonstrate relatively lesser ecological friendliness compared to certain other modes of transportation. Specifically, for the UAM use case, a Multicopter consumes an average UAM mission of 1.65 kg of CO_2 equivalent per person. When compared to other means of transport, the Multicopter consumes 47% less than the average conventional helicopter, making it a more environmentally conscious choice for urban air mobility. However, it does consume 13% more than a petrol car, 19% more than a diesel car, 92% more than a hybrid car, 143% more than a metro–bus–tram, and 256% more than an electric car. It is evident that multicopters for the use case UAM generally exhibit higher CO_2 emission values per passenger compared to conventional cars.

The key findings of CO_2 emissions by an eVTOL compared to conventional transportation modes during a regional flight are shown in the following Fig. 18:

In the regional context, eVTOLs, such as the Lift-and-Cruise 1, showcase substantial CO_2 reductions compared to average conventional helicopters, petrol, diesel, and hybrid vehicles. Specifically, the Lift-and-Cruise 1 eVTOL consumes 77% less CO_2 equivalent than the average conventional helicopter, 46% less than a petrol car, 44% less than a diesel car, and 9% less than a hybrid car. This highlights the valuable CO_2 emission comparison between eVTOLs and different conventional transportation modes. However, it is crucial to note that eVTOLs emit significantly 68% more CO_2 than electric vehicles and 96% more than electric trains on selected regional routes.

Consequently, while the adoption of eVTOLs can significantly reduce the carbon footprint compared to using conventional helicopters and certain ground vehicles, it is essential to consider the broader spectrum of available transportation modes as ground-based electric vehicles and public transportation still offer lower CO_2 emissions for urban and regional transit.

The following key findings can be highlighted:

- eVTOLs can save more than 20 min on average by direct flight compared to cars and public transportation on urban level (< 50 km)
- eVTOLs can save essential time by direct flight on the regional level (< 300 km) compared to cars around 76 min and 69 min compared to train
- eVTOL concepts can reduce the operational CO_2 emissions compared to combustion engine-driven helicopter flights
- eVTOLs consume in urban areas more energy than ground transport options
- eVTOLs can save CO_2 emissions compared to combustion engine cars on regional routes
- Electric trains are the most environmentally friendly alternative for regional transport

These results highlight the need to continue research and development to improve the environmental performance of eVTOL technology and prioritize the introduction of greener transportation alternatives to reduce the environmental impact of greenhouse gas emissions. The most obvious impacts are energy requirements during take-off, start-up, and shutdown, especially for UAM flights, and lower CO_2 emissions during cruise for regional flights.

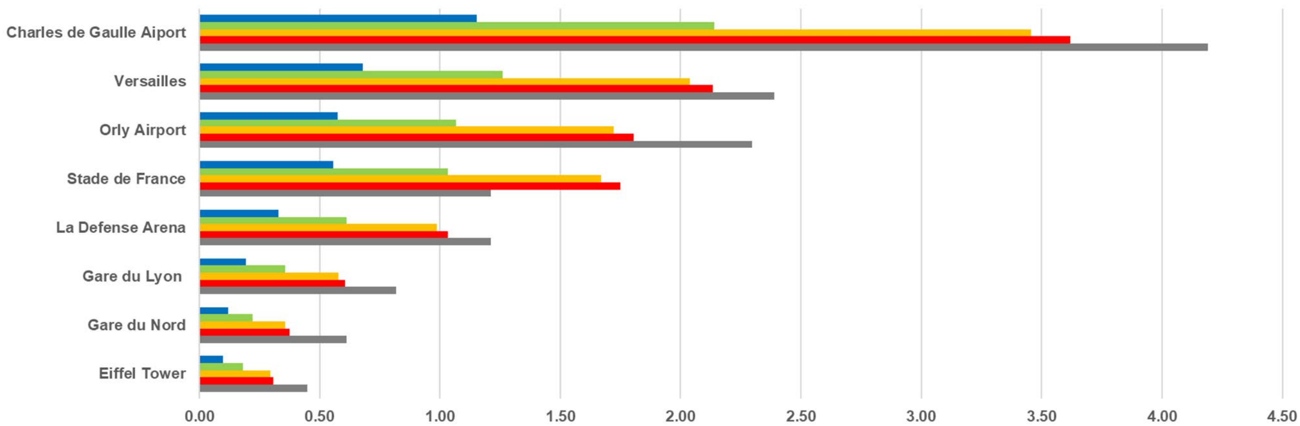
As battery technology advances, eVTOLs are likely to become increasingly efficient, paving the way for a cleaner and more sustainable mode of transportation in future. However, it is also prudent to focus on renewable energy sources. In summary, the carbon footprint of UAM vehicles is largely dependent on the type of energy source used to power them.

Efforts to promote and invest in efficient transportation and greener technologies have an important role to play in achieving a more sustainable and environmentally conscious future.

Appendix

See Figs. 19, 20, 21, 22; Tables 9, 10, 11, 12, 13, 14, 15, 16, 17, 18

The detailed CO_2 emission for UAM by multicopter

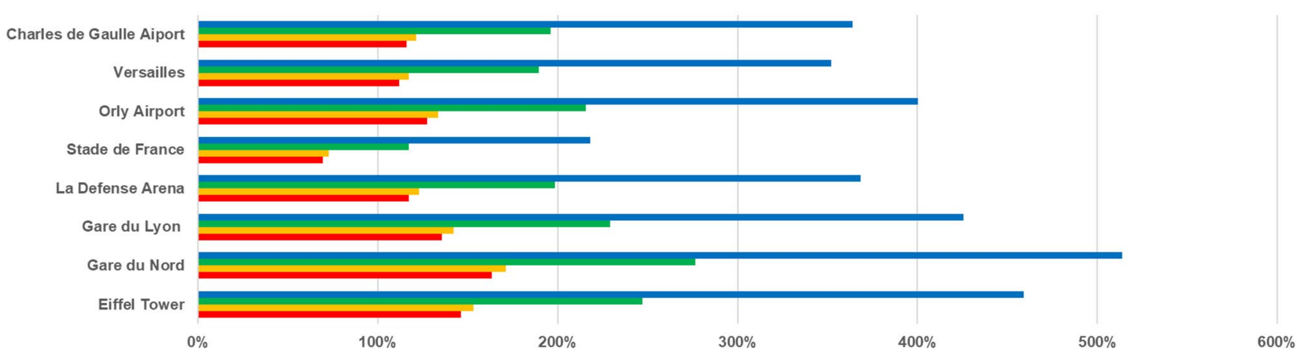


	Eiffel Tower	Gare du Nord	Gare du Lyon	La Defense Arena	Stade de France	Orly Airport	Versailles	Charles de Gaulle Aiport
Car - Electric	0.10	0.12	0.19	0.33	0.56	0.57	0.68	1.15
Car - Hybrid	0.18	0.22	0.36	0.61	1.03	1.07	1.26	2.14
Car - Diesel	0.29	0.36	0.58	0.99	1.67	1.72	2.04	3.45
Car - Petrol	0.31	0.37	0.61	1.03	1.75	1.80	2.13	3.62
Multicopter	0.45	0.61	0.82	1.21	1.21	2.30	2.39	4.19

CO2(eq) [kg]/PAX

Car - Electric   Car - Hybrid   Car - Diesel   Car - Petrol   Multicopter

Fig. 19 Use Case: UAM—total CO_2 emission by multicopter and cars



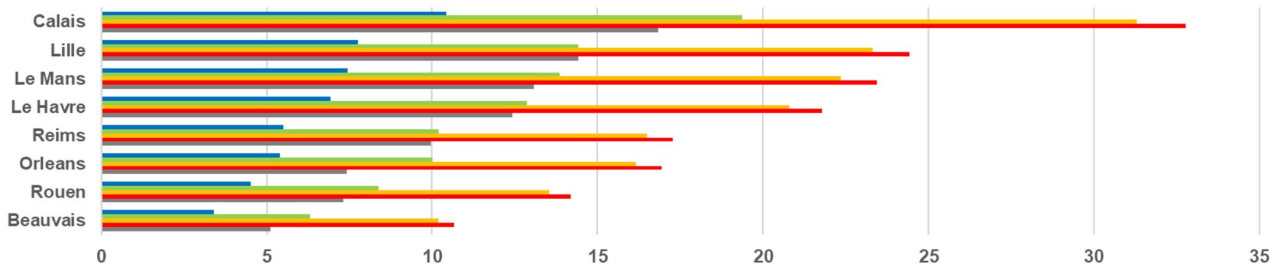
	Eiffel Tower	Gare du Nord	Gare du Lyon	La Defense Arena	Stade de France	Orly Airport	Versailles	Charles de Gaulle Aiport
Multicopter/ Car - Electric	459%	514%	426%	369%	218%	400%	352%	364%
Multicopter/ Car - Hybrid	247%	277%	229%	198%	117%	216%	190%	196%
Multicopter/ Car - Diesel	153%	171%	142%	123%	73%	133%	117%	121%
Multicopter/ Car-Petrol	146%	163%	135%	117%	69%	127%	112%	116%

CO2-Comparision eVTOL / Vehicle [%]

Multicopter/ Car - Electric   Multicopter/ Car - Hybrid   Multicopter/ Car - Diesel   Multicopter/ Car-Petrol

Fig. 20 Use Case: UAM—percentage CO2 emission comparison multicopter vs. car

The detailed CO_2 emission for RAM by lift-and-cruise

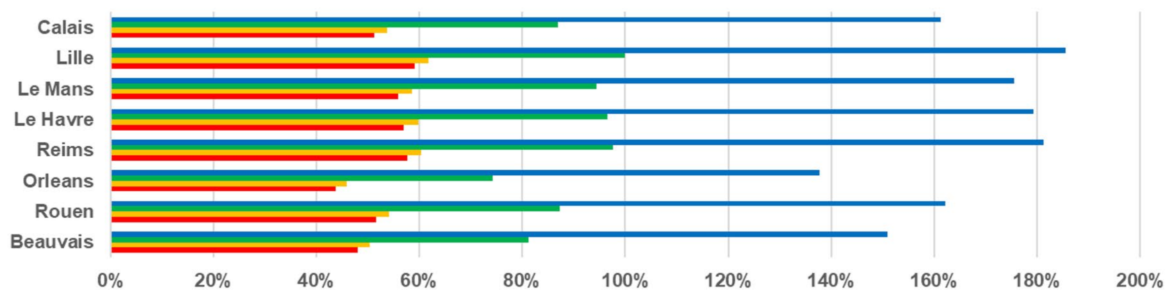


	Beauvais	Rouen	Orleans	Reims	Le Havre	Le Mans	Lille	Calais
Car - Electric	3.40	4.52	5.39	5.50	6.93	7.46	7.77	10.43
Car - Hybrid	6.31	8.39	10.01	10.21	12.87	13.85	14.43	19.37
Car - Diesel	10.19	13.55	16.17	16.49	20.79	22.37	23.31	31.29
Car - Petrol	10.67	14.19	16.94	17.27	21.78	23.43	24.42	32.78
Lift & Cruise 1	5.12	7.32	7.43	9.96	12.42	13.08	14.42	16.82

CO2(eq) [kg]/PAX

Car - Electric　Car - Hybrid　Car - Diesel　Car - Petrol　Lift & Cruise 1

Fig. 21 Use Case: RAM—total CO2 emission by lift-and-cruise 1 and car



	Beauvais	Rouen	Orleans	Reims	Le Havre	Le Mans	Lille	Calais
Lift & Cruise 1/Car - Electric	151%	162%	138%	181%	179%	175%	186%	161%
Lift & Cruise 1/Car - Hybrid	81%	87%	74%	98%	97%	94%	100%	87%
Lift & Cruise 1/Car - Diesel	50%	54%	46%	60%	60%	58%	62%	54%
Lift & Cruise 1/ Car-Petrol	48%	52%	44%	58%	57%	56%	59%	51%

CO2-Comparision eVTOL / Vehicle [%]

Fig. 22 Use Case: RAM—percentage CO_2 emission comparison lift-and-cruise 1 vs. car

The detailed calculated results for time-saving on the UAM level: use case: UAM—intra-city (< 50 km). Start: place de la concorde (48.880079377411434, 2.3209529783314298)

Table 9 Use case: UAM—distance and travel time by eVTOL, cars & public transportation

Destination: UAM	Flight range [km]	Flight time [min]	Car distance [km]	Car time [min]	Train time [min]
Eiffel tower	1.94	2	2,8	7	20
Gare du Nord	3.21	3	3,4	25	21
Gare de Lyon	4.59	4	5,5	26	16
La Défense Arena	7.42	5	9,4	35	24
Stade de France	7.45	5	15,9	35	34
Orly airport	15.33	10	16,4	37	57
Versailles	15.92	10	19,4	38	49
Charles de Gaulle airport	28.94	19	32,9	46	63

Table 10 Use case: UAM—latitude and longitude of destination

Destination: UAM	Latitude and longitude
Eiffel tower	48.85860133062431, 2.294521555637876
Gare du Nord	48.88135187311856, 2.355220655293813
Gare de Lyon	48.84467549552589, 2.374281457292527
La Défense Arena	48.89563213687809, 2.22961956012617
Stade de France	48.92601522501372, 2.3602917068864584
Orly airport	48.7302053462825, 2.365637273265505
Versailles	48.80705182917126, 2.120254946559202
Charles de Gaulle airport	49.01171630623034, 2.5518109714304003

The detailed calculated results for time-saving on RAM level: use case: RAM (< 300 km). Start: place de la concorde (48.880079377411434, 2.3209529783314298)

Table 11 Use case: RAM—distance and travel time by eVTOL, cars & public transportation

Destination: RAM	Flight range [km]	Flight time [hr:min]	Car distance [km]	Car time [hr:min]	Train time [hr:min]
Calais	240	01:21	298	03:13	04:09
Le Mans	185	01:03	213	02:25	02:35
Beauvais	69	00:24	97	01:21	01:37
Lille	205	01:09	222	02:31	02:31
Orleans	103	00:36	154	01:58	02:12
Le Havre	179	01:01	198	02:22	03:21
Reims	140	00:48	157	01:30	02:30
Rouen	101	00:35	129	01:47	02:38

Table 12 Use case: RAM—latitude and longitude of destination

Destination: RAM	Latitude and longitude
Calais	51.014019961073494, 1.9589627300023547
Le Mans	47.971754926169446, 0.19406329470439904
Beauvais	49.47374521207076, 2.1076144873066
Lille	50.63954613506171, 3.1071012113886605
Orleans	47.940949692303505, 2.1667537797583964
Le Havre	49.56180450545073, 0.09679634369569831
Reims	49.228246054031615, 4.159641967594461
Rouen	49.40050050927563, 1.1862262267802346

The detailed energy demand and CO_2 emission for UAM

Table 13 Use case: UAM—energy demand and CO_2 emission per passenger by eVTOL

Destination: UAM	eVTOL	
	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]
Eiffel tower	1.9	0.45
Gare du Nord	2.71	0.61
Gare de Lyon	3.63	0.82
La Défense Arena	5.37	1.21
Stade de France	5.38	1.22
Orly airport	10.17	2.30
Versailles	10.58	2.39
Charles de Gaulle airport	18.55	4.19

Table 14 Use case: UAM—energy demand and CO_2 emission per passenger by cars

Destination: UAM	Petrol car		Diesel car		Hybrid car		Electric car	
	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]
Eiffel tower	0.96	0.31	0.91	0.29	0.45	0.18	0.21	0.10
Gare du Nord	1.17	0.37	1.10	0.36	0.55	0.22	0.26	0.12
Gare de Lyon	1.89	0.61	1.79	0.58	1.10	0.36	0.41	0.19
La Défense Arena	3.24	1.03	3.05	0.99	1.53	0.61	0.71	0.33
Stade de France	5.48	1.75	5.17	1.67	2.58	1.03	1.19	0.56
Orly airport	5.65	1.80	5.33	1.72	2.66	1.07	1.23	0.57
Versailles	6.68	2.13	6.30	2.04	3.15	1.26	1.46	0.68
Charles de Gaulle airport	11.33	3.62	10.69	3.45	5.35	2.14	2.47	1.15

Table 15 Use case: UAM—energy demand and CO_2 emission per passenger by public transportation

Destination: UAM	Public transport	
	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]
Eiffel tower	0.29	0.12
Gare du Nord	0.48	0.21
Gare de Lyon	0.69	0.29
La Défense Arena	1.11	0.47
Stade de France	1.12	0.48
Orly Airport	2.30	0.98
Versailles	2.39	1.02
Charles de Gaulle airport	4.34	1.85

The detailed energy demand and CO_2 emission for RAM

Table 16 Use case: RAM—energy demand and CO_2 emission per passenger by eVTOL

Destination: RAM	eVTOL	
	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]
Beauvais	22.68	5.12
Rouen	32.41	7.32
Orleans	32.86	7.43
Reims	44.05	9.96
Le Havre	54.97	12.42
Le Mans	57.88	13.08
Lille	63.79	14.42
Calais	74.44	16.82

Table 17 Use case: RAM—energy demand and CO_2 emission per passenger by cars

Destination: RAM	Car—petrol		Car—diesel		Car—hybrid		Car—electric	
	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]
Beauvais	33.41	10.67	31.52	10.19	15.76	6.31	7.28	3.40
Rouen	44.43	14.19	41.92	13.55	20.96	8.39	9.68	4.52
Orleans	53.04	16.94	50.04	16.17	25.02	10.01	11.55	5.39
Reims	54.07	17.27	51.02	16.49	25.51	10.21	11.78	5.50
Le Havre	68.19	21.78	64.34	20.79	32.17	12.87	14.85	6.93
Le Mans	73.36	23.43	69.21	22.37	34.61	13.85	15.98	7.46
Lille	76.46	24.42	72.14	23.31	36.07	14.43	16.65	7.77
Calais	102.63	32.78	96.84	31.29	59.59	19.37	22.35	10.43

Table 18 Use case: RAM—energy demand and CO_2 emission per passenger by electric train

Destination: UAM	Electric train	
	Energy demand/PAX [kWh]	CO_2eq/PAX [kg]
Beauvais	10.42	2.50
Rouen	15.26	3.66
Orleans	15.50	3.72
Reims	21.01	5.04
Le Havre	26.86	6.45
Le Mans	27.84	6.68
Lille	30.80	7.39
Calais	36.06	8.65

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References

1. NASA: Advanced air mobility LG-2022-04-090-HQ. https://www.nasa.gov/sites/default/files/atoms/files/aam-litho.pdf (2022). Accessed 24 Aug 2023
2. City of Paris, Green Parks, and Environment Urban Ecology Agency: Paris climate action plan, towards a carbon neutral city, 100% renewable energies, resilient, fair and inclusive (2020)
3. Boztas, S.: Electric air taxis being developed for the Paris olympics in 2024. The guardian. https://www.theguardian.com/world/2023/mar/21/sb-paris-taxis (2023). Accessed 24 Aug 2023
4. Société du Grand Paris: The grand Paris express is making headway | grand Paris express. https://www.societedugrandparis.fr/gpe-headway (2023). Accessed 19 Apr 2023
5. Our World in Data: Climate change and flying: what share of global CO2 emissions come from aviation?. https://ourworldindata.org/co2-emissions-from-aviation (2023). Accessed 19 Apr 2023
6. Choose Paris Region: Paris region facts & figures 2022. L'Institut Paris Region, and the Paris Île-de-France regional chamber of commerce and industry (2022)
7. Île-de-France Mobilités: La nouvelle enquête globale transport, Présentation des premiers résultats 2018, Assises de la mobilité en Île-de-France. http://www.omnil.fr (2019)
8. Naser, F., Peinecke, N., Schuchardt, B.I.: Air taxis vs. taxicabs: a simulation study on the efficiency of UAM. AIAA Aviation 2021 Forum. Virtual. (2021). https://doi.org/10.2514/6.2021-3202
9. Liberacki, A., Woroniecka, P., Stańczyk, A.: acceptance safety and sustainability recommendations for efficient deployment of UAM, ASSURED UAM, D2.3-UAM ELCC+E estimation. Łukasiewicz research network—institute of aviation
10. Asmer, L., Pak, H., Shivaprakasha, P., et al.: Urban air mobility use cases, missions and technology scenarios for the horizonUAM project. AIAA Aviation Forum 2021. Virtual. (2021). https://doi.org/10.2514/6.2021-3198

11. EASA: Urban air mobility. https://www.easa.europa.eu/en/domains/urban-air-mobility-uam (2023). Accessed 29 Jun 2023
12. Vertical Flight Society: eVTOL aircraft directory. https://evtol.news/aircraft (2023). Accessed 24 Aug 2023
13. Palaia, G., Abu Salem, K., Cipolla, V., et al.: A conceptual design methodology for e-VTOL aircraft for urban air mobility. Appl. Sci. (2021). https://doi.org/10.3390/app112210815
14. Finger, D.F., Götten, F., Braun, C., et al: Initial sizing for a family of hybrid-electric VTOL general aviation aircraft, Bonn, Germany (2018)
15. Ugwueze, O., Statheros, T., Horri, N., et al.: Investigation of a mission-based sizing method for electric VTOL aircraft preliminary design. AIAA SCITECH 2022 Forum. San Diego, CA & Virtual. (2022). https://doi.org/10.2514/6.2022-1931
16. Kadhiresan, A.R., Duffy, M.J.: Conceptual design and mission analysis for eVTOL urban air mobility flight vehicle configurations. AIAA Aviation 2019 Forum. Dallas, Texas. (2019). https://doi.org/10.2514/6.2019-2873
17. Johnson, W., Silva, C., Solis, E. (eds.): Concept vehicles for VTOL air taxi operations. Technical Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, USA, 16–18 January 2018 (2018)
18. Liu, Y.-T., Liu, S., Li, G.-R., et al.: Strategy of enhancing the volumetric energy density for lithium-sulfur batteries. Adv. Mater. (2021). https://doi.org/10.1002/adma.202003955
19. Bacchini, A., Cestino, E.: eVTOL configurations comparison. MDPI J. Aerosp. (2019). https://doi.org/10.3390/aerospace6030026
20. Sripad, S., Viswanathan, V.: The promise of energy-efficient battery-powered urban aircraft Nr. 45. http://arxiv.org/pdf/2106.09513v1 (2021). https://doi.org/10.1073/pnas.2111164118
21. Leishman, J.G.: Principles of helicopter aerodynamics, Cambridge, United Kingdom (2017)
22. van der Wall, B.: Grundlagen der Hubschrauber Aerodynamik. Springer, Berlin (2020). https://doi.org/10.1007/978-3-662-60365-9
23. FuelsEurope: Statistical report 2023. GHG emisson trend by sector in the EU-27. https://www.fuelseurope.eu/statistics (2023). Accessed 12 Dec 2023
24. Inernational Energy Agency (IEA): Vehicle fuel economy in major markets 2005–2019 (October 202)
25. European Envionment Agency: Fuel consumption in the EU-27, per fuel type. https://www.eea.europa.eu/data-and-maps/figures/fuel-consumption-trends-per-fuel-type-2 (2023)
26. Eurostat: glossary: Carbon dioxide equivalent. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent (2023). Accessed 25 Aug 2023
27. Roland Berger: The-urban-air-mobility-revolution. https://www.rolandberger.com/en/Insights/Publications/The-Urban-Air-Mobility-Revolution.html (2016). Accessed 19 Apr 2023
28. Khavarian, K., Kockelman, K. M.: Life-cycle analysis of eVTOL vehicles. Bridging Transportation Researchers (BTR) Conference. Virtual. 7–8 January 2020. https://www.caee.utexas.edu/prof/kockelman/public_html/TRB20eVTOL.PDF (2020). Accessed 19 Apr 2023
29. Rodrigues, T.A., Patrikar, J., Oliveira, N.L., et al.: Drone flight data reveal energy and greenhouse gas emissions savings for very small package delivery. Patterns (N Y) (2022). https://doi.org/10.1016/j.8patter.2022.100569
30. European Envionment Agency: CO2 emissions performance of new passenger cars in Europe. https://www.eea.europa.eu/en/analysis/indicators/co2-performance-of-new-passenger (2024). Accessed 25 May 2024
31. Hagag, N., Büddefeld, M., Eduardo, H., et al.: Maximum total range of eVTOL under consideration of realistic operational scenarios. 11th SESAR innovation days. Virtual. 09. 10.12.2021. https://www.sesarju.eu/sites/default/files/documents/sid/2021/papers/SIDs_2021_paper_69.pdf (2021). Accessed 19 Apr 2023
32. US EPA: Greenhouse gases equivalencies calculator-calculations and references | US EPA. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (2015). Accessed 25 Aug 2023
33. European Environment Agency: Electricity and heat generation-emission factors and reference years, 2020. https://www.eea.europa.eu/data-and-maps/data#c0=5&c11=&c5=all&b_start=0 (2022). Accessed 09 May 2023