

Well-to-Wheel Greenhouse Gas Emissions from Flying Cars: A Focus on Air Shuttles

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ABSTRACT

Flying cars are becoming a key technology in future transportation, because of their ability to travel fast and to reduce traffic jams. Air shuttles are an important application scenario of flying cars. They can carry 19 passengers, playing a similar role as medium on-road buses. However, it is still unclear which has a better performance on carbon emissions, air shuttles or road buses. Based on the analysis of the flying car's flying process, lifecycle greenhouse gas emissions from flying cars which are used as air shuttles are calculated and further compared with on-road bus emissions. For thorough consideration, improvements in battery specific energy are considered, and different propulsion systems for buses are also calculated. The results show that at the current battery technology level (200 Wh/kg specific energy), air shuttles have much more emissions than all kinds of road buses. But if the battery technology progresses to the level of 2030 (400 Wh/kg specific energy as predicted), air shuttles will have a lower emission than fuel cell buses within the range of 250 km, and will be competitive with battery electric bus that carries an equal number of passengers.

KEYWORDS

Air Shuttles; Greenhouse Gas Emissions; Flying Cars; eVTOL; Lifecycle Assessment.

1. INTRODUCTION

In the modern landscape of transportation, flying vehicles represent the epitome of technological progress and hold significant potential for revolutionizing mobility systems (Ayyaswamy et al., 2023; Sutherland, 2019). Consequently, these airborne automobiles are gathering increasing attention due to their ability to offer fast point-to-point transport at high velocities (André & Hajek, 2019; Lin et al., 2020). The National Aeronautics and Space Administration (NASA) envisions diverse applications for flying cars, such as air shuttles, air taxis, and medical air ambulances (Goyal, 2018). In recent years, many researchers and companies have come up with advanced models and many places have started trial operational lines. The German company Volocopter is going to provide 5 flying car airlines during the 2024 Paris Olympic Games (Lynn, 2023). Including Joby Aviation, SkyDrive, Volocopter, and Vertical Aerospace, several companies are going to put their flying cars into mass production after the 2025 Osaka World Expo (Martin, 2023). Governments of countries are also giving support and permission to this rising way of transportation. The Civil Aviation Administration of China (CAAC) has given a flying car the type certificate, specifically the model EH216-S by Ehang, which means that it is qualified for manned commercial operation (Alcock, 2023). The US Air Force had also given the airworthiness certificate to 5 models of flying cars made by Joby Aviation (Reed, 2023).

Numerous research studies have been undertaken to explore the efficiency and cost implications of Vertical Take-Off and Landing (VTOL) vehicles (Fredericks et al., 2018; Sripad & Viswanathan, 2021; Yang et al., 2021). Bacchini et al. (Bacchini & Cestino, 2019) performed calculations on

various VTOL configurations, demonstrating that a 30 km mission could be completed in just 8.2 minutes. Turning to cost implications, Uber's comprehensive investigation in 2016 indicated that the cost per ground mile equivalent for VTOLs was around \$2 to \$3 (Uber, 2016). NASA's work (Goyal, 2018) estimated a passenger price of \$6.25 per mile for a five-seater VTOL, making it pricier than traditional taxis. Liu et al. comprehensively estimated the total cost of ownership of flying cars with different propulsion systems, pointing out that the cost of airport shuttle flying cars can be a priority for application since they can show close or even lower cost than on-road vehicles (Liu et al., 2023). The infrastructure impact was also explored, with NASA highlighting barriers like cost and availability (Ullman, 2017).

Furthermore, several studies have examined the greenhouse gas (GHG) emissions associated with different propulsion systems. Battery-electric VTOLs (BE-VTOLs) are environmentally favorable for short distances, while Fuel Cell VTOLs (FC-VTOLs) are suited for trips spanning 200-250 km. Kasliwal et al. (Kasliwal et al., 2019) established a VTOL model and compared its environmental and economic impacts against those of conventional vehicles. Their findings suggested that VTOLs could emit less GHG than internal combustion engine vehicles in a trip with more than 35 km range, but their emissions are still much higher than battery electric vehicles. Internal combustion engine VTOLs (ICE-VTOLs) are deemed appropriate for long-distance travel (Liu, Qian, Luo, et al., 2022). As advancements occur in battery energy density technology and grid emission factors, BE-VTOLs are expected to become sustainable across a wider range of distances. Improvement in battery specific energy and grid emission factors will largely improve the environmental performance of the 4-seated BE-VTOLs (Liu, Qian, Hao, et al., 2022).

While existing research forms a solid foundation for understanding flying cars, most studies have centered on small VTOLs accommodating up to four passengers. Limited attention has been given to air shuttles, which have a capacity of 19 passengers and the potential to replace medium buses. Operating with a similar point-to-point transit purpose, air shuttles offer significantly shorter travel times, but we still don't know its carbon emissions. How it performs environmentally really affects its future of development, since it cannot betray the country's large goal of reaching carbon zero by 2060. As a result, this study seeks to address this gap by examining the Well-to-Wheel (WTW) emissions of VTOLs carrying 19 passengers, assessing their GHG emissions under various battery energy density scenarios, and comparing this data to electric-powered and fuel cell medium buses. The results show that though BE-VTOL still has a very high emission at today's technology level, it can reach a lower emission to Fuel-Cell Ground Vehicles (FC-GV) and is competitive to Battery Electric Ground Vehicles (BE-GV) once the battery specific energy reaches 400 Wh/kg by 2030, within the range of 200 km. For longer distance travel, buses are still better performed environmentally.

2. METHOD

2.1. Research Framework

Figure 1 illustrates the conceptual framework underpinning this research. The focal system delineates the intricacies and operations inherent in the provision of transportation services via airborne vehicles. This system is delineated into two principal operational phases: upstream, entailing the production of fuel, and downstream, which involves the utilization of said fuel. Noteworthy is the fact that, due to the absence of carbon dioxide emissions during electric-powered operations, all GHG emissions can be attributed to the process of electricity generation.

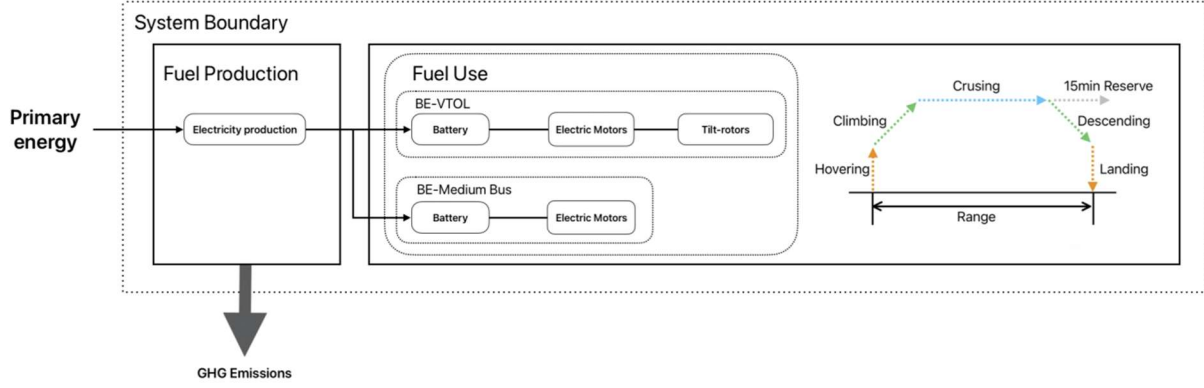


Figure 1. Research framework.

2.2. Flying Process

In the context of VTOL aircraft, a flight trajectory can be dissected into five distinct sub-phases: hovering, climbing, cruising, descending, and landing. During the hovering and landing phases, VTOLs execute vertical takeoff and landing maneuvers. In the climbing and descending phases, VTOLs navigate towards or away from their designated cruising altitude while maintaining a specific angle of attack (AOA). During the cruising phase, VTOLs traverse horizontally at a predefined cruising speed and altitude. The power requirements for each of these sub-phases can be determined by analyzing their respective kinematic and dynamic characteristics, as delineated in Equations 1 to 3 (Liu, Qian, Hao, et al., 2022).

$$P_{hove} = \frac{m_{TO}}{\eta_{hover}} \sqrt{\frac{\delta}{2\rho}} \quad (1)$$

$$P_{climb} = \frac{m_{TO}g}{\eta_{climb}} \left(ROC + \frac{V_{climb}}{L/D_{climb}} \right) \quad (2)$$

$$P_{cruise} = \frac{m_{TO}g}{\eta_{cruise}} \frac{V_{cruise}}{L/D_{cruise}} \quad (3)$$

where,

P_i is the power demand of the VTOL while sub-phase i (kW);

m_{TO} is its maximum takeoff-mass (kg);

η_i is its propulsion system efficiency while sub-phase i ;

δ is its disk loading, defined as the total mass of the VTOL divided by the lifting surface area (N/m²);

ρ is the air density (kg/m³);

ROC is the rate of climb (m/s);

V_i is the velocity while sub-phase i (m/s);
 L/D_i is the lift-to-drag ratio while sub-phase i ;
 g is the acceleration due to gravity (9.81 m/s²).

The cumulative energy consumption can be derived by aggregating the energy expenditures across all sub-phases. This summation is achieved by multiplying the power demand within each sub-phase by the respective temporal duration (as articulated in Equation 4). Specifically, in the instances of hovering and landing, the hover duration remains constant. Conversely, in the remaining sub-phases, the temporal span is computed through the division of the distance traveled by the aircraft by its velocity, as expounded in Equation 5. Furthermore, the energy reserve is ascertained by taking the product of the power demand during the cruising phase and the supplementary cruising duration necessitated to adhere to regulatory requirements, as delineated in Equation 6. The pertinent parameters employed in this computational endeavor are furnished in Table 1.

$$E_c = \sum P_i \times t_i \quad (4)$$

$$t_i = \frac{d_i}{V_i} \quad (5)$$

$$E_r = P_{cruise} \times t_{add} \quad (6)$$

where,

E_c is the energy consumption while flying (MJ);
 E_r is the energy reserve (MJ);
 t_i is the duration of time in sub-phase i (s);
 d_i is the flying distance of sub-phase i (m);
 P_{cruise} is the power demand while cruising (kW);
 t_{add} is additional cruising time (s).

2.3. VTOL Component Sizing

In this research, the sizing of critical components within the VTOL aircraft, including the structure, energy storage apparatus, and propulsion system, is meticulously executed to fulfill the stipulated criteria related to range, payload capacity, and power capabilities, as previously computed in the aerial operation modeling phase (Liu et al., 2023). In the case of BE-VTOLs, batteries function as the primary energy reservoir, delivering electrical power to propel the tilt rotors through electric motors.

The total takeoff mass of VTOLs can be partitioned into four constituent segments, as articulated in Equation 7: structural mass, payload mass, energy storage device mass, and drive system mass. To meet the specified range of prerequisites, the energy storage device must be endowed with adequate energy reserves, catering to both energy consumption and the requisite energy reserve, as indicated in Equation 8. Similarly, to satisfy the stipulated power capacity requisites, the drive system must

deliver sufficient power to enable VTOLs to achieve hovering, as defined in Equation 9. The structural aspect of VTOLs chiefly encompasses the frame of the aircraft, which is assumed to be directly proportional to the maximum takeoff mass, as postulated in Equation 10. Additionally, for BE VTOLs, the mass attributed to battery protection imposes its own structural requirements, with mass proportionality linked to battery mass, as also articulated in Equation 10. All pertinent parameters essential for this computational phase are thoughtfully outlined in Table 1. The influences of increased component volume on VTOL performance are not considered in this study, given that a large amount of mechanical structure is eliminated from BE VTOLs and FC VTOLs, leaving extra space.

$$m_{TO} = m_{ES} + m_{PS} + m_S + m_P \quad (7)$$

$$m_{ES} \times \rho_{energy} = E_c + E_r \quad (8)$$

$$m_{PS} \times \rho_{power} + m_0 = P_{hover} \quad (9)$$

$$m_S = Ratio_{ST} \times m_{TO} + Ratio_{SB} \times m_{ES} \quad (10)$$

where,

m_{ES} is VTOLs' energy storage device mass (kg);

m_{PS} is VTOLs' powertrain system mass (kg);

m_S is VTOLs' structural mass (kg);

m_P is VTOLs' payload (kg);

m_0 is the initial mass of powertrain system (kg);

ρ_{energy} is battery specific energy (Wh/kg);

ρ_{power} is the power density of the powertrain system (kW/kg);

$Ratio_{ST}$ is the ratio of the structural mass of the vehicle body frame to the takeoff mass;

$Ratio_{SB}$ is the ratio of the structural mass for battery protection to the battery mass.

2.4. WTW CO2 Emissions Calculation

The determination of the comprehensive emissions stemming from BE-VTOLs involves a multiplicative process, entailing the total energy consumption of BE-VTOLs and the grid emission factors unique to various countries. It is imperative to highlight that the plant-gate emission factors, sourced from extant statistical data, undergo further refinement through division by transmission and charging efficiencies. These refined emission factors are subsequently utilized in the computational procedures. The quantification of per-functional-unit emissions, expressed in grams of CO₂ per passenger-ground kilometer equivalent, is achieved by dividing the total emissions by both the number of passengers and the corresponding ground distance traversed by BE-VTOLs, as

encapsulated in Equation 11. It is crucial to acknowledge that while rendering transportation services between two points, the aerial distance covered by BE-VTOLs coincides with the direct linear distance separating the two locations. In contrast, conventional ground vehicles often follow indirect and circuitous routes due to the non-linearity of road networks when traveling from one point to another. In this study, the cumulative flying range of BE-VTOLs is translated into an equivalent ground range, a conversion facilitated by the ratio of ground distance to aerial distance.

$$E_{CO_2} = \frac{E_c \times f_j}{N_p \times R_{TO} \times Ratio_F \times \eta_T \times \eta_C} \quad (11)$$

where,

E_{CO_2} represents the CO₂ emissions from BE-VTOLs (g CO₂/passenger-ground km eq.);

f_j is the grid emission factor in country or region j (g CO₂/MJ);

η_T is transmission efficiency;

η_C is charging efficiency;

N_p represents the number of passengers in a BE-VTOL;

R_{TO} is BE-VTOLs' total flying range (km);

$Ratio_F$ is the ratio of ground distance to flying distance.

2.5. Data and Assumptions

Table 1. Key assumptions for BE-VTOL component sizing. (Liu, Qian, Hao, et al., 2022)

Parameter	Notation	Unit	Value
Disk loading	δ	Nm ⁻²	450
Air density	ρ	kgm ⁻³	1.29
Cruising-altitude	h	m	305
Cruising-speed	v	ms ⁻¹	150
Energy reserve	E_r	min cruising range	15
Angle of flight	α	degree	10-20
Battery capacity	—	—	100%
L/D while cruising	L/D_{cruise}	—	14
L/D while climbing	L/D_{climb}	—	10.5
Rate of climb	ROC	ms ⁻¹	5
Rate of descent	ROD	ms ⁻¹	5
Battery specific energy	—	Wh/kg	200
Motor power density	—	kW/kg	2
Battery efficiency	$\eta_{battery}$	—	90%
Motor efficiency	η_{motor}	—	90%
Transmission efficiency	η_T	—	95%
Charging efficiency	η_C	—	90%
Structural-mass fraction considering takeoff-mass	$Ratio_{ST}$	—	44.0%
Ratio of structural-mass to battery-mass	$Ratio_{SB}$	—	40.1%
Number of passengers	N_p	—	19
Ratio of ground range to flying range	$Ratio_F$	—	1.1
Hover-time	t_{hover}	s	30

Table 1 presents the pivotal assumptions employed in the sizing of components for BE-VTOL aircraft. The allocation of the structural mass fraction for the vehicle body frame, contingent upon the takeoff mass, is predicated on the mass distribution characteristics of helicopters. Furthermore, the proportion of structural mass designated for battery protection, relative to the battery mass, is established considering extant empirical data on electric aircraft. In this study, the available battery capacity is assumed to be 100%, implying that batteries can be utilized across their entire State of Charge (SOC) spectrum.

Table 2 delineates the core assumptions underpinning the computation of CO₂ emissions arising from BE-VTOLs and conventional on-road vehicles. An examination of the potential impact of a cleaner power grid on emissions in the future is undertaken by considering grid emission factors for various countries or regions in both 2020 and 2030, as per the guidelines outlined by the International Energy Agency (IEA). Energy consumption rates for BE-GVs and FC-GVs are posited at 54.07 and 75.07, respectively (García-Afonso, 2023).

Table 2. Key assumptions for CO₂ emissions calculation. (Liu, Qian, Hao, et al., 2022)

Parameter			Unit	Value		
Grid emission factor	Global average	2020	gCO_2/MJ	144		
		2030		102		
	China	2020		179		
		2030		143		
	The United States	2020		120		
		2030		99		
	European Union	2020		74		
		2030		58		
	Japan	2020		145		
		2030		103		
	Energy consumption rate of BE-GVs				kWh/km	1.33
	Energy consumption rate of FC-GVs				kWh/km	3.06

3. RESULT

3.1. Range

As shown in Fig.2, as the battery technology is still at the level of 200 Wh/kg, there is a great restriction to BE-VTOL's range. Because of the heavy battery, the maximum range an Air Shuttle can reach is about 150 km. This range is enough for intra-city transportation, which makes it possible to replace some of the bus lines going through the city. However, road bus is also a way for inter-city transportation, which usually have a distance longer than 150 km. So, at the current battery technology level, the air shuttles are still unable to provide transportation between nearby cities.

However, as the battery energy increases to 400 Wh/kg, the traveling range of air shuttles can increase to more than 300km, which is sufficient for inter-city transportation. From my graph, its travel distance can go up to 350 km, and it is still not reaching its ceiling. With this progress, air shuttles gained the ability to have a long span and lightweight, helping t to cover almost all neighboring cities' travel, maybe replacing the on-road inter-city buses.

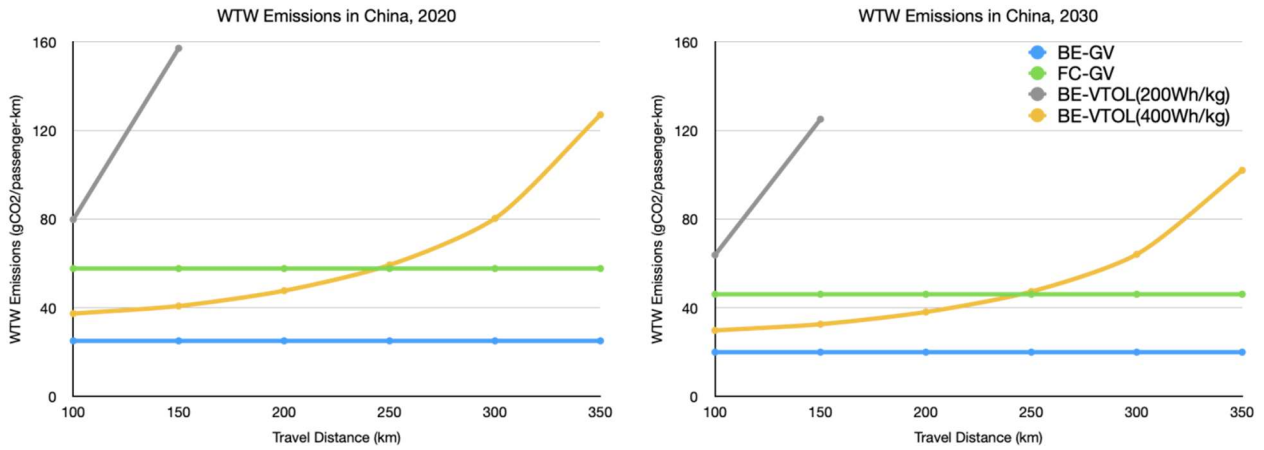


Figure 2. The WTW Emission comparison in China of BE-GV, FC-GV, and BE-VTOLs, for the years 2020 and 2030 respectively.

3.2. CO₂ Emissions

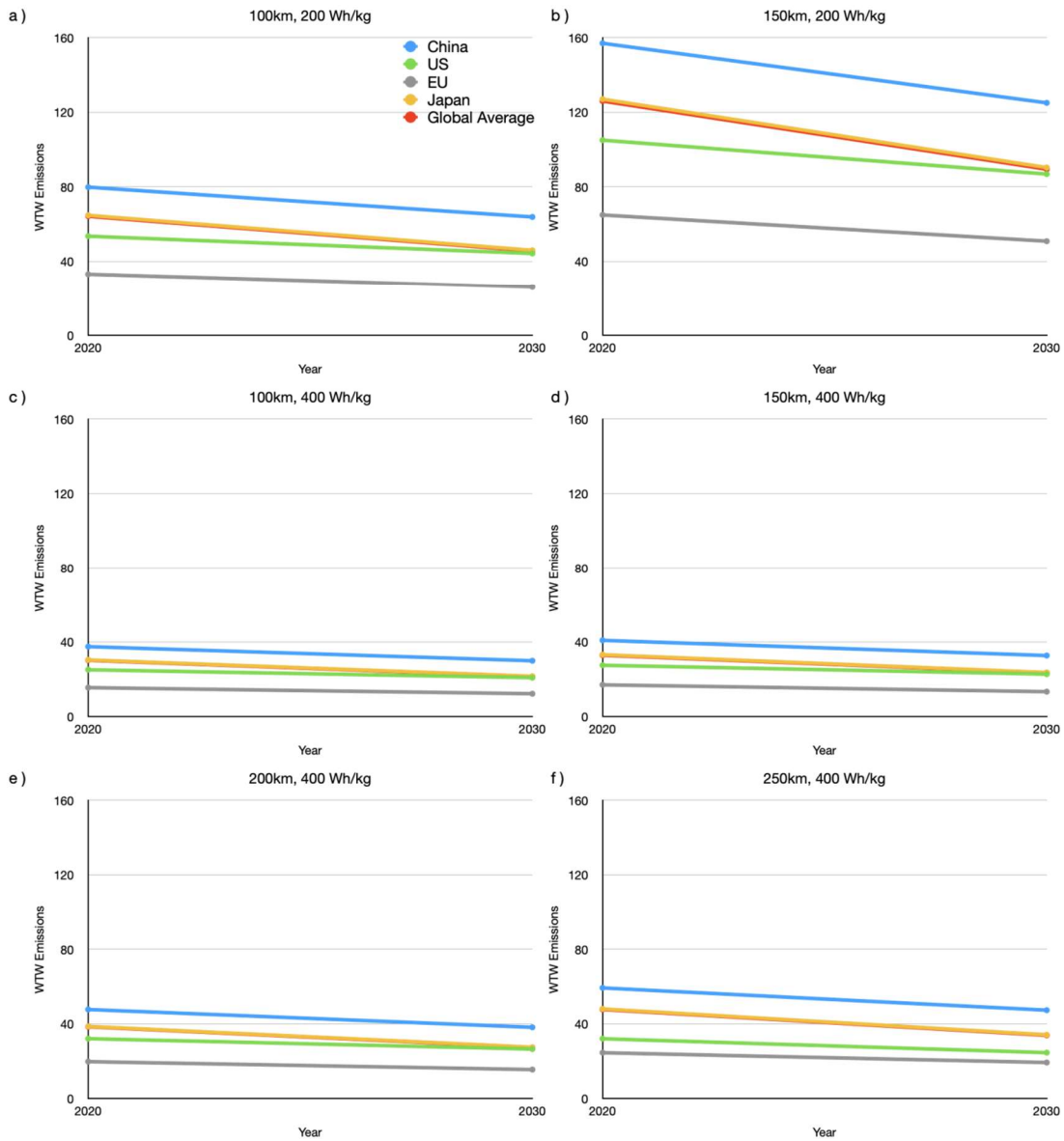


Figure 3. The comparison of WTW Emissions for BE-VTOL in different countries or regions. Graphs for different ranges and battery specific energy are shown respectively.

Fig. 3 shows the WTW Emissions of BE-VTOL, BE-GV, and FC-GV, for 2020 and 2030. Two values of battery specific energy for BE-VTOL are considered, 200 Wh/kg for the present technological level and 400Wh/kg for future idealistic technology for battery. Significantly, with battery specific energy of 200Wh/kg, BE-VTOLs have a WTW emission of 80 g CO₂ /passenger-ground km at the range of 100km, which is 38% and 218% higher than FC-GVs and BE-GVs, respectively. With range increases, the emissions also increase rapidly. For the range of 150km, the emission rises to 157 g CO₂ /passenger-ground km, which is 172% and 525% higher than FC-GVs and BE-GVs. As WTW Emissions from air shuttles are substantially higher than those from ground buses, it shows that at present, air shuttles in China are still incomparable to electric and hybrid buses.

With battery specific energy increasing up to 400Wh/kg, reduced battery mass and structure mass help air shuttles reduce carbon emissions. For the range of 100km, the WTW emission is 37 g CO₂ /passenger-ground km, 35% lower than FC-GVs and 21% higher than BE-GVs. As the range increases, the emissions also increase, with an increasing rate of rise, but the rate is still lower than that of VTOLs with 200 Wh/kg battery. It reaches the level of hybrid buses at the range of 250 km. But once it reaches this emission level, it starts to rise rapidly. At the range of 300km, the emission is 80 g CO₂ /passenger-ground km, 39% and 220% higher than FC-GVs and BE-GVs, respectively. This says, under the range of 250km, the air shuttle is better than hybrid buses and comparable to electric buses, although there are still some gaps. But for traveling distances over 250 km, the BE-VTOL becomes uncompetitive to ground vehicles again.

From 2020 to 2030, the power grid will become cleaner, and the grid emissions factor will decrease, bringing down the WTW Emissions of BE-VTOLs. While the general conditions remain the same as in 2020, with the grid emission factor decreasing from 179 to 143, WTW emissions for all types of vehicles have a 20% reduction. The difference between BE-VTOLs with 400 Wh/kg battery and BE-GVs also decreased, making the air shuttles more competitive.

With improvements in both battery specific energy and grid emission factors, emissions from air shuttles can be reduced significantly. With battery specific energy of 400 Wh/kg and emission factor in 2030, for the ranges of 150 km, the CO₂ emission is 33 g CO₂ /passenger-ground km, 79% lower than those under the 200 Wh/kg battery specific energy and 2020 emission factor case. With only 10 g CO₂ /passenger-ground km gap between BE-GVs and BE-VTOLs at the range of 100km in 2030, it states an increasing possibility of putting air shuttles into actual use.

3.3. Comparison between Countries

Different countries and regions have different grid emission factors, so they have varied results of WTW emissions. According to Fig.3, the EU has the lowest carbon emission of all the other areas, stating that maybe the EU is the most suitable for trying out the use of air shuttles. In 2020, the EU's WTW emission is 59% and 49% lower than China's and the global average. The percentage differences are almost the same across all ranges. The level of global average is still high, almost the same as Japan's, so it could take a long time for air shuttles to be used globally. But as we approach the year 2030, the battery specific energy can reach 400 Wh/kg and the grid emission factors can be decreased by different levels. From Fig.4c, by 2030, the differences between countries are very small, so it is reasonable to predict that by 2030 the air shuttles may be globalized.

4. DISCUSSION

There are many advantages that air shuttles have over fuel-cell buses, especially by the time of 2030 when technology will be developed for better use of VTOLs. Under the range of 250, which can cover most of the trips that a bus generally takes, the BE-VTOL has a better performance on the WTW Emissions, which states that it is more environmentally friendly. Also, the infrastructure for electric battery vehicles is already well-established, like charging points or battery charging points. Although

the structures are made for electric cars, maybe an adaptor can solve the problem of compatibility. There are few hydrogen stations established, so the use of fuel-cell buses would not be as convenient as the use of air shuttles. Also, VTOLs have a more complete industrial chain than FC-GVs. China is a big country of batteries and makes lots of batteries with top qualities. So, the production of batteries for air shuttles will not need to be concerned. But fuel-cell is in a different situation. The industry of fuel cells is just starting, and the industrial line and supporting facilities are all incomplete. So, under full aspects of consideration, air shuttles are significantly more competitive and practical than fuel-cell buses. In the foreseeable future, the air shuttle is always a better option than fuel-cell buses, in terms of short/medium distance travel. But for long-distance travel, the fuel cell is more environmentally friendly. Long-distance travel is less frequent so the requirement for infrastructure would not be that high and relatively easy to satisfy.

For electric buses, there's a different situation. Unlike air shuttles that have a fixed number of seats and passengers, the number of passengers carried by a road bus may vary (Figure 4). Regularly, a bus has 40 seats and carries 40 passengers. However, some lines at some times are so popular that many people crowd onto the bus. In that case, the bus may carry 60 passengers. Also, some lines are not that popular, maybe there will be only 20 passengers on the bus. Since the WTW Emissions I calculate have a unit of gCO₂/passenger-ground-km, the number of passengers affects my result. So, in Fig.4, the emissions of road buses with different numbers of passengers are shown. Under the range of 200, air shuttles with 400Wh/kg batteries have a lower carbon emission than the bus that carries 20 passengers. This means that air shuttles are completely capable of replacing some lines that are not in popular demand. However, its emissions are still higher when the bus carries 40 passengers or more.

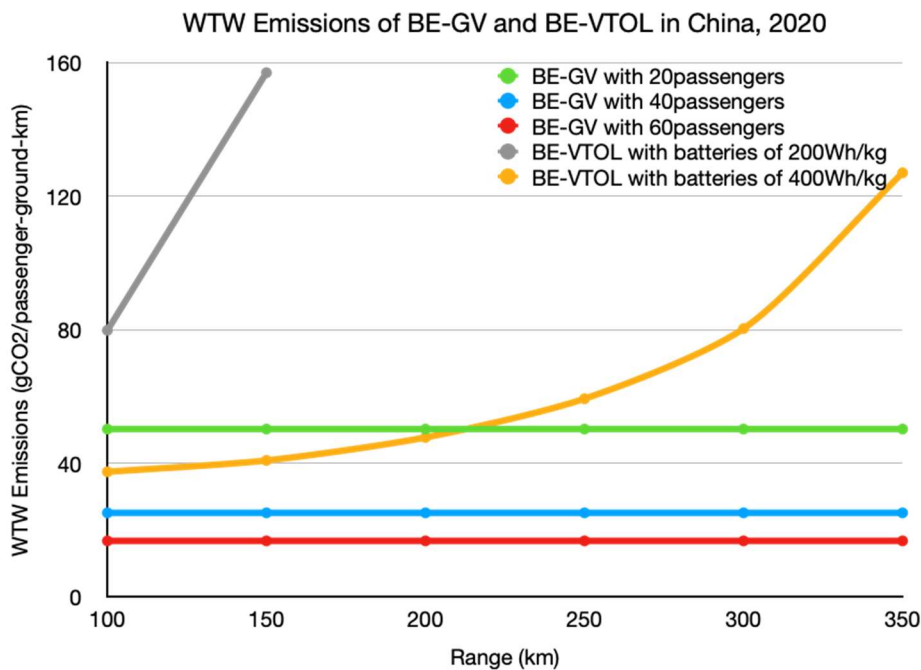


Figure 4. The WTW Emission Comparison between BE-GVs, with various numbers of passengers, and BE-VTOLs, with different battery-specific energy.

Consequently, it is better to start the trial operation of the air shuttles somewhere that doesn't have many people. Not only because air shuttles have a lower emission than buses that take few people, but also it wouldn't be safe if it's carried out at a place that always crowds since the technology is still immature, and it will make a lot of noise. Maybe it is better to start a few lines with exemplary operation, to see if it works well. If the air shuttles indeed work well practically and can maintain a low carbon emission, the government can try to subsidize this rising industry, lowering its cost, and boost the development of the air shuttle industry, shortening people's traveling time while easing the traffic pressure.

The development of battery technology plays a significant role for the development of the flying car industry. At the current level, the battery energy density can only reach a maximum of 200Wh/kg, which restricts air shuttles to traveling no more than 150 km while having a high WTW emission. With battery energy density increasing to 400Wh/kg, the air shuttles have a large increase in range and a large decrease in carbon emissions. For range, it can reach 350km, and no restrictions are found at this level. For emissions, although it has an increasing trend as the range increases, it has a lower or equal emission than FC-GV under the range of 250km. Under 200km, it has a lower emission than BE-GV which carries an equal number of passengers. All these show that improvement in battery technology can largely increase its application area, pushing the development of BE-VTOLs.

However, the improvement of battery technology needs a large scale of inputs, including the top researchers who dig into this area and the finest lab equipment, which are all very expensive. Those BE-VTOL companies generally are all start-ups, which do not have that many funds that can be invested into research. So, this is still a high-risk industry to enter. Furthermore, air shuttles cannot charge a much higher price than road buses, since it will bring air shuttles disadvantages in the economic market. So, this industry is still in a starting period, which is really a hard time.

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