

Flying Cars and eVTOLs—Technology Advancements, Powertrain Architectures, and Design

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Abstract—Flying cars and electric vertical takeoff and landing (eVTOL) aircraft could become the future of personal transportation and taxis, which would significantly reduce greenhouse gas emissions. Presently, over 250 companies are developing flying cars and eVTOLs, and at least a few vehicles are expected to be commercialized soon. This article presents the current trends and technology of VTOL flight mechanisms and identifies the vehicles in each category to evaluate their advantages and limitations. Most of the flying cars that are being developed do not have VTOL capability because of the requirement for high power during takeoff/landing for a roadworthy vehicle. This article proposes the powertrain architectures for incorporating VTOL capability for flying cars based on dual power sources, such as fuel cells and batteries. Besides, possibilities of using a single propulsion system for both drive and flight modes are explored. General design guidelines are presented for the proposed powertrain architecture to estimate the maximum takeoff weight (MTOW), power/energy demands, and source capacities. Furthermore, the technologies of the powertrain components, such as electric motors and power converters, are also discussed in this article.

Index Terms—Battery, electric motors, electric vertical takeoff and landings (eVTOLs), flight mechanism, flying cars, fuel cell, powertrain.

I. INTRODUCTION

OVER the past few decades, there has been significant growth in the use of personal vehicles globally, contributing to climate change, traffic congestion, and increased commuting duration, particularly in large metropolitan areas [1]. Flying cars and electric vertical takeoff and landings (eVTOLs) are considered to be the future of personal transportation as they provide reduced/zero-emission and will ease traffic congestion [2], [3]. In fact, fully loaded eVTOLs can have lower emissions than electric cars [4]. In this article, flying cars refer to transformable vehicles that can fly like an aircraft and drive like an automobile. Though there have

been several attempts to develop flying cars for more than 100 years, with the recent advancements in batteries, fuel cells, motors, power converters, sensors, and communications, there is now an increasing interest in flying cars with eVTOL capability [3], [5]. Over 250 companies are working on these vehicles with the support and encouragement from policymakers and worldwide regulatory boards providing a path to reduce emissions from the Urban Air Mobility (UAM) and Rural Air Mobility (RAM) missions [6], [7]. A few of these vehicles are likely to be commercially available in the very near future. Specifically, by 2024, Lilium's 7-seater Jet is likely to receive the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) certifications, while Vertical Aerospace's VA-X4 is planning to obtain U.K. Civil Aviation Authority and EASA certifications and Joby Aviation's S4 to receive FAA Part 23 certification. HT Aero, an affiliate of electric vehicle (EV) maker Xpeng, also plans to commercialize its recently launched flying car, as shown in Fig. 1, by 2024. However, to obtain the commercial certifications, these vehicles must meet stringent requirements, such as reliability and safety standards of both the automotive and aerospace industry, emit minimal noise as they fly relatively close to the ground, and have a means by which the rotating parts are secured while on the road for vehicle and human safety [8]. In addition, a short drive-to-flight transition time is expected, and the vehicles must fit the standard parking/garage space for convenience though there is no regulation in this regard as yet.

Flight control systems that aid in guiding and stabilizing during hovering, cruise, and flight modes are important for eVTOL applications [9], [10]. Willis *et al.* [9] present review of tracking control methods that find optimal thrust and pitch for winged eVTOLs. An adaptive flight control method along with its simulation validation and flight tests on a 120 kg-class eVTOL vehicle is presented in [10].

This article reviews technological advancements and future advancements of flying cars and eVTOLs, with a greater emphasis on flying cars, assuming that most future developments will prefer this. Several wing configurations and flight mechanisms are being investigated for the flying cars and eVTOLs to support vertical lift for the takeoff/landing and forward flight for the cruise. To understand their advantages and limitations, each flight mechanism is analyzed by identifying the flying cars and eVTOLs in that category. A detailed

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Fig. 1. HT Aero and Xpeng's flying car [11].

list of flying cars and eVTOLs with the key specifications is presented. In the current scenario, most of the available flying cars have gasoline or hybrid energy sources and do not have VTOL capability. Achieving a fully electric long-range VTOL flying car is still a challenge due to the additional weight of drive mode components. This article presents fully electric powertrain architectures with dual sources, such as combined battery and fuel cells, to achieve an extended range. Furthermore, to aid the VTOL capability and reduce the maximum takeoff weight (MTOW) of the flying car, the use of a single propulsion system, instead of two, for both drive and flight modes is explored. Despite the practical difficulties, a few companies are exploring innovative methods to implement such systems [12], [13]. General design guidelines to estimate MTOW, power and energy demands, source capacities, and range for such dual source-based flying cars are also presented [14], [15]. A review of power converters, with a focus on the use of wide bandgap (WBG) devices and cryogenic cooling of these converters, is also discussed. In addition, the feasibility of different types of electric motors for application in flying cars and eVTOLs is also presented.

The article is organized as follows. Section II presents different flight mechanisms and technologies of flying cars and eVTOLs. Section III presents the powertrain architectures with the combined battery and fuel cell sources, while Section IV presents general design guidelines for the same. The technological advancements of the battery and fuel cell sources for the transportation systems are discussed in Section V. Section VI presents the review of various WBG devices for power converter topologies, while Section VII presents different types of motors considered for eVTOL/flying car applications. The conclusions are finally drawn in Section VIII.

II. FLYING CARS/EVTOLS TECHNOLOGY AND FLIGHT MECHANISM

As flying cars and eVTOLs are considered the transportation system's future, they will have diverse requirements based on the purpose. For instance, personal vehicles must be lightweight, economical, and fit in parking spaces, while air taxis are expected to have speed and range according to their UAM and RAM missions. Flying car manufacturers find an innovative way of shrinking the vehicle's size using retractable



(a)



(b)

Fig. 2. Flying car TF-X with retractable wings [16]. (a) Flight mode. (b) Drive mode.



(a)



(b)

Fig. 3. Flying car Pop-Up Next with detachable propellers and wheels [17]. (a) Flight mode. (b) Drive mode.

wings or detachable propellers for drive mode and garage parking. Fig. 2 shows Terrafugia's conceptual flying car TF-X with folded wings for the drive mode. Similarly, flying car models, such as Aska, AeroMobil V5.0, Pal-V Liberty, AirCar, and The Transition, have foldable wings for the on-road mode. The flying car Pop-Up Next (jointly developed by Audi and Airbus) has innovative detachable propellers and wheels to reduce dead weight and size for drive and flight modes, respectively, as shown in Fig. 3.

TABLE I
SPECIFICATIONS OF THE AVAILABLE FLYING CARS AND eVTOLs

Vehicle Model	TOL	Power Source	Flight Mechanism	Pax	MTOW	Power	Range	
AeroMobil V.5.0	VTOL Flying Car	All-electric	Wingtip lift and thrust rotor	4	-	Flight: 75 kW	Flight: 700 km	
TF-X	VTOL Flying Car	Hybrid	Tilt-rotor	4	-	-	Flight: 800 km	
Aska	VTOL Flying Car	Electric with range extender	N/A	4	-	-	Flight: 402 km	
AirCar	HTOL Flying Car	Gasoline	N/A	2	1100 kg	Flight: 120 kW	Flight: 1000 km	
PAL -V Liberty		IC engine	Single rotor with autogyro	2	910 kg	Drive: 75 kW Flight: 150 kW	Drive: 1315 km Flight: 400 km	
The Transition		Hybrid	-	2	649 kg	Flight: 75 kW	Drive:1296 km Flight: 787 km	
AeroMobil V.4.0	STOL Flying Car	Gasoline	N/A	2	960 kg	Drive: 80 kW Flight: 224 kW	Drive: 100 km Flight: 700 km	
Kitty Hawk Flyer	VTOL Hoverbike	Fully electric	Octocopter with lift fans	1	204 kg	-	10 km	
EHang 184	VTOL		Multi-rotor with coaxial double-blade design	1	360 kg	1216 kW	16 km	
SD - 03				1	499 kg	-	30 km	
EHang 216				2	600 kg	-	35 km	
Kitty Hawk Heaviside			Tilt-rotor	1	374 kg	-	160 km	
Archer Maker				4	3175 kg	325 kW	97 km	
Joby S4				5	2177 kg	200 kW	277 km	
VA-X4				5	-	1 MW	160 km	
TF-2A			Lift + cruise	2	1200 kg	-	100 km	
CityAirbus NextGen				5	2200 kg	560 kW	80 km	
Lilium Jet 7-seater				Ducted vectored thrust	7	3175 kg	1 MW	250 km
Volocopter 2X				Multi-rotor	2	450 kg	70 kW	35 km
Skai			Fuel cell		5	-	300 kW	644 km
City Hawk	Jet fuel	Lift+Cruise	5	1930 kg	-	150 km		
Soar		Fuel cell and Battery	Multi-large ducted turbofans tilt and small fans on the fixed-wings	6	-	-	480 km to 1450 km	
Aero3		Hybrid	Tilt-wing	8	2800 kg	-	1020 km	

Despite the retractable wings, different flight mechanisms are adopted in the flying cars and eVTOLs to provide the basic functionality of vertical lift for takeoff/landing and forward flight for the cruise. Table I presents a few well-known flying cars and eVTOLs with their technical specifications and flight mechanism category. The popularly known flight mechanisms, and their advantages and limitations with examples are discussed in Sections II-A–II-C. There is no standardized way

of classifying these flight mechanisms in the literature, so a suitable one is adopted here.

A. Wingless

Multirotor aircraft is the category of wingless vehicles with multiple rotors used for lift. As these are wingless, the vehicle's overall weight is relatively low and hence economical. This aircraft has a large disk surface area leading to

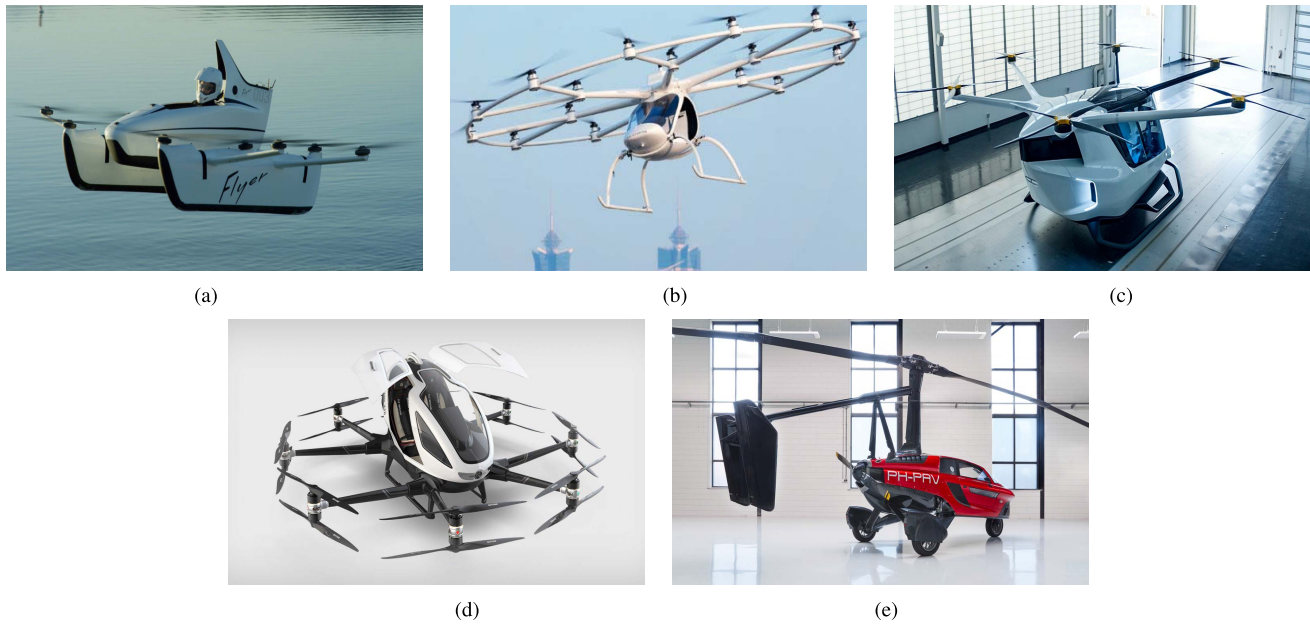


Fig. 4. Wingless multirotor flying cars and eVTOLs [18]–[22]. (a) Kitty Hawk Flyer-Hoverbike. (b) Volocopter 2X-eVTOL. (c) Skai-Fuel cell eVTOL. (d) EHang 216-eVTOL. (e) Pal-V Liberty-Flying Car.

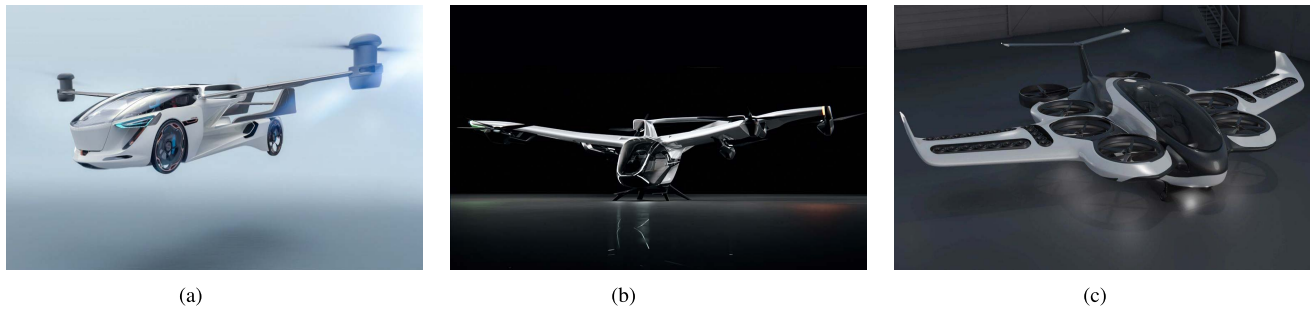


Fig. 5. Lift + Cruise flying cars and eVTOLs [23]–[25]. (a) AeroMobil 5.0-Flying Car. (b) CityAirbus NextGen-eVTOL. (c) Soar-Fuel cell eVTOL.

a lower disk-loading, thereby being efficient during hover. However, they have poor cruise efficiency limiting the speed and range [1]. Fig. 4 shows a few multirotor flying cars and eVTOLs. The Kitty Hawk Flyer hoverbike in Fig. 4(a), Volocopter 2X eVTOL in Fig. 4(b), and Alaka's fuel cell eVTOL Skai in Fig. 4(c) are a few multirotor aircraft. At the same time, EHang 184, EHang 216 in Fig. 4(d), and SkyDrive's SD-03 are multirotor aircraft but with coaxial double-blade. The wingless category vehicles are generally preferred for UAM or short-distance missions with less than 50 mi due to their short range, as shown in Table I. However, Skai, being a fuel cell-based aircraft, has a range of 741 km. Some industries prefer wingless aircraft with a main rotor similar to that of a traditional helicopter. One such is a Pal-V's Liberty in Fig. 4(e), which is an IC engine-based flying car with a horizontal takeoff landing (HTOL) feature but no VTOL capability.

B. Lift + Cruise

This aircraft category has independent thrusters for lift and cruise, with the lift rotors usually mounted vertically on the fixed wing. This aircraft is efficient on a cruise due to the presence of fixed wing. The VTOL flying car

AeroMobil V5.0 in Fig. 5(a), Terrafugia's TF-2A, and Airbus's CityAirbus NextGen are a few examples of lift + cruise aircraft. The wings of the AeroMobil V5.0 are retractable for convenient on-road driving and parking. In addition, aviation firm Paragon has revealed a dual-source battery and fuel cell-powered eVTOL Soar, which is based on a lift + cruise flight mechanism. Fig. 5(c) shows Soar having an interesting but complex flight mechanism with eight large ducted coaxial turbofans, two being capable of tilting and several smaller fans on the fixed wings [26].

C. Vectored Thrust

Vectored thrust aircraft uses the same propulsion system for lift and cruise, unlike the lift + cruise class. This aircraft can orient the direction of thrust, providing flexible aerodynamic control [29], [30]. The change in the thrust direction can be achieved either by tilting the rotor or the wing, and eVTOL aircraft can be further subcategorized based on the vectored thrust mechanism into tilt-rotor or tilt-wing, respectively.

1) *Tilt-Rotor*: Tilt-rotor aircraft consists of rotors mounted on the rotating shaft at the fixed wing for thrust vectoring. The plane of rotation of the rotors is parallel to the ground during hover and progressively rotates to the vertical position once the

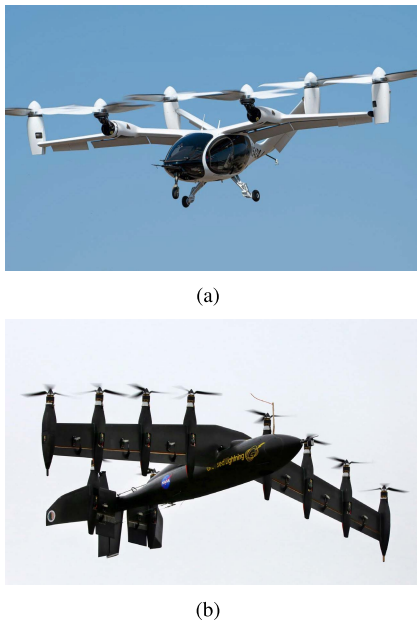


Fig. 6. Tilt-rotor and Tilt-wing eVTOLs [27], [28]. (a) Joby S4-Tilt-rotor eVTOL. (b) Greased Lightning-Tilt-wing eVTOL.

aircraft gains speed, thereby providing more control flexibility. As a result, this aircraft category achieves good speed and range. Most of the aircraft with over 100-km range, such as Joby S4, Kitty Hawk Heaviside, Vertical Aerospace's VA-1X, and VA-X4, belong to this category. Besides, Terrafugia's TF-X hybrid-electric flying car shown in Fig. 2 is also based on a tilt-rotor mechanism with about an 800-km flight range with a cruise speed of 320 km/h. This aircraft has high reliability as, even if one or few rotors fail, the rest can be controlled individually, thus avoiding total failure.

2) *Tilt-Wing*: In tilt-wing aircraft, the entire wing with the mounted rotors rotates as a single unit. This class has higher hover efficiency than the tilt-rotor type as the fixed wings in the latter reduce the thrust, which is avoided here with wing rotation. Dufour Aerospace's Aero3 is one such tilt-wing aircraft. Control of this aircraft has simple due to a single tilting structure as opposed to tilt-rotors. However, the loss of the engine could cause catastrophic failure due to a single point of failure. According to the National Aeronautics and Space Administration (NASA), its Greased Lightning hybrid VTOL shown in Fig. 6(b) solves the issue mentioned above with electric motors and electronic control [31]. Besides, the tilting mechanisms and hinge can be designed multiredundant and tolerant to structural damage to avoid a single point of failure.

3) *Ducted Vectored Thrust*: Apart from the abovementioned vectored thrust aircraft, there is also a "ducted vectored" thrust class available. In this category, the fan is placed inside a duct or cylindrical shroud. The significant advantage of this class is that it reduces the blade tip losses. In addition, the ducted fan provides higher disk loading improving the cruise efficiency at the cost of increased hover power [29]. The Lilium jet shown in Fig. 7(a) is a well-known ducted vector aircraft. There are tilt-wing-based ducted vectored aircrafts, such as the unmanned aerial vehicle Aurora XV-24 Light-

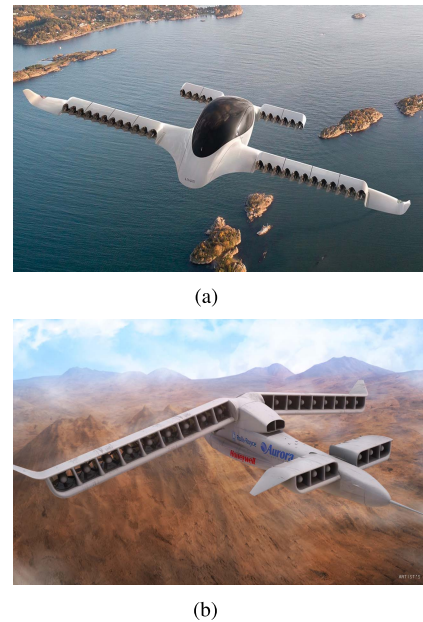


Fig. 7. Ducted thrust eVTOLs [32], [33]. (a) Lilium 7-seater-eVTOL. (b) LightningStrike-eVTOL.



Fig. 8. Archer Maker eVTOL with fixed rotor for lift and tilt-rotor for vectored thrust [34].

ningStrike in Fig. 7(b), which has tilt-wings with 24 ducted fans. In addition, multirotor aircraft can also be ducted with coaxial double-blade as in the Airbus and Audi's two-seater flying car Pop-Up Next in Fig. 3 and eVTOL CityAirbus.

Besides the above-discussed classifications, a few vehicles adopt a combination of two or more flight mechanisms to facilitate more degrees of aerodynamic control for efficient maneuvering. One such is Archer's Maker, as shown in Fig. 8, which has six tilt-rotors for providing vectored thrust for lift and cruise modes, and six fixed rotors for providing only lift. Although the hybrid flight mechanisms provide better aerodynamic control, the power plant becomes complex, and hence, careful architecture selection and design are necessary, which are discussed in Sections III–VII.

III. POWERTRAIN ARCHITECTURES

Distributed electric propulsion (DEP) having multiple small propellers seems more promising in aircraft due to high reliability and enhanced aerodynamic control compared to conventional propulsion with single or a few large propellers [35]. The architectures discussed in this work adopt such a DEP

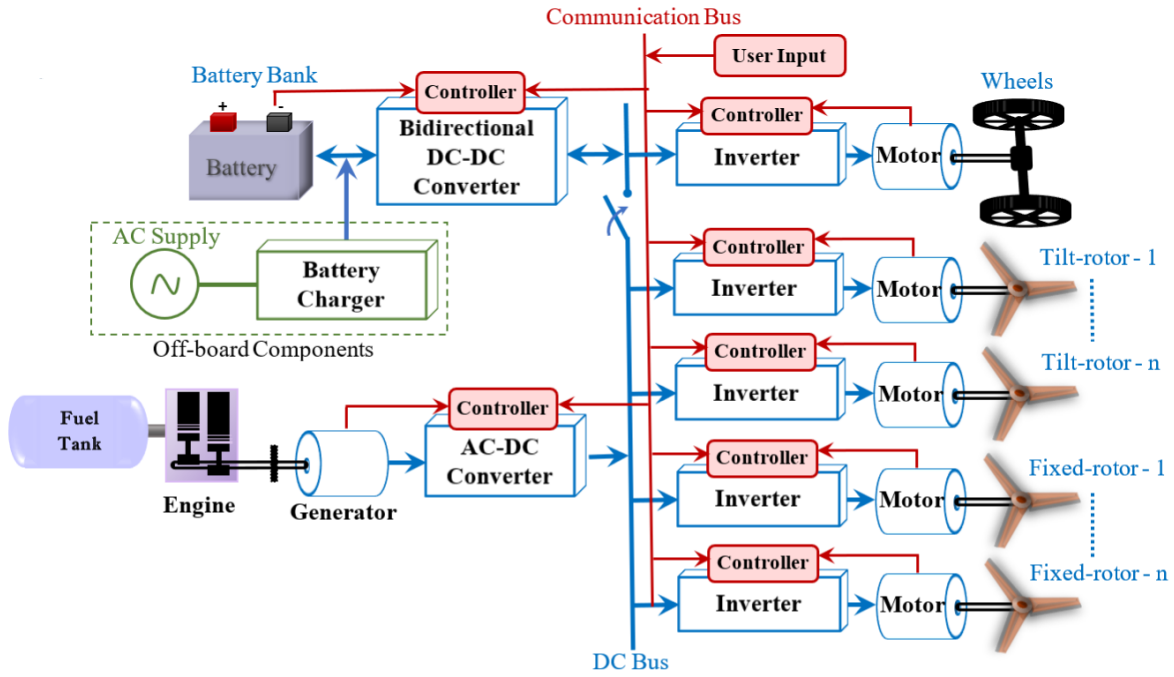


Fig. 9. Hybrid powertrain architecture with pure electric for drive and fuel engine for flight modes.

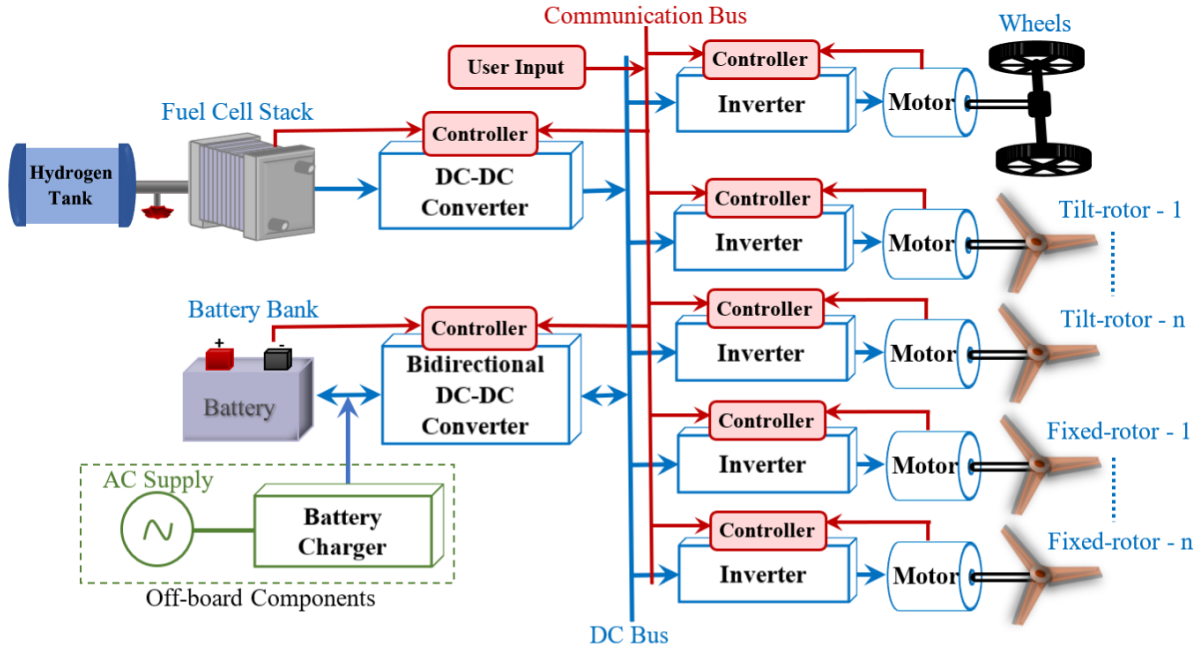


Fig. 10. Full-electric powertrain architecture with dual source-battery and fuel cell.

system and are valid for any flight mechanism and wing configuration. In this article, a hybrid flight mechanism with tilt- and fixed-rotors, as shown in Figs. 9–11, is considered for design and analysis.

Flying cars demand higher power than eVTOLs, usually in the range of hundreds of kilowatts to a few megawatts during vertical takeoff and landing because of increased weight for on-road capability. The battery alone will not be sufficient to meet the peak power demand and achieve an extended range because of the limitations in energy density, cycle life, and higher charging times. Therefore, a few manufacturers

choose to adopt hybrid-electric systems with batteries and engines similar to the architecture shown in Fig. 9. In this architecture, the engine–generator set is connected to a common dc bus through an ac–dc converter, while the battery bank is connected through a bidirectional dc–dc converter to facilitate recharging from the engine. The battery can also be charged from the grid with the use of an ac charger, which is kept external to reduce the dead weight in the vehicle. The power from the dc bus is distributed to the rotors or wheels by the electric motors, which are individually controlled by the inverters. As the specific power for the engine is higher,

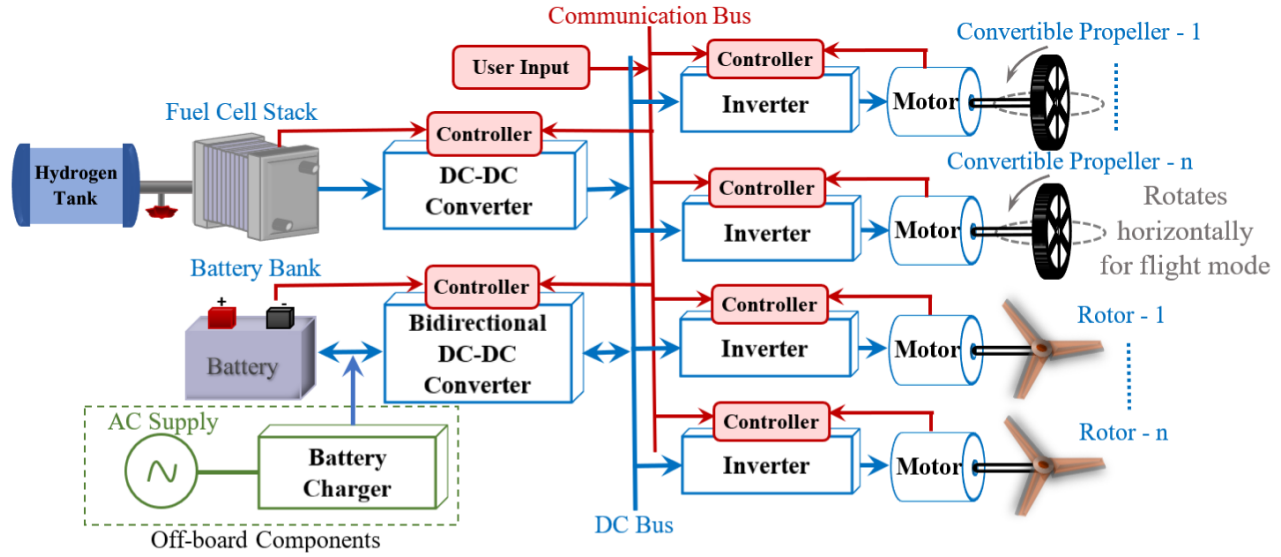


Fig. 11. Full-electric dual sourced powertrain architecture with convertible propeller wheel.

it supplies the peak power demand during the flight mode. At the same time, the battery provides most of the energy required for the drive mode to reduce emissions. However, during failure or emergency situations, energy/power from both sources is utilized. Terrafugia's The Transition and TF-X shown in Fig. 2 are a few examples of hybrid-electric flying cars. In The Transition, hybrid-electric motors and lithium iron phosphate battery supply the drive mode power, while a piston engine is used for flight mode [36]. These flying cars have over 700-km flight range compared to the battery-powered aircraft having only about 200 km range, as given in Table I. A few VTOLs, such as Dufour's Aero3, are also hybrid-electric with over 1000-km range.

Although the hybrid-electric powertrain enables long range, emissions from the fuel engine are not attractive, particularly when targeting zero-emission goals. To overcome this, yet achieve the required performance, this article presents a potential fuel cell-based architecture, as shown in Fig. 10. The hydrogen in the fuel cell has higher specific energy than gasoline and, hence, can independently satisfy the vehicle's energy demand. Battery energy storage is used for satisfying the peak power demand, which can be charged from the fuel cell or grid. This architecture uses multiple dc buses and redundant components to avoid a single point of failure and improve reliability. However, for simple representation, only one dc bus is shown in Fig. 10. Like a hybrid-electric powertrain, this also uses different propulsion systems for drive and flight modes, increasing the flying car's MTOW. As a result, high specific power motors are employed to optimize the weight. Some manufacturers even prefer an integrated motor drive to improve efficiency and reduce wiring complexity and weight, such as CityAirbus using Siemens SP200D direct-drive electric motor. Though there are no commercially available fuel cell flying cars in the market currently, it could be a potential choice in the future for long range and for increasing the passenger capacity. Presently, there are a few eVTOLs, such as Skai and Soar in the developmental stage.

As different propulsion systems for flight and drive modes increase the overall weight of flying cars, conceptual designs with a common propulsion system for both modes have rapidly emerged. In 2018, Toyota filed a patent for the conceptual flying car with transitioning wheels that act as rotors for the flight mode [12]. The tire manufacturing company Goodyear has also proposed a similar concept for its Aero-Tire [13]. The potential powertrain architecture for such a concept is shown in Fig. 11. In this architecture, the convertible propeller wheels will rotate so that their plane of rotation will be perpendicular to the ground during drive mode and parallel during the flight mode. As this architecture uses the same components for both modes, this helps to reduce the MTOW of the vehicle. In this concept, as the motor load profiles during the drive and flight modes are completely different, hence, optimizing the motor's performance for both operations will be challenging. This offers a possibility for further investigation to optimize the overall propulsion system for flying cars.

IV. DESIGN APPROACH OF FUEL CELL-BASED FLYING CARS

Based on the above-discussed architecture, general design guidelines for fully electric flying cars with fuel cell and battery sources are presented. The design provides the estimation of the maximum takeoff and empty weights, fuel capacity, energy/power demand, and range of the flying car for the mission profile shown in Fig. 12.

The parameters that are required for the design of the flying car are given in Table II. These data are based on the available eVTOL/flying cars manufacturers' data and references. The lift-to-drag (L/D) ratio of a vehicle approximately ranges between 12 and 18.26, with Lilium 7-seater having 18.26, Joby 5-seater and Kitty Hawk Heaviside having 18, Beta Alia-250 having 16, and Archer having as low as 12. The disk-loading ranges from 450 to 650 N/m², where vehicles with fixed wings sometimes have much higher values. For instance, Lilium

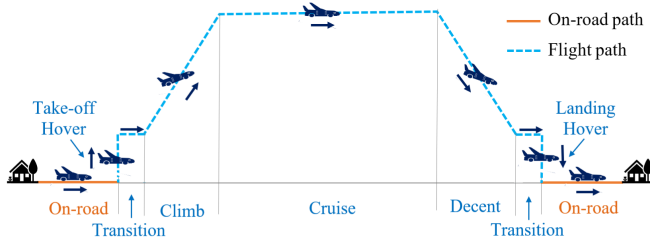


Fig. 12. Potential mission profile of a flying car.

TABLE II
EXAMPLE DESIGN PARAMETERS OF A FLYING CAR

Parameters	Legend	Values	Units	Source
Lift-Drag ratio	L/D	17	-	[4]
disc-loading	δ	450	N/m ²	[37]
Climb angle	ϕ	5	deg	[4]
Rate of climb	ROC	5.08	m/s	[4]
Rate of decent	ROD	5.08	m/s	[4]
Battery cell specific energy	S_{bat}	320	Wh/kg	[29]
Usable hydrogen specific energy	S_{H_2}	33.6	kWh/kg	[38]

7-seater with tilt-rotor has a high disk-loading of 11 890 N/m², while Joby has 450 N/m² [29], [39].

A. Maximum Takeoff Weight

The design of a flying car starts with evaluating the amount of energy and power required for the mission, which depends on the vehicle's total mass. The aircraft's total weight is distributed among three parts: payload (passengers + pilot), source, and the rest. The source weight consists of the battery pack, fuel cell stack, and the hydrogen tank, while all the mechanical fixtures are part of the empty aircraft weight. About 22% of the total weight is allotted for passengers, while the empty aircraft weighs about 50%, thereby leaving the remaining 28% for the sources in the fully electric eVTOLs. These ratios are based on the data presented by eVTOL manufacturers and references [5], [29]. For example, the Lilium 7-seater air mobility has the empty weight and battery pack ratios as 48% and 22%, while Joby has 33% and 20%, respectively.

The MTOW of the aircraft, which is a crucial parameter to determine the power and energy demand, is approximately estimated using the weight ratios. To begin with, the total weight of the payload (passengers + luggage) is computed by considering about 100 kg for one passenger with luggage. By knowing the total payload weight, MTOW is calculated using the payload ratio. Similarly, the allotted source and empty weights are calculated using the respective weight ratios [29]. It is worth noting that the MTOW must be below 7000 lb/3175 kg to seek EASA's certification under Special Conditions rules [40].

B. Energy Consumption at Different Flight Stages

A flying car's power and energy demand are different at different mission stages, such as hover, transition, climb,

and cruise. Therefore, individually computing the demands is necessary to design the power sources appropriately. During hover, the flight must be able to provide enough lift to overcome the gravity and MTOW, for which the power demand will be given in (1). In most flying cars, particularly with fixed-wing configurations, the hover power demand is high due to high disk-loading and low hover efficiency [4], [5]

$$P_{\text{hover}} = \frac{m_{\text{MTOW}} g}{\eta_h} \sqrt{\frac{\delta}{2\rho}} \quad (1)$$

where g is the gravity, δ is the disk-loading (N/m²), η_h is the hover stage efficiency, ρ is the air density (kg/m³), and m_{MTOW} is the MTOW of the flying car.

The energy consumption during hover is determined from the total duration t_{hover} . Although the power is expected to be high, energy demand will be comparatively lower due to the short hover duration. For example, Lilium 5-seater demands about 187-kW power, but only 1.6 kWh energy, which is low compared to its 16.1-kWh cruise energy demand for the 100-km range [30].

For the vectored aircraft, before climbing to the cruise height, there will be a transition stage during which the aircraft accelerates from 0 km/h to the climb speed [29]. The power in this stage reduces quadratically; however, it is assumed to be linear for ease of computation, resulting in (2) [4], [29]. At the end of the transition, power drops to a lower value, say to about one-tenth of the hover power as in the case of Lilium jet

$$P_{\text{transition}} = \frac{(P_{\text{hover}} + \frac{P_{\text{hover}}}{k})}{2} \quad (2)$$

where k is the factor by which the power drops. This factor is 10 for Lilium 7-seater jet [29].

After the vertical takeoff, the flying car climbs (or decent for landing) to the cruising height. The power requirement during this stage is generally lower than the hover power, which is given by [4], [5], [29]

$$P_{\text{climb}} = \frac{m_{\text{MTOW}} g}{\eta_{\text{cl}}} * \left(\text{ROC} + \frac{V_{\text{cl}}}{L/D_{\text{cl}}} \right) \quad (3)$$

where L/D_{cl} is the transition L/D ratio, which is typically 13% lesser than the cruise L/D ratio [5].

Once the aircraft reaches cruising height, the flight is primarily parallel to the ground throughout the cruise duration. For vehicles with high disk-loading, the cruise efficiency is good. For this reason, most long-range vehicles prefer to have high disk-loading though there is a compromise on the hover efficiency. The cruise power P_{cruise} is calculated as [4], [5]

$$P_{\text{cruise}} = \frac{m_{\text{MTOW}} g}{L/D} * \frac{V}{\eta_c} \quad (4)$$

C. Source Capacity

With the estimated power demand, the battery and fuel cell capacities are designed using iterative processes, ensuring that the overall weight does not exceed the allotted value. There are several methods of designing the source capacities, and one such method is discussed in this section.

TABLE III
DESIGNED PARAMETERS OF eVTOLs AND FLYING CARS FOR DIFFERENT CONCEPT MODELS

Parameters	Units	eVTOLs		Flying Cars	
		Model 1 (Battery-electric)	Model 2 (Battery and Fuelcell hybrid)	Model 3 (Battery-electric)	Model 4 (Battery and Fuelcell hybrid)
Pax	#	4	4	4	4
MTOW*	kg	2000	2000	2000	2000
Empty weight*	kg	1040	1040	1040	1040
Payload weight*	kg	400	400	400	400
Source weight*	kg	560	560	560	560
Battery weight*	kg	560	416.5	560	416.5
Fuel Cell weight	kg	-	143.5	-	143.5
Battery Energy	kWh	179.2	133.28	179.2	133.28
Fuel Cell energy	kWh	-	168	-	168
P hover	kW	450.68	450.68	450.68	450.68
P climb	kW	281.48	281.48	281.48	281.48
P cruise	kW	147.96	147.96	147.96	147.96
E hover	kWh	7.511	7.511	7.511	7.511
E climb	kWh	70.53	70.53	70.53	70.53
E on-road	kWh	-	-	32	32
On-road range	km	-	-	160.93	160.93
Flight range	km	205.1	452.63	140.48	388.46

*Alloted maximum weight

To begin the design process, the weight of the battery bank and fuel cell stack (including the hydrogen gas and tank) is assumed to share the allotted weight equally. From the battery weight, battery power is estimated. As there is a maximum power delivery limit on the fuel cells, the estimated battery power must be sufficient to meet the power demand. Otherwise, the battery weight is recalculated, leading to the iterative process. From the final battery weight, the energy is computed from the battery cell specific energy, about 330 Wh/kg in the present technology [29]. It must be noted that the available battery energy must be underrated according to the minimum state-of-charge restrictions. Similarly, fuel cell stack weight is calculated based on the maximum power. In contrast, the hydrogen gas and tank weight is calculated from hydrogen gas specific energy of usually about 33.6 kWh/kg and hydrogen gas-tank weight ratio, which is between 4.5% and 6% with the current technology [38], [41]. Further details on various battery and fuel cell technologies are discussed in Section V.

D. Flying Car Range

The drive mode of the flying car in this work is intended for commuting between the destination and vertiports (both ways), which can be a total of 100 mi. Based on this and the fuel economy, the required energy for driving is calculated as

$$E_{\text{drive}} = \text{Fuel Economy} * \text{Range}_{\text{drive}}. \quad (5)$$

From the estimated total available energy and the energy required for the drive mode, the available energy for the flight mode is estimated from

$$E_{\text{flight}} = E_{\text{available}} - E_{\text{drive}}. \quad (6)$$

The energy for the flight mode is distributed among the different flight stages, hover, transition, climb, and cruise. Using the previously calculated energy demand of hover, transition, and climb stages, the energy available and duration of a cruise are determined. Therefore, the cruise range of the flying car is computed based on the targeted cruise speed, usually about 250 km/h for RAM mission and 100 km/h for UAM mission.

Using the above design guidelines, four different aircraft models with the difference in the on-road capability and sources are designed, as presented in Table III. The conceptual design considers the hover, climb, and cruise efficiencies to be 59%, 65%, and 65%, respectively. The total hover and climb durations are taken as 60 and 902 s, respectively [29]. Other parameters are given in Table II. All these values are based on the existing eVTOLs/flying cars. In Table III, Model 1 is an eVTOL with only a battery as an energy source, while Model 2 has both battery and fuel cell as energy sources. Similarly, Model 3 is a flying car with only the battery source, and Model 4 is with both battery and fuel cell energy sources.

As per the example design presented in Table III, the flying car propulsion is feasible with only a battery source achieving 70% of the range of its eVTOL counterpart (Model 1). The calculated flight range is inclusive of the reserve energy. However, an additional weight of on-road car safety items, such as airbags and bumpers, makes the flying cars heavier, which further decreases the flight range and increases the peak power demand. Therefore, a flying car with both battery and fuel cells, as shown in Fig. 10, will be more efficient and viable.

The design presented here provides the estimation of the empty weight of the flying car and the source capacity

requirements. Based on the estimation, the components of the powertrain are selected. The following sections discuss the current technological advancements and selection of the major powertrain components.

V. POTENTIAL POWER SOURCES

In most fully electric flying cars and eVTOLs, batteries are the primary power source. As weight is a crucial parameter in a flying car, high specific energy batteries are essential. Lithium-ion (Li-ion) battery is identified as one of the best-suited due to its high cell specific energy (300 Wh/kg), voltage capacity, lower self-discharge rate, and no-memory effect. For example, the Li-ion battery used in the Lilium 7-seater has a specific energy of 330 Wh/kg [29], and Li-ion 811 Nickel–Manganese–Cobalt (NMC) that Joby uses has the specific energy of 270 Wh/kg with over 10000 charge-cycle capability. Besides high specific energy, batteries must be designed to meet the peak power demand, which can be high. This is particularly for high disk-loading flying cars, such as Lilium 7-seater jet, which demands 2570 kW during hover [29], [30].

Although there are significant advancements in battery technology, the maximum specific energy achieved is about 350 Wh/kg, much lower than the conventional gasoline fuel. Although the battery cell specific energy can go up to 1000 Wh/kg, for technologies such as lithium air, in the future as per the Forbes report, with the current technology, achieving an extended range is challenging [39]. As an alternate, hydrogen fuel cells can provide higher specific energy of about 33 kWh/kg, fast refilling, and zero-emission. In recent times, fuel cell technology is becoming popular in heavy-duty vehicles, such as trucks, buses, and some EVs, as refilling the hydrogen is as fast as refueling gasoline, while battery charging could take a longer time. Although the hydrogen refueling stations are presently limited, this issue is of no concern for the flying cars as the hydrogen refilling stations can be installed near the vertiports. However, the fuel to tank weight ratio of fuel cells is low, about 5.5 wt%. In addition, maximum power delivery is limited to about 100 kW with the current technology. For example, Nuvera, a Proton-exchange membrane fuel cell (PEMFC) manufacturer in the U.S. and Europe, provides a maximum of 75–120-kW power output fuel cells for power generation and transportation applications. Furthermore, presently the cost is high but is expected to go lower than conventional gasoline in the future. The U.S. Department of Energy (DOE) target is to achieve \$1/kg by 2030. To best exploit the advantages of both batteries and fuel cells, the future flying cars will potentially carry dual sources with batteries providing the required peak power and fuel cells meeting the energy demand.

VI. POWER ELECTRONIC CONVERTERS

As can be seen from the powertrain architectures presented in Section III, various power electronic converters, such as ac–dc converters, inverters, and dc–dc converters, are required in eVTOL/flying car applications. The choice of power semiconductor devices, converter topologies, modulation, control, and thermal management is critical. WBG devices, such as silicon carbide (SiC) and gallium nitride (GaN), can withstand

higher operating voltages and temperatures. These devices can support almost ten times higher breakdown voltages compared to silicon devices. Besides, the high-switching-frequency operation of WBG devices enables higher power densities, resulting in reduced weight and cost of the inverters used in flying cars and eVTOLs.

The technology of SiC devices is well matured since its discovery. Many EV companies have already started using SiC devices for various applications that include battery chargers, inverters, and auxiliary dc–dc converters. The SiC-based field-effect transistor (SiC-FET) is also proven to reduce the power loss by about three to four times compared to silicon devices [42]. This results in reduced cooling requirements, lighter heat sinks, and lower cost of the system.

GaN is a promising solution for flying cars. Compared to SiC/Si devices, GaN devices offer many advantages that include reduced ON-state resistance, higher electron mobility, breakdown voltage, and faster switching speeds. The lower conduction and switching losses of GaN-based converters also result in improved efficiency and power density, thus reducing the weight of the overall system.

Cryogenic cooling of power electronic converters can also be a viable solution for the future flying car/eVTOLs in order to achieve lightweight and higher efficiencies for the power converters used [43], [44]. The operation of WBG-based materials at cryogenic temperatures has been reported to show excellent improvement in their physical properties, such as switching speed, ON-state resistance of the device, and higher breakdown voltages. SiC devices exhibit poor performance at lower temperatures. This is because of the negative coefficient of the channel resistance of SiC MOSFETs, resulting in the increased ON-state resistance at cryogenic temperatures. The carrier freeze out phenomenon at lower temperatures results in a large number of electronics getting trapped, resulting in only few electrons being available for conduction [45]. Hence, SiC is not a suitable candidate for cryogenic operation in flying car/eVTOL applications.

GaN-based power converters can result in better efficiencies and reduced size at cryogenic operation due to lower conduction and switching losses. This is because of the lower ON-state resistance and improved switching characteristics of GaN devices at low temperatures compared to their operation at room temperature [46]. The battery sizing can also be significantly reduced, as the weight of the battery in eVTOL propulsion systems is directly related to the efficiency of power converters used.

The choice of converter topology is also equally important for flying car applications. A two-level converter is the most basic form of dc–ac converter. Though this topology is advantageous in terms of simple structure and lower switch count, it requires relatively higher filtering requirements.

Multilevel converter topologies are attractive in terms of improved total harmonic distortion (THD) of voltages and currents, reduced electromagnetic interference, and filter requirements. Cascaded H-bridge topology that contains separate dc sources was used in EV applications, as this can integrate different power sources, such as batteries and fuel cells [47]. Neutral point clamped or diode clamped converters are also investigated in the literature. These topologies require only

TABLE IV
MOTORS USED IN VARIOUS FLYING CARS AND eVTOLs

S.No	Model	Type of Motor	No of motors	Source
1	Volocopter 2X	PM synchronous brushless DC electric motors	18	[6]
2	Airbus CityAirbus	Siemens SP200D BLDC direct-drive electric motors	8	[58]
3	XV-24A LightningStrike	PM lift fan motors	-	[6]
4	Vinata Aeromobility	BLDC motors	8	[59]
5	Lilium Jet	PM synchronous motors with sinusoidal emf	-	[6]
6	Kitty Hawk Flyer	DC electric motor	10	[60]

a single dc source, but neutral point voltage fluctuation of dc-link voltage makes it very difficult to control [48]. Another common topology is the capacitor clamped or flying capacitor topology. However, the requirement of additional circuitry during the precharging of the capacitor during startup limits its application [49].

VII. MOTORS FOR eVTOLs

The requirements of motors for flying cars or eVTOLs are completely different from that of EV applications. Flying cars require high-torque and low-speed motors, as this results in reducing the tip speed of propellers and mitigating the noise. This low-speed operation also demands electric motors to be designed for very high torque levels. CityAirbus uses eight propellers rotating at a speed of around 950 rpm only, resulting in the motors delivering a high torque. To address this challenge, Rolls Royce developed an electric motor (RRP200D) with an exceptional torque-to-weight ratio of about 30 Nm/kg while delivering 200-kW output power [50].

While designing motors, it also becomes important to minimize the weight of vertical lift motors, as these are not in operation during forward flight for flying cars [51]. Present flying cars/eVTOLs generally require multiple motors, each spinning a separate propeller to generate the thrust required, with a distributed propulsion system.

Most of the eVTOL/flying car propulsion systems today use brushless dc motors (with trapezoidal back emf) and permanent magnet (PM) synchronous motors (with sinusoidal back emf) directly attached to fan blades [52], [53]. This is because of their relative advantages that include increased power density, higher efficiency, and ease of control. Induction motors, switched reluctance and synchronous reluctance motors can also find scope for the applications in flying cars and eVTOLs. The types of motors used by different flying car companies are summarized in Table IV.

The noise-free operation and associated simpler closed-loop schemes make the brushless machines an attractive solution for eVTOL propulsion systems. Volcopter 2X uses 18 three-phase PM brushless dc machines driving fixed pitch propellers arrayed on a lattice ring. CityAirbus A³ Vahana uses an integrated motor drive consisting of eight 100-kW Siemens SP200D direct-drive motors, as shown in Fig. 13. Vinita Aeromobility that soon plans to launch a fully autonomous hybrid eVTOL uses eight BLDC motors, with eight fixed pitch propellers. Thus, most of the eVTOL/hybrid flying car companies today use brushless motors because of their inherent advantages discussed above.



Fig. 13. Siemens direct-drive motor (Airbus A³ vahana) [54].

The Lightning strike XV 24A uses PM lift fan motors designed with composite stators and embedded electromagnetic conductors. Lilium jet also uses PM motors that produce sinusoidal back emf. Some flying car companies also use hybrid power sources to combine the advantages of both hydrocarbon fuel and electrical power. AeroMobil V.4.0, which employs a hybrid-electric system, uses the same engine to power the flying car in flight mode that also powers a pair of motors present in the front axle of the vehicle [55]. The integration of electric motors and inverters into a single unit enhances the power density, thus saving the space and weight consumption for flying cars. For example, H3X developed a power-dense integrated motor drive HPDM-250 with a power density of about 13 kW/kg [56].

The use of superconducting machines in flying car/eVTOL applications can offer advantages that include higher operating efficiencies and power densities. Advanced Superconducting Motor Experimental Demonstrator (AsuMED), funded by the Horizon 2020 Programme of the European Union, is developing a fully superconducting motor, with an integrated cryogenic cooling system and power converter to achieve a power-to-weight ratio of 20 kW/kg and efficiency of greater than 99% [57]. The unique load profiles of flying cars and eVTOL aircraft, including the high power and short-term duty during takeoff and landing, have to be considered in selecting the optimal design of the electric motor and drive. At the larger power levels, liquid cooling may have to be employed to achieve high specific power, but this depends on the overall the thermal management scheme selected for the electric motor and drives and the energy storage system.

VIII. CONCLUSION

This article discusses the current and future trends in the technology of flying cars and eVTOLs. Various flight

mechanisms and wing configurations that support vertical lift for takeoff/landing and a forward flight for the cruise are discussed. Besides, the advantages and limitations of each flight mechanism are analyzed. As the wingless configuration has good hover efficiency and the overall weight of the vehicle is lower due to the absence of wings, this is preferred for short-haul missions. However, for long-range flights, vectored thrusts or hybrid flight mechanisms are used. This work presents fully electric powertrain architectures of flying cars with VTOL capability, as most are currently hybrid-electric without VTOL capability. In addition, the possibility of having a common propulsion system for both drive and flight modes is discussed. Based on the powertrain architectures, general design guidelines to estimate the MTOW of the flying car, power and energy demands for each flight stage, source capacities, and range of flying cars are presented. Furthermore, the technological advancements in key powertrain components, such as power sources, electrical motors, and power converters, are discussed. The power converters with WBG devices and cryogenic cooling, which results in increased efficiency and power density, are investigated. The article also presents the requirements of motors for both the flight and drive modes of flying cars, highlighting the use of different types of motors.

REFERENCES

- [1] M. D. Patterson, K. R. Antcliff, and L. W. Kohlman, "A proposed approach to studying urban air mobility missions including an initial exploration of mission requirement," Annu. Forum Technol. Display, Phoenix, AZ, USA, Tech. Rep., 2018.
- [2] P. Wheeler, T. S. Sirimanna, S. Bozhko, and K. S. Haran, "Electric/hybrid-electric aircraft propulsion systems," *Proc. IEEE*, vol. 109, no. 6, pp. 1115–1127, Jun. 2021.
- [3] K. Rajashekara, Q. Wang, and K. Matsuse, "Flying cars: Challenges and propulsion strategies," *IEEE Electrific. Mag.*, vol. 4, no. 1, pp. 46–57, Mar. 2016.
- [4] A. Kasliwal *et al.*, "Role of flying cars in sustainable mobility," *Nature Commun.*, vol. 10, no. 1, pp. 1–9, Dec. 2019.
- [5] S. P. Melo, F. Cerdas, A. Barke, C. Thies, T. S. Spengler, and C. Herrmann, "Life cycle engineering of future aircraft systems: The case of eVTOL vehicles," *Proc. CIRP*, vol. 90, pp. 297–302, Jan. 2020.
- [6] K. Rajashekara, "Flying cars and e-VTOL vehicles: The future of transportation for reducing emissions," *EET&D Mag.*, vol. 24, no. Q2, pp. 22–27, 2021.
- [7] A. P. Cohen, S. A. Shaheen, and E. M. Farrar, "Urban air mobility: History, ecosystem, market potential, and challenges," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 9, pp. 6074–6087, Sep. 2021.
- [8] J. D. Littell, "Challenges in vehicle safety and occupant protection for autonomous electric vertical take-off and landing (eVTOL) vehicles," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp. (EATS)*, Aug. 2019, pp. 1–16.
- [9] J. B. Willis and R. W. Beard, "Pitch and thrust allocation for full-flight-regime control of winged eVTOL UAVs," *IEEE Control Syst. Lett.*, vol. 6, pp. 1058–1063, 2022.
- [10] Z. Wang, Z. Gong, C. Zhang, J. He, and S. Mao, "Flight test of 11 adaptive control on 120-kg-class electric vertical take-off and landing vehicles," *IEEE Access*, vol. 9, pp. 163906–163928, 2021.
- [11] *XPeng HT Aero Flying Car*. Accessed: Mar. 2, 2022. [Online]. Available: <https://evtol.news/xpeng-ht-aero-flying-car>
- [12] Y. U. T. Nam, "Dual-mode vehicle with wheel rotors," U.S. Patent 20180257447 A1, Jun. 6, 2020.
- [13] *The Goodyear AERO—A Concept Tire for Autonomous, Flying Cars*. Accessed: Nov. 10, 2021. [Online]. Available: <https://news.goodyear.eu/aero/>
- [14] J. Xiao, N. Salk, and K. Haran, "Conceptual design of an eVTOL air shuttle for rapid intercity transport," in *Proc. IEEE Power Energy Conf. Illinois (PECI)*, Feb. 2020, pp. 1–8.
- [15] J. M. Vegh, E. Botero, M. Clark, J. Smart, and J. J. Alonso, "Current capabilities and challenges of NDARC and SUAVE for eVTOL aircraft design and analysis," in *Proc. AIAA/IEEE Electr. Aircr. Technol. Symp. (EATS)*, Aug. 2019, pp. 1–19.
- [16] *Terrafugia Unveils New Design for TF-X Flying Car—Image Gallery*. Accessed: Mar. 2, 2022. [Online]. Available: <https://www.carbodydesign.com/gallery/2015/07/terrafugia-unveils-new-design-for-tf-x-flying-car/>
- [17] *Audi, Italdesign and Airbus Update Pop.Up Next, the Self-Driving-Car—Flying-Drone Combo*. Accessed: Mar. 2, 2022. [Online]. Available: <https://drivemag.com/news/audi-italdesign-and-airbus-update-pop-up-next-the-self-driving-car-flying-drone-combo>
- [18] *Kitty Hawk Flyer (Defunct)*. Accessed: Mar. 2, 2022. [Online]. Available: <https://evtol.news/kitty-hawk-flyer/>
- [19] *Volocopter Raises \$240 m in Mission to Develop Air Taxis for Cities Around the World*. Accessed: Mar. 2, 2022. [Online]. Available: <https://www.commercialdroneprofessional.com/volocopter-raises-240m-in-mission-to-develop-air-taxis-for-cities-around-the-world/>
- [20] *Skai Flying Car Powered by Hydrogen Fuel Cells*. Accessed: Mar. 2, 2022. [Online]. Available: <https://www.electrichunter.com/commercial-vehicles/skai-flying-car-powered-hydrogen-fuel-cells>
- [21] *EHang 216*. Accessed: Mar. 2, 2022. [Online]. Available: <https://transportup.com/ehang-216/>
- [22] *Explore the PAL-V*. Accessed: Mar. 2, 2022. [Online]. Available: <https://www.pal-v.com/en/explore-pal-v>
- [23] *AeroMobil 5.0*. Accessed: Mar. 2, 2022. [Online]. Available: <https://evtol.news/aeromobil-5-0/>
- [24] *Airbus Reveals the Next Generation of CityAirbus*. Accessed: Mar. 2, 2022. [Online]. Available: <https://www.airbus.com/en/newsroom/press-releases/2021-09-airbus-reveals-the-next-generation-of-cityairbus>
- [25] *Paragon Looks to Hydrogen Engines for its Ultra-Long-Range Soar eVTOL*. Accessed: Mar. 2, 2022. [Online]. Available: <https://newatlas.com/aircraft/paragon-soar-hydrogen-evtol/>
- [26] *A New Hydrogen-Powered eVTOL Aircraft Can Soar 800 Miles*. Accessed: Oct. 22, 2021. [Online]. Available: <https://interestingengineering.com/a-new-hydrogen-powered-evtol-aircraft-can-soar-800-miles>
- [27] *Joby S4*. Accessed: Mar. 2, 2022. [Online]. Available: <https://evtol.news/joby-s4>
- [28] *NASA's 'Greased Lightning' Drone is Part Chopper, Part Airplane*. Accessed: Mar. 2, 2022. [Online]. Available: <https://edition.cnn.com/2015/05/14/tech/nasa-greased-lightning-drone/index.html>
- [29] P. Nathen, A. Strohmayer, R. Miller, S. Grimshaw, and J. Taylor, "Architectural performance assessment of an electric vertical take-off and landing (e-VTOL) aircraft based on a ducted vectored thrust concept," Lilium GmbH, Claude-Dornier StraeSse, Weßling, Germany, Tech. Rep., 2021.
- [30] A. Bacchini and E. Cestino, "Electric VTOL configurations comparison," *Aerospace*, vol. 6, no. 3, p. 26, Feb. 2019. [Online]. Available: <https://www.mdpi.com/2226-4310/6/3/26>
- [31] R. G. McSwain, L. J. Glaab, and C. R. Theodore, "Greased lightning (GL-10) performance flight research—Flight data report," NASA, Washington, DC, USA, Tech. Rep. TM-2017-219794, 2017. Accessed: Oct. 15, 2021. [Online]. Available: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180000765.pdf>
- [32] *Electric Air-Taxi Startup Lilium Set to Merge With Former GM Executive's SPAC in \$3.3 Billion Deal*. Accessed: Mar. 2, 2022. [Online]. Available: <https://markets.businessinsider.com/news/stocks/electric-air-taxi-startup-lilium-merge-spac-3-billion-deal-2021-3-1030259352>
- [33] *Aurora XV-24 LightningStrike*. Accessed: Mar. 2, 2022. [Online]. Available: https://en.wikipedia.org/wiki/Aurora_XV-24_LightningStrike
- [34] *Archer Unveils A Luxe Two-Person 150 MPH EVOTL With A 60-Mile Range*. Accessed: Oct. 1, 2021. [Online]. Available: <https://hiconsumption.com/archer-urban-vtol/>
- [35] D. Ullman, V. Homer, and P. Horgan, "Comparing electric sky taxi visions," Tech. Rep., Jun. 2017.
- [36] *Terrafugia Reveals New Details on Transition Flying Car Due in 2019*. Accessed: Nov. 10, 2021. [Online]. Available: https://www.motorauthority.com/news/1046814_terrafugia-reveals-new-details-on-transition-flying-car-due-in-2019
- [37] A. Stoll, "Analysis and full scale testing of the Joby S4 propulsion system," Transformative Vertical Flight Workshop, Tech. Rep., Aug. 2015.
- [38] *Toyota FCV Mirai launches in LA; Initial TFCS Specs; 57,500or499 Lease; Leaning on Prius Analogy*. Accessed: Oct. 1, 2021. [Online]. Available: <https://www.greencarcongress.com/2014/11/20141118-mirai.html>
- [39] *Has Joby Cracked the Power Problem to Make Electric Air Taxis Work?* Accessed: Aug. 26, 2021. [Online]. Available: <https://www.forbes.com/sites/jeremybogaisky/2020/11/23/joby-batteries-electric-aviation/?sh=43836e9176a7>

- [40] *Special Condition for Small-Category VTOL Aircraft*, Eur. Union Aviation Saf. Agency (EASA), Cologne, Germany, 2019.
- [41] *Hydrogen Storage*. Accessed: Oct. 1, 2021. [Online]. Available: <https://www.energy.gov/eere/fuelcells/hydrogen-storage>
- [42] *Silicon Carbide Breakthroughs to Accelerate Electric Vehicle Innovation*. Accessed: Nov. 24, 2021. [Online]. Available: <https://www.automotiveworld.com/articles/silicon-carbide-breakthroughs-to-accelerate-electric-vehicle-innovation/>
- [43] H. Gui *et al.*, "Review of power electronics components at cryogenic temperatures," *IEEE Trans. Power Electron.*, vol. 35, no. 5, pp. 5144–5156, May 2020.
- [44] R. Chen and F. F. Wang, "SiC and GaN devices with cryogenic cooling," *IEEE Open J. Power Electron.*, vol. 2, pp. 315–326, 2021.
- [45] H.-Y. Cha, H. Kim, and J. Lim, "DC characteristics of wide bandgap semiconductor field effect transistors at cryogenic temperatures," *J. Korean Phys. Soc.*, vol. 56, no. 5, pp. 1523–1526, May 2010.
- [46] C. B. Barth *et al.*, "Design, operation, and loss characterization of a 1-kW GaN-based three-level converter at cryogenic temperatures," *IEEE Trans. Power Electron.*, vol. 35, no. 11, pp. 12040–12052, Nov. 2020.
- [47] M. Malinowski, K. Gopakumar, J. Rodriguez, and M. A. Pérez, "A survey on cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197–2206, Jul. 2010.
- [48] P. Qashqai, A. Sheikholeslami, H. Vahedi, and K. Al-Haddad, "A review on multilevel converter topologies for electric transportation applications," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Oct. 2015, pp. 1–6.
- [49] S. Kouro *et al.*, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.
- [50] *Electric Propulsion for a Disruptive Mobility Concept*. Accessed: Nov. 30, 2021. [Online]. Available: <https://www.rollroyce.com/products-and-services/electrical/propulsion/air-taxis.aspx>
- [51] *Turning Volts to VTOL*. Accessed: Nov. 24, 2021. [Online]. Available: <https://evtol.news/news/turning-volts-to-vtol/>
- [52] J. Ramoul, G. Wathewaduge, A. D. Callegaro, B. Nahid-Mobarakkeh, A. Baronian, and A. Emadi, "Analysis of open phase and phase-to-phase short circuit fault of PMSM for electrical propulsion in an eVTOL," in *Proc. 47th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2021, pp. 1–6.
- [53] W. Huang, Z. Zhang, W. Huang, and H. Gao, "Optimal design of high speed electric ducted fan for private eVTOL considering specific power and temperature distribution," in *Proc. 24th Int. Conf. Electr. Mach. Syst. (ICEMS)*, Oct. 2021, pp. 2523–2528.
- [54] *Siemens SP200D Direct Drive Motor for Aviation Applications*. Accessed: Nov. 24, 2021. [Online]. Available: <https://commons.wikimedia.org/wiki/>
- [55] G. Pan and M.-S. Alouini, "Flying car transportation system: Advances, techniques, and challenges," *IEEE Access*, vol. 9, pp. 24586–24603, 2021.
- [56] *Integrated Motor Drives for Electric Aircraft*. Accessed: Nov. 30, 2021. [Online]. Available: <https://www.h3x.tech/>
- [57] *Advanced Superconducting Motor Experimental Demonstrator*. Accessed: Nov. 30, 2021. [Online]. Available: <https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/aviation/asumed>
- [58] *Airbus CityAirbus*. Accessed: Nov. 24, 2021. [Online]. Available: https://en.wikipedia.org/wiki/Airbus_CityAirbus
- [59] *Vinata Aeromobility*. Accessed: Nov. 24, 2021. [Online]. Available: <https://vinataeromobility.com/flying-car/>
- [60] *Kitty Hawk Flyer*. Accessed: Nov. 24, 2021. [Online]. Available: <https://evtol.news/kitty-hawk-flyer/>



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