Technology Maturity Roadmaps of Power System Components for eVTOL Aircraft

White paper September 2022

Shadan Altouq

Shadan.altouq@strath.ac.uk

Chung M. Fong

Kenny.fong@strath.ac.uk

Patrick J. Norman

Patrick.norman@strath.ac.uk

Graeme Burt

Graeme.burt@strath.ac.uk

Institute of Energy and Environment, Department of Electronics and Electrical Engineering,

Technology and Innovation Centre, Glasgow, UK.

1. Introduction

The viability of aerial taxi missions is highly dependent on the mass and reliability of the electrical power system to supply uninterrupted power to the propulsion [1–3]. Yet, the electrical power system is limited by the low maturity, in terms of power and energy density, of the current available critical technologies. Therefore, the integration of the technologies into a single power and propulsion system requires significant attention to provide a viable solution capable of supporting the mission requirements.

Following from this, there is a clear need for a consolidated capture and project of relevant electrical technology capability and availability in order to develop effective solutions. This white paper presents a summary and discussion of 10-year roadmaps for key electrical technologies required for electrical vertical take-off and landing (eVTOL) aircraft design. The technologies covered are critical to the power system design and include energy storage, power electronics, power machines, and protection devices. Power-to-weight and energy-to-weight ratios have been obtained from public domain sources on existing technologies, market projections, and projection targets from advisory bodies in order to establish technology progression trendlines. These can subsequently be used to influence electrical power and propulsion system design choices and strategies for future platforms.

2. Energy Storage – Battery Technologies

Higher specific energy density battery technology can provide longer mission range and/or increased mission rates between recharging. While power dense batteries are required for eVTOLs to allow high discharge rate for the high power requirement during the hovering and landing phases, and allows faster charging which help extends batteries' longevity and safety margins. Batteries with high power discharging are especially essential for eVTOL aircraft designs with high disc loading which compromises the energy density of the battery [4, 5]. This shows an evident trade-off between high energy and power dense batteries to support the flight mechanism and mission economics of eVTOL aircraft. From this, depending on the aircraft design, appropriate selection of batteries can be attained through a tailored combination of battery cell chemistry to achieve energy dense with high power capabilities to satisfy the mission requirements with focus on maintaining low weight and volume.

Lithium-ion batteries are the main energy dense, market-available option for eVTOL applications, whereas the emerging Lithium air (Li-air)/Lithium-Sulfur (Li-S) [6–8] and Lithium metal polymer/Solid State battery technologies [9, 10], are being pursued for further increased energy density. In terms of energy density levels of battery technology, the urban air mobility (UAM) community have published various projections. At a cell level, Roland Berger indicated that in 2019, the maximum Lithium-ion battery cell level energy density was around 300 Wh/kg [11], but by 2025 Lithium metal polymer/solid state batteries should achieve energy densities of greater than 400 Wh/kg, and by 2030 an energy density of greater than 500 Wh/kg may be achieved using lithium air technologies. In conjunction, NASA has published projected cell level projections of 400 Wh/kg by 2025 and with a higher projection of 600 Wh/kg by 2030 [12]. The UK ATI also provides a 500 Wh/kg cell level projection for 2030, similar to Roland Berger [11].

Combining the various energy density data projected by the UAM community above with other publicly available information for cell level energy density from manufacturers [14-38]. Figure 1 presents a combined roadmap of battery technology from 2016 to 2030 (including the 10 year projection from 2020 to 2030). In this, a trendline linking past and projected energy densities are shown. In contrast to the UAM specific data presented in the roadmap, there is evidence that automotive and UAV sectors have already reached or exceeded the 400 Wh/kg threshold in 2018-2019 [16, 17].

An outlier to the Lithium-ion battery projections is discussed above, in 2019 Innolith announced intentions to develop a novel electrolyte variant aimed for cell level energy density of 1000 Wh/kg battery by 2024 with lifespan greater than 800 cycles [39]. To this date, the company has not posted any following up of the technology in development. Additionally, Lyten is currently developing a graphene-based Li-S battery with potential to achieve 900 Wh/kg with cycles greater than 1,400 for electric vehicles [38].

In Figure 1, the data points for cell energy density are labelled as “prior” for technology available from 2017 to the start of 2022 and projected densities from later 2022 to 2032 are labelled as “projected” densities. Although purely electric eVTOL propulsion is possible with lower battery energy density levels, Roland Berger [11] states that a 500 Wh/kg cell level energy density or above is required for electric propulsion to become competitive, compared to traditional propulsion options. From the in Figure 1, Equation (1) is extracted and can be used to estimate the energy density progression of batteries in the following years.

$$\textit{Energy Density}\ (\textit{Wh/kg}) = 20.938 \cdot \textit{Year} - 41961 \qquad (1)$$

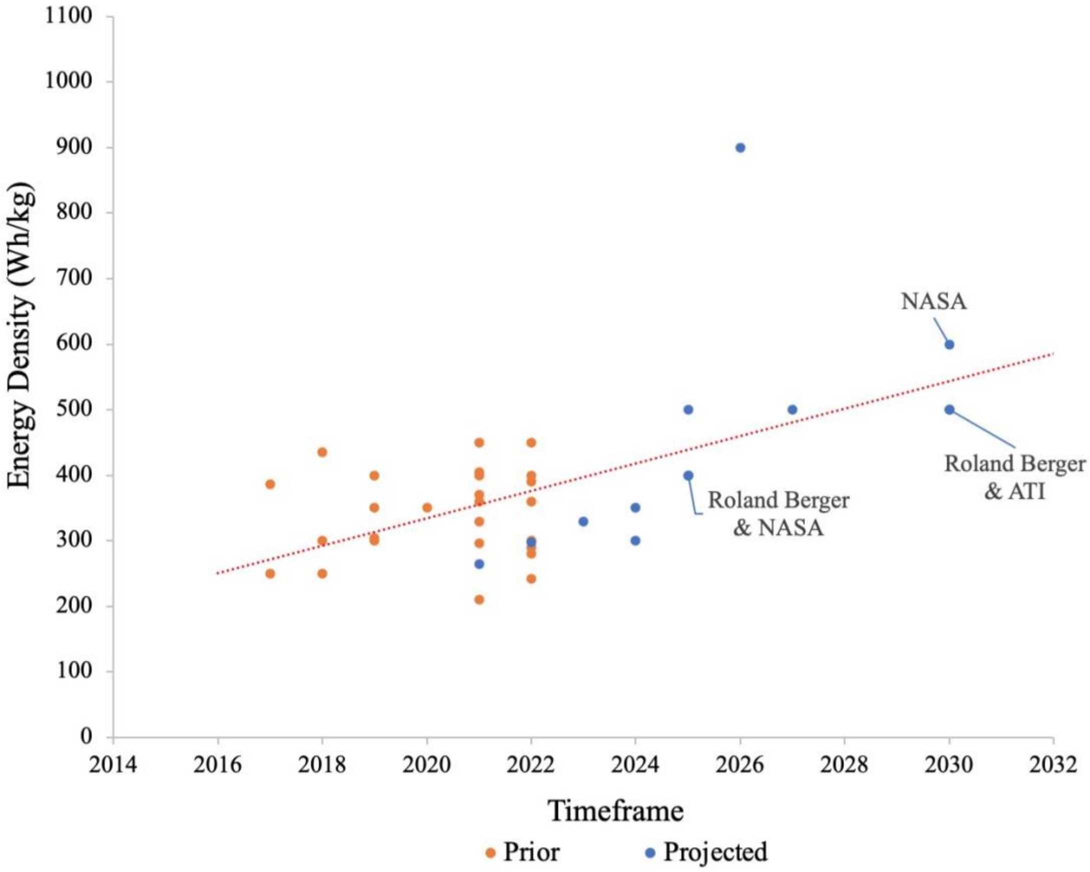

Figure 1. Batteries Roadmap Highlighting Technology Energy Density Prior to 2022 and Projected.

In addition to the cell level energy density road mapping, the battery energy density is reduced by roughly by a further 25% when taking into account the battery overhead packaging and the operating range of the battery's state of charge [22, 23], thus reducing the usefulness of the full energy density. The lifespan of some of the novel cell technologies are currently limited to a low cycle which increases the operational and maintenance costs of the aircraft. Furthermore, a range of technologies are in the process for production in the upcoming year/s [28, 29], while others are in continued development requiring additional years for certification, production, and ready for commercialisation [20, 24, 38, 39].

3. Electric Motors for Propulsion

Electric motors convert the power from the electrical system to mechanical propulsion system to provide the thrust required to maintain flight. The main design drivers for electric motors in the UAM market and eVTOL applications is high power and torque density, and efficiency for a light-weight design [40, 41, 42]. The design and the nature of flight phases of the eVTOL aircraft demands a motor with high torque capability and limited speed range. DEP enable significant reduction of the noise level to operation requirement in UAM setting compared to helicopters [43–45]. While the current available and technology progression of motors in the automotive industry are focused on the production of high speed motors for EV applications [42]. However, high-torque electric motors are currently available at low power density thus suffer from increased weight in comparison to high speed motors.

With regards to motor types, permanent magnet motors (e.g., permanent synchronous Motor (PMSM) appear to be the most appropriate choice for eVTOL aircraft propulsion. This is as a result of its high torque density, compact sizing, high efficiency and fast transient response [46, 47]. The capability PMSM to maintain full torque is well suited for the requirements of eVTOLs', in particular the higher consumption take-off and landing flight phases. Having said that, PMSM are costly and require complex control system when compared to other motor technologies [46, 47].

In terms of current technology levels, the automotive industry have been the main application driver for developing light-weight high speed motors for EV applications. Recent advancement in the automotive industry have published achieved power densities up to 13 kW/kg with plans to excel beyond 15 kW/kg [48, 49]. These technologies are high speed motors with a potential use for aerospace applications but require mechanical reduction gearbox to control the speed range of the motors. Whereas motors operating at low speed range with high-torque capability offer a direct drive system which enables low noise emission without the need of a gearbox and reduces the reliability and power loss of the mechanical system [40].

In terms of technology projections, the ATI have published the achieved power density by 2020 is at around 3 kW/kg for small aircraft/urban air transport applications, with subsequent projections of 7.5 kW/kg by 2026 [13] for sub-regional aircraft, and 12 kW/kg by 2030 for mid-size commercial aircraft. While NASA 10 years research goals are targeting a power density of 13 kW/kg by 2025, and 15-years goals of 16 kW/kg by 2030 with improved efficiency [50].

However, the high power densities achievable might still not be all suitable for eVTOL applications due to their aforementioned low speed high torque requirements coupled with noise requirements. Two roadmaps for electrical machines might be suitable for eVTOL aircraft are presented. The first roadmap is for machines configured for rated speeds between 1000 RPM and 2500 RPM consistent with ranges of known eVTOL designs with ten or less rotors shown in Figure 2. An additional roadmap shown in Figure 3, is to cover the progression of higher speed motors, which may be more suited to small diameter eVTOL applications with over ten rotors, which the machines can operate at higher RPM while maintaining low noise levels [51, 52]. This could be achievable as Lilium claims their aircraft is well under the regulation requirements to operate in urban areas while having an aircraft design with 36 small diameter motors rotating in a high RPM [53].

To reiterate the fact that the selection of electric motors is highly dependent on the aircraft design, weight budget, and the product availability. The recent development of technologies has presented different options for electrical motors suitable for eVTOL applications, such as direct driven high torque motors, high speed motors with a reduction gearing system, or compact motor design with integrated power electronics. The current aerospace and automotive market show an increase of development in integrated high speed electric motors design which includes power electronics and reduction gears, if needed, in a single compact packaging. This integrated design offer increased power density for power electronics and machines altogether up to and greater than 11 kW/kg (e.g., [54–59]). For high power dense products introduced by the automotive industry, re-design or re-packaging is required to comply with the aerospace standards, these changes might reduce the published power density of the product. Besides that, the detrimental factor of the selection is based on the noise emitted from the propeller tip speed and propulsion system, which in turn is heavily dependent on the aircraft design and motor arrangement.

Combining the power density data projected by ATI and NASA discussed with other publicly available power density references for existing 1000 RPM to 2500 RPM range motors from manufacturers [60]- [69], Figure 2 presents a combined roadmap of motor technology eVTOL designs with less than 10 rotors. The data points are labelled as “prior” for technology available from 2016 to the start of 2022 and projected densities from later 2022 to 2032 are labelled as “projected” densities. In this, a trendline linking past and projected power densities are again included. From the trendline in Figure 2, Equation (2) is extracted and can be used to estimate the energy density progression of electric motors with a speed of 1000 RPM to 2500 RPM in the following years.

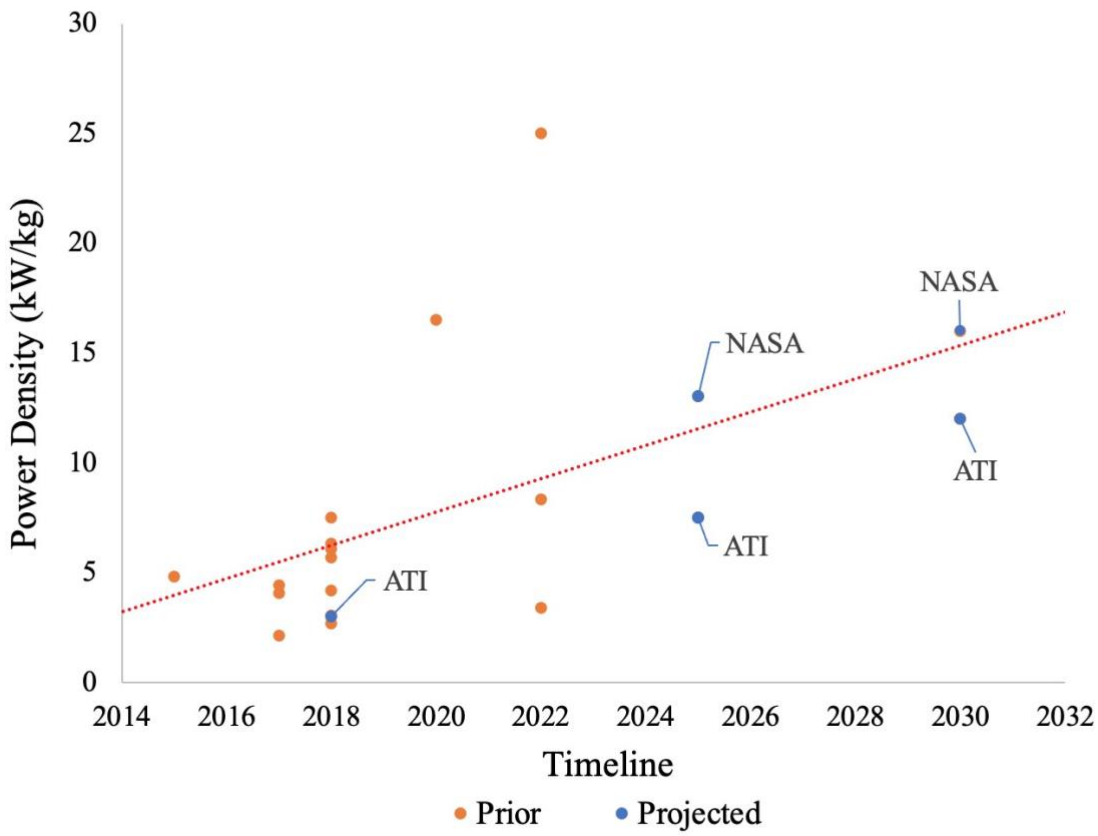

Figure 2. High Torque Electric Propulsion Motor Roadmap Highlighting Technology Power Density Prior to 2022 and Projected. Suitable for eVTOL of and less than 10 Direct Drive Rotors.

$$\textit{High Torque Motor}\ (kW/kg) = 0.5769 \cdot \textit{Year} - 1160.3 \qquad (2)$$

Similar to Figure 2, Figure 3, presents a combined roadmap of motor technology eVTOL designs with 10 rotors and higher in the range of 2500 RPM up to 10,000 RPM from manufacturers [70]-[80]. The projections of power density for high speed motors (2500+ RPM) are higher than low speed motors (1000-2500 RPM), this is mainly due to the automotive efforts to develop high speed motors for EV applications [42]. All the data presented for the projections are based on what is available in the public domain. From the in Figure 3, Equation (3) is extracted and can be used to estimate the energy density progression of electric motors with a speed of 2500+ RPM in the following years.

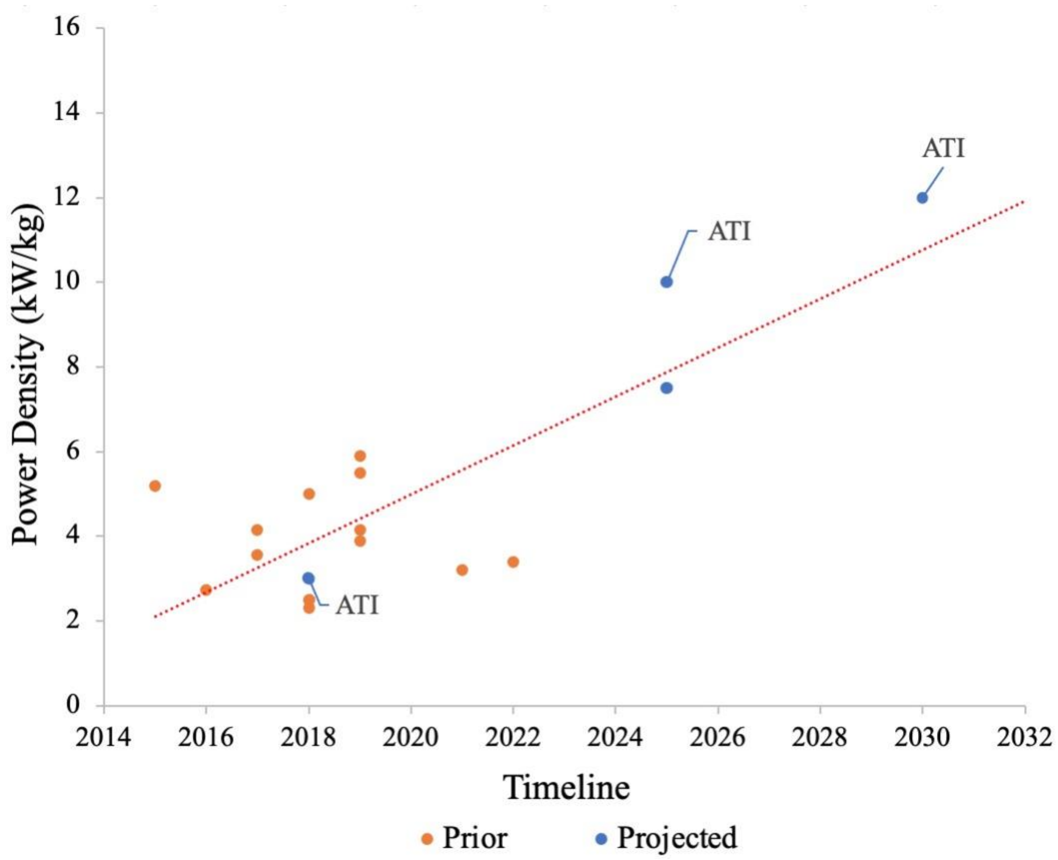

Figure 3. High Speed Electric Propulsion Motor Roadmap Highlighting Technology Power Density Prior to 2021 and Projected Suitable for eVTOL with More Than 10 Geared Rotors.

$$\textit{High Speed Motor}\ (kW/kg) = 0.7582 \cdot \textit{Year} - 1523.9 \quad (3)$$

In addition to the presented roadmaps, thermal cooling system is an important factor to consider as the choice of the cooling method highly affects the weight and motor arrangement. According to [81], the thermal cooling system can contribute up to 30% of the motor dry weight. However, the weight of the thermal cooling system is often not incorporated as a part of the published power density of the motor, it is considered separate which reduces the published power density. There are many types of cooling system, yet for eVTOL aircraft and high torque density applications air-cooling is widely used due to the airflow surrounding the motors [40]. Air-cooling motors are thus lighter in weight due to the use of the surrounding air and less complex in design than liquid cooled motors [40]. However, they have less effective heat rejection than liquid cooled motors. As such, cooling system is chosen depending on the propulsion design, location, and access to abundant airflow around the motors.

4. Power Electronics

Power electronics are used to regulate the power from the energy storage in order to drive the electric motors. The main requirements of power electronics devices is to regulate and control the power flow with high efficiency and reduced volume and weight.

Recent development in wide-band gap materials i.e. Gallium Nitride (GaN) and Silicon Carbide (SiC) offers lighter switches and fewer losses than Silicon modules. SiC modules are expensive and are currently utilised in aerospace niche markets thereby widely available in high voltages [82]. With the current demands for the electrification of the automotive industry, mass production will drive the costs of power electronics modules down [83]- [86]. Additionally, Cree, Inc. is investing heavily in SiC and is expected to mass produce devices in 2024 [87]. Whereas GaN is less costly but the voltage is limited to roughly 600 V as it is used in consumer applications. With the high demands of GaN in the automotive industry, the voltage is expected to reach 900 V in the near future [11, 82]. The progress of these technologies is mainly for the automotive industry and thus would require further adaption for aerospace airworthiness certification to be used in eVTOL aircraft.

In terms of power density targets for power conversion devices, advisory bodies have divided the projections for AC/DC and DC/AC devices and the DC/DC devices. For AC/DC and DC/AC inverters, the US Department of Energy (DOE) has funded research projects in widegap semiconductors and inverters for the automotive industry for a power density target of more than 14.1 kW/kg by 2020 [88]. The UK Advanced Propulsion Centre (APCUK) has set different targets for the power density by 2025 for Inverter to be 22 kW/kg [89], while Horizon 2020 European project aims to achieve a target of 15 kW/kg with an efficiency of 99%, a reported TRL was 5 in 2018 [90]. The ATI aims to achieve a target of 10 kW/kg by 2025 [13].

The power density targets for DC/DC converter are as following, the DOE funded research projections for 2-port (bidirectional buck-boost) to be 15 kW/kg and 6 kW/kg by 2025 [89]. NASA has set a power density goal of 19 kW/kg sponsoring research with General Electric to produce SiC/Silicon DC/DC converter but has not set a specific date. The 2-port DC/DC converter is bidirectional buck-boost with 2-ports non-isolated [89].

Although SiC and GaN based power conversion devices is the trend in automotive and aerospace industries, yet there are limited data on the weight and power density of power conversion devices available in the public domain. Combining the power density data projected by DOE and ATI discussed with other publicly available power density references for AC/DC devices [84] [91-100], Figure 4 presents a combined roadmap of AC/DC power conversion devices. From this, a trendline linking past and projected power densities is again included. In the Figure, the data points for the power density advertised from manufacturers and from research prototypes are labelled as “Prior” are available from 2014 to the start of 2022. Projected densities from later 2022 to 2032 are labelled as “projected” densities. From Figure 4, Equation (4) is extracted and can be used to estimate the energy density progression of inverters (AC/DC) in the following years.

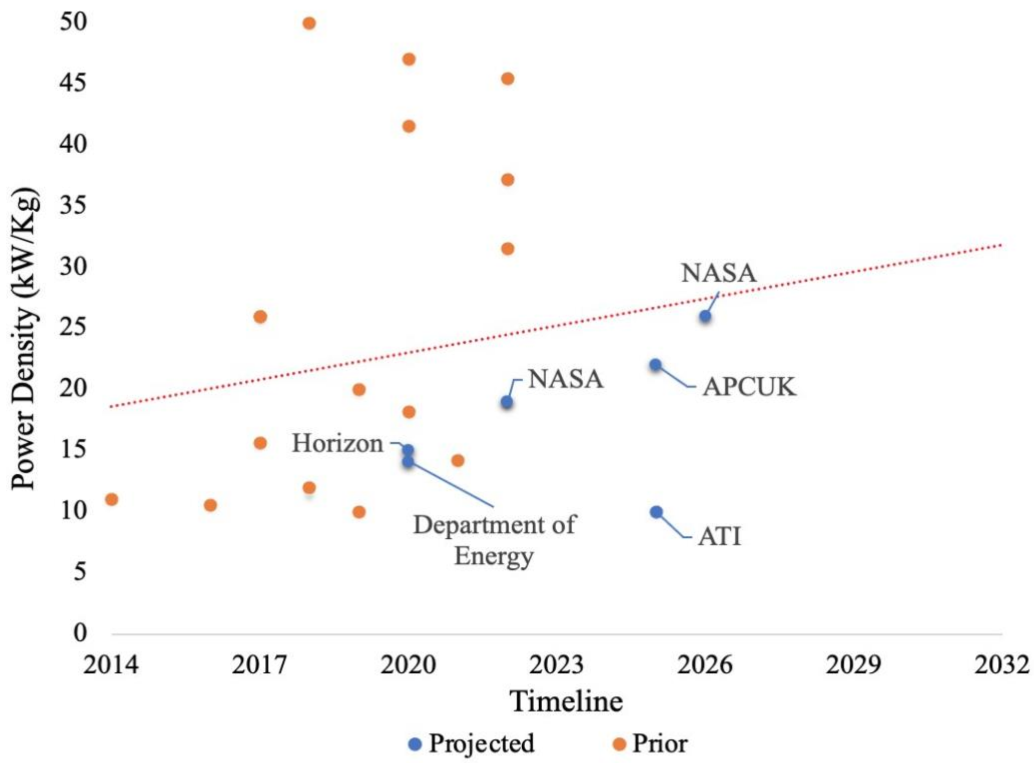

Figure 4. AC/DC Power Conversion Roadmap Highlighting Technology Power Density Prior to 2022 and Projected.

$$AC/DC\ (kW/kg) = 0.7331 \cdot Year - 1457.8 \tag{4}$$

While Figure 5 presents a combined roadmap of DC/DC converters power density [90][101-108]. In the Figure, the data points for the power density advertised from manufacturers and from research prototypes for DC/DC devices power density are labelled as “prior” for technology available from 2014 to the start of 2022 and projected densities from later 2022 to 2032 are labelled as “projected” densities. From Figure 5, Equation (5) is extracted and can be used to estimate the energy density progression of converter (DC/DC) in the following years.

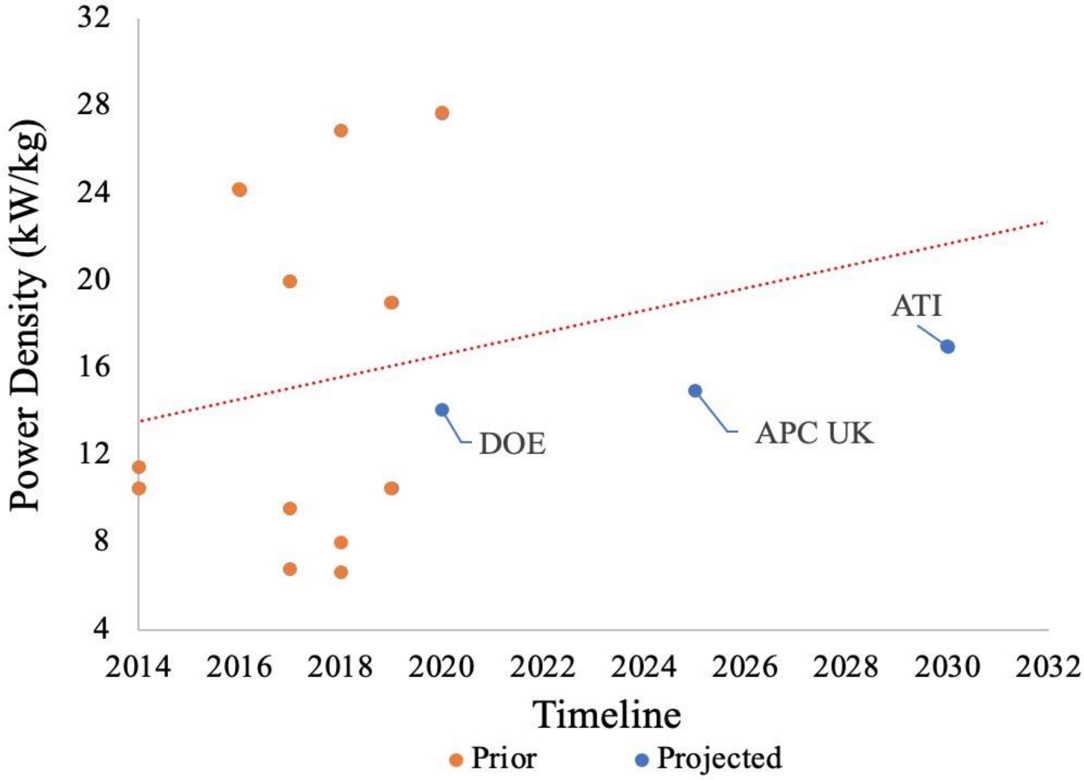

Figure 5. DC/DC Power Conversion Devices Roadmap Highlighting Technology

$$DC/DC\ (kW/kg) = 0.5094 \cdot Year - 1012.3 \quad (5)$$

The presented data points of the power electronics devices have limited information regarding what is included in the advertised power density, such as the filtering components. The weight and size of the Electromagnetic Interference (EMI) filter has a significant impact to the overall weight of the power electronics devices contributing to between 25% to 40% of the total device weight [109, 110].

5. Power Protection

Protection devices are essential to isolate any potential faults that might occur during a journey, as well as ensure the safety of the electric aircraft power system and its inclusion. The main requirement of protection devices for eVTOL aircraft is the ability to isolate the fault rapidly for high voltages and fault current.

Conventional resettable protection devices are Electro-mechanical molded case circuit breaker (MCCB), circuit breakers and DC contactors. MCCBs are available in high DC voltages for the

Photovoltaic industry [111, 112], yet they have relatively slow response time for DC systems and are also susceptible to arcing damage causing low lifetime [113]. The DC contactors and conventional circuit breakers have their limitations for high voltage and high power demands for EV or electric aircraft applications [114].

Fuses are available in a wide range of high voltage, cheap, and small in size. With the recent development in the automotive industry, hybrid Pyrofuse protection device was developed as a solution to similar issues faced in the state of the art electric vehicles [114, 115]. Pyrofuse is unlike conventional fuses as it has characteristics such as: excellent at clearing low fault currents, better cycling performance, lower conduction losses, and the time-current curve can be tuned to fit the system [114, 115]. In terms of current development, Panasonic and Gmbh [116] have presented a new type of Pyrofuse to provide fault protection and isolation for high power density battery applications. Bosch [117] and Texas Instruments [118] are developing current sensing circuits for externally triggered Pyrofuses. Mersen have developed a hybrid Pyrofuse protection solution for fast DC overcurrent limitation suitable for high voltage requirements for aerospace applications [114, 119]. The authors in [114] have presented the testing of Mersen’s self-triggered Xp-series Pyrofuse with a fault level of 11 kA at 500 VDC.

With regards to the implementation of Pyrofuses in aerospace environment, Mersen [119] in 2016 had also stated its intention to test the Xp-series Pyrofuse in an Airbus concept aircraft, although no publicly available update on this test has been provided to date. Safran and Pyroalliance are also developing protection solutions using Pyrofuses for high voltage electric aircraft applications [120]. However, Pyrofuse devices are non-resettable which introduces further challenges in certifying the device for use in aerospace application.

The recent development in resettable semiconductor devices succeeded in the limitation of conventional protection devices, offering a fast tripping speed against short circuit faults [121]. As a consequence, solid-state circuit breaker (SSCB) and solid-state power controller (SSPC) have recently received extensive attention in research [113]. The SSCBs offer fault current interruption; it trips when the current exceeds the threshold. Similarly, SSPC can detect abnormal excess of fault energy (I^2) which trips according to a threshold current. In addition to that, the SSPC also has the capability to detect arc faults, fast fault clearance, and power-load management with the control of a digital processor [122, 123].

SSCBs are available commercially in high voltages for non-aerospace applications (e.g., 1kV and up to 5 kA [124]). Similarly, SSPCs are available but at low voltages, as shown in Table 1. The on-state losses of a SSCB are significantly greater than in typical circuit breakers [125]. Therefore when scaling up, the increased on-state and energy losses of both SSPCs and SSCBs leads to increased requirements for cooling which contributes to a significant portion of the devices' weight [125, 126]. Active and liquid cooling systems offers reduced size and weight of the overall system than passive cooling methods [125]. Further development is required to reduce the volume and weight of the cooling and packaging of these devices to reduce the weight of the power system in eVTOL aircraft. Nevertheless, it is important to highlight that the presented weight of the SSPC modules in Table 1 obtained from the manufacturer datasheet doesn't include heatsink nor external cooling.

Table 1. List of Current Available SSPCs [125]- [130]

Reference no.	**Voltage (V)**	**Current (A)**	**Power (kW)**	**Weight (g)**	**Power Density (kW/kg)**
SPDP50D375	375	50	1.5	650	28.8
SPDP50D28-1	55	50	2.75	40	68.75
SSP-21116	270	15	4.05	115	35.2
MDSPC270M-50xL	270	500	135	350	385.7
P800	28	150	4.2	500	8.4
P600	28	80	2.24	500	4.48

As there is limited information available on protection devices in the public domain thus with insufficient data points a 10-year technology roadmap is not feasible. The following projections can provide a timeline for SSPCs maturity. From the roadmap in [132], SSPC fault current interruption devices with 100 kW and 750 VDC is highly confident to be available into market in N+1 timeframe (according to [133], initial operational capability in 2015-2025), and power up to 1MW and 750 VDC in N+2 timeframe (According to [133], translates to 2025-2030). While SSCBs devices maturity will have a TRL of 4-6 by 2025 [132].

6. Conclusion

From the presented literature review in this white paper there is a notable increase in the development of battery and power electronics technologies suitable for the use in eVTOL aircraft. While the requirement for the development of power machines for the automotive industry is different than the requirement for eVTOL and aerospace application; the s show slower pace improvement in the power density. Additionally, there is a lack of information published from manufacturers regarding development targets and power density of the power protection devices in the public domain. Whilst solid-state switches improvements in power electronics can potentially be transferred to the development of power protection components, but nothing is published regarding that as well.

Using the trendlines from the Figures presented in this white paper, Table 2 provides a summary of the power and energy density of current existing technologies from 2017 and future projections in 2025 and 2030. The technologies covered are critical to the power system design and include batteries for the energy storage, power electronics, and power machines. With regards to protection devices, due to insufficient data points, a 10-year technology roadmap was not feasible.

Table 2. Current Existing and Future Projections of Technological Parameters Abstracted from the Roadmaps

Technologies		**Energy/Power Density**		
		2017	**2025**	**2030**
Batteries (Wh/kg)	Cell level	270.9	438.5	543.1
	Pack level	203.2	328.8	407.35
Electric Machines	High torque motors	3.3	7.9	10.8
(kW/kg)	High speed motors	5.4	11.5	15.2
Power Electronics	Converter (DC/DC)	15.2	19.2	21.78
(kW/kg)	Inverter (AC/DC or DC/AC)	20.9	26.7	30.39

Most importantly to not is that these technologies are still low in maturity for the use in eVTOL aircraft which can hinder the exploration of novel designs, and increasing the challenges of designing light weight aircraft with high reliability and redundancy viably satisfy a range of missions. This highlights the need to understand their integration into a viable design and set requirements for future targets to achieve the mission targets without compromising the safety of the aircraft and its inclusion.

The recently introduced Pyrofuse device in the literature show a potential for use in aerospace applications. This device can offer low-weight solutions for the use as a protection device in the power system architecture. However, it is non-resettable which requires further work to investigate the performance and robustness of the Pyrofuse device to assist the acceleration this emerging market. Therefore, the first step into assessing the use of the Pyrofuse is by modelling the device in an aerospace environment enabling the capability for further investigations.

References

[1] J. Booker, C. Patel and P. Mellor, "Modelling Green VTOL Concept Designs for Reliability and Efficiency", *Designs*, vol. 5, no. 4, p. 68, 2021. doi:10.3390/designs5040068.

[2] O. Bertram, F. Jager, V. Voth and J. Rosenberg, "UAM Vehicle Design with Emphasis on Electric Powertrain Architectures", in *AIAA SCITECH 2022 Forum*, San Diego, CA Virtual, 2022.

[3] C. Jones, K. Millar, K. Fong, R. Alzola, P. Norman and G. Burt, "A Modelling Design Framework for Integrated Electrical Power and Non-Electrical Systems Design on Electrical Propulsion Aircraft," in *2022 IEEE Transportation Electrification Conference Expo (ITEC)*, 2022. doi:10.1109/ITEC53557.2022.9813810.

[4] B. Hinman, "Hang in There: Why Hovering Matters in eVTOL Design", *Medium*, 2019. [Online]. Available: https://brian-is-flyin.medium.com/hang-in-there-whyhovering-matters-in-evtol-design-bf60aa5b69db. [Accessed: 10- Aug- 2022].

[5] E. Head, "What we know about Lilium's eVTOL batteries so far", *The Vertical Flight Society*, 2021. [Online]. Available: https://evtol.com/features/lilium-evtolbatteries-what-we-know/. [Accessed: 10- Aug- 2022].

[6] OXIS Energy, "OXIS ENERGY Progresses its Lithium Sulfur (Li-S) cell technology to 450 Wh/kg.", 2018.

[7] "AboutAmprius Technologies", *Amprius*. [Online]. Available: https://www.amprius.com/about. [Accessed: 03- Aug- 2022].

[8] "Product Pipeline", *PolyPlus*. [Online]. Available: https://polyplus.com/product-pipeline/. [Accessed: 09- Aug- 2022].

[9] "Building the Future of Batteries", *Sion Power*. [Online]. Available: https://sionpower.com. [Accessed: 09- Aug- 2022].

[10] T. Spendlove, "New HIU lithium-metal battery boasts 560 Wh/kg specific energy", *Charged EVs*, 2021. [Online]. Available: https://chargedevs.com/newswire/new-hiu-lithium-metal-battery-boasts-560wh-kg-specific-energy/. [Accessed: 09- Aug- 2022].

[11] Roland Berger, "Aircraft Electrical Propulsion - Onwards and Upwards", [online]. URL: https://www.rolandberger.com/publications/publication pdf/roland berger aircraft electrical propulsion 2.pdf [retrieved 21 Jan. 2020].

[12] Misra, A., "Summary of 2017 NASA Workshop on Assessment of Advanced Battery Technologies for Aerospace Applications", [online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001539.pdf.

[13] ATI, "Electrical Power Systems", [online]. Available: https://www.ati.org.uk/media/ntlocbb4/insight07-electrical-power-systems.pdf [retrieved 20 Jun. 2019]

[14] K. Field, "Tesla Model 3 Battery Pack & Battery Cell Teardown Highlights Performance Improvements", *Clean Technica*, 2019. [Online]. Available: https://cleantechnica.com/ 2019/01/28/tesla-model-3-battery-pack-cellteardown-highlights-performance-improvements/. [Accessed: 09- Aug- 2022].

[15] *High Energy Rechargeable Metal Cells for Space (LMP063767)*. Solid Energy Systems, 2017.

[16] "Amprius' Silicon Nanowire Lithium Ion Batteries Power Airbus Zephyr S HAPS Solar Aircraft", Amprius, 2018. [Online]. Available: https://amprius.com/corporate-announcements/amprius-silicon-nanowirelithium-ion- batteries-power- airbus-zephyr-s-haps-solar-aircraft. [Accessed: 09Aug- 2022].

[17] OXIS Energy, "OXIS ENERGY Progresses its Lithium Sulfur (Li-S) cell technology to 450WH/kg.", 2018.

[18] 24M, "24M Technologies, Inc. Awarded $9 Million From ARPA-E for Transformational Energy Technology", 2022.

[19] P. Lima, "CATL achieves 304 Wh/kg in new battery cells", *Push Electric Vehicles Forward*, 2022. [Online]. Available: https://pushevs.com/2019/03/30/catlachieves-304-wh-kg-in-new-battery-cells/. [Accessed: 09- Aug- 2022].

[20] B. Wang, "Tesla's Maxwell Dry Battery and a Five Year Lead on the World", *Next Big Future*, 2019. [Online]. Available: https://www.nextbigfuture.com/2019/03/teslas-maxwell-dry-battery-and-afive-year-lead-on-the-world.html. [Accessed: 09- Aug- 2022].

[21] M. Kane, "Amprius Ships First 450 Wh/kg, 1150 Wh/l Battery Cells", *Inside EVs*, 2022. [Online]. Available: https://insideevs.com/news/566876/ampriusships-450whkg-battery-cells/. [Accessed: 09- Aug- 2022].

[22] "Battery500 project has achieved 350 Wh/kg and more than 350 cycles", *Green Car Congress*,2020.[Online].Available:https://www.greencarcongress.com/2020/05/20200528-battery500.html. [Accessed: 09- Aug- 2022].

[23] M. Kane, "Farasis Batteries With Silicon-Carbon Anode Get 25% Energy Boost", *Inside EVs*, 2021. [Online]. Available: https://insideevs.com/news/539398/ farasis-batteries-energy-density-boost/. [Accessed: 09- Aug- 2022].

[24] M. Kane, "OXIS To Offer 450 Wh/kg Quasi Solid-State Li-S Cells In Fall 2021", *Inside EVs*, 2021. [Online]. Available: https://insideevs.com/news/502505/oxis450-whkg-solidstate-cells/. [Accessed: 09- Aug- 2022].

[25] "Sion Power Introduces a Full-Scale Rechargeable Battery Targeting the Electric Vehicle Industry, Over 400 Wh/kg and 810 Wh/L", *Business wire*, 2021. [Online]. Available: https://www.businesswire.com/news/home/20210824005064/en/SionPowerIntroduces-a-Full-Scale-Rechargeable-Battery-Targeting-the-Electric-VehicleIndustry-Over-400-Whkg-and-810-WhL. [Accessed: 09- Aug- 2022].

[26] "Technology - Innolith", Innolith. [Online]. Available: https://innolith.com/technology/. [Accessed: 09- Aug- 2022].

[27] C. Randall, "SVOLT is reaching up to 400 Wh/kg in solid-state batteries", *electrive*, 2022. [Online]. Available: https://www.electrive.com/2022/07/22/svolt-isreaching-up-to-400-wh-kg-in-solid-state-batteries/. [Accessed: 09- Aug- 2022].

[28] M. Kane, "Solid Power Installs Pilot Production Line For SolidState Battery Cells", *Inside EVs*, 2022. [Online]. Available: https://insideevs.com/news/590430/solid-power-pilot-production-batteries/. [Accessed: 09- Aug- 2022].

[29] P. Zhang, "Gotion to mass-produce semi-solid-state batteries this year", *Cn EV Post*, 2022. [Online]. Available: https://cnevpost.com/2022/05/27/gotion-hightech-to-mass-produce-semi-solid-state-batteries-this-year/. [Accessed: 09- Aug2022].

[30] M. Kane, “NIO Announces 150 kWh Solid-State Batteries For 2022”, *In-side EVs*, 2021. [Online]. Available: https://insideevs.com/news/465188/nio-150kwh-solid-state-batteries-2022/. [Accessed: 09- Aug- 2022].

[31] F. Lambert, “Tesla receives 4680 battery cell samples from Panasonic ahead of mass production”, Electrek, 2022. [Online]. Available: https://electrek.co/2022/06/01/tesla-4680-battery-cell-samples-panasonic/. [Accessed: 09- Aug- 2022].

[32] “INR21700-P45B”, *Molicel*. [Online]. Available: https://www.molicel.com/inr21700-p45b/. [Accessed: 09- Aug- 2022].

[33] “series production of battery cells ‘made in Germany’”, *CUSTOMCELLS*. [Online]. Available: https://www.cct-batteries.com. [Accessed: 09- Aug- 2022].

[34] “Lithium Primary Battery Packs”, Custom Power. [Online]. Available: https://www.custompower.com/custom-battery-packs/lithium-primary. [Accessed: 09- Aug- 2022].

[35] N. Manthey, “InoBat scores lithium-silicon battery deal with Group14 - electrive.com”, *electrive*, 2021. [Online]. Available: https://www.electrive.com/2021/08/24/inobat-scores-lithium-silicon-batterydeal-with-group14/. [Accessed: 09- Aug- 2022].

[36] G. Ruffo, “InoBat Proposes To Abandon Standard Battery Formats With AI”, *Inside EVs*, 2020. [Online]. Available: https://insideevs.com/news/448170/inobatabandon-standard-battery-formats-ai/. [Accessed: 09- Aug- 2022].

[37] “Solid Power awarded up to $12.5M to develop nickel- and cobalt-free all-solidstate battery cells; 500 Wh/kg target”, *Green Car Congress*, 2021. [Online]. Available: https://www.greencarcongress.com/2021/10/20211002-solid.html. [Accessed: 09- Aug- 2022].

[38] “Lyten introduces next generation Lithium-Sulfur battery for EVs; 3X energy density of Li-ion”, Green Car Congress, 2021. [Online]. Available: https://www.greencarcongress.com/2021/09/20210923-lyten.html. [Accessed: 09- Aug- 2022].

[39] “Innolith Claims It’s On Path To 1,000 Wh/kg Battery Energy Density”, *Inside EVs*, 2022. [Online]. Available: https://insideevs.com/news/343771/innolithclaims-its-on-path-to-1000-wh-kg-battery-energy-density/. [Accessed: 09- Aug2022].

[40] Duffy, M., Sevier, A., Hupp, R., Perdomo, E., Wakayama, S. , "Propulsion Scaling Methods in the Era of Electric Flight", in 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, Cincinnati, Ohio, 2018, doi: 10.2514/6.2018-4978

[41] Gulloci, F. "Turning Volts to VTOL", *The Vertical Flight Society* [online]. Available: https://vtol.org/files/dmfile/eVTOL-motors-Colucci VF-JF181.pdf [Accessed: 21- Jan - 2020].

[42] DENSO, "Weight Reduction, Cooling Performance, and Reliability: Key Requirements for Air Mobility Motors — Mechanism of motors for DENSO's flying cars", 2021.

[43] "How Loud is an eVTOL?", Archer, 2022. [Online]. Available: https://archer.com/news/how-loud-is-an-evtol. [Accessed: 03- Aug- 2022].

[44] "Joby Confirms Revolutionary Low Noise Footprint Following NASA Testing — Joby", Joby Aviation, 2022. [Online]. Available: https://www.jobyaviation.com/news/joby-revolutionary-low-noise-footprint- nasa-testing/. [Accessed: 03- Aug- 2022].

[45] J. Bevirt, "How Quiet is the Joby Aircraft during Hover?", Youtube, 2021. [Online]. Available: https://www.youtube.com/watch?v=GHmXR0wBOiI. [Ac- cessed: 03- Aug- 2022].

[46] H. Lin, H. Guo and H. Qian, "Design of High-Performance Permanent Magnet Synchronous Motor for Electric Aircraft Propulsion", in *21st International Conference on Electrical Machines and Systems (ICEMS)*, Jeju, Korea (South), 2018.

[47] E. Agamloh, A. von Jouanne and A. Yokochi, "An Overview of Electric Machine Trends in Modern Electric Vehicles", *Machines*, vol. 8, no. 2, p. 20, 2020. Available: 10.3390/machines8020020.

[48] YASA. "YASA 750", [online]. Available: https://www.yasa.com/yasa-750/ [Accessed: 21-Jan-2020].

[49] MAGNAX, "Next Generation Axial Flux Machines". [online] Available: https://www.magnax.com/technology [Accessed: 21-Jan-2020].

[50] NASA, "Electrical Machines", [online], Available: https://www1.grc.nasa.gov/aeronautics/electrified-aircraft-propulsion-eap/eapfor-larger-aircraft/electric-machines/ [Accessed: 21-Jan-2020].

[51] Volocopter, "Pioneering the urban air taxi revolution", [online], URL: https://press.volocopter.com/images/pdf/Volocopter-WhitePaper-1-0.pdf [Accessed: 29 Jan. 2020]

[52] Moore, M., “Distributed Electric Propulsion (DEP) Aircraft”, [online], Available: https://aero.larc.nasa.gov/files/2012/11/Distributed-Electric-PropulsionAircraft.pdf [Accessed: 29-Jan-2020]

[53] P. Nathen, A. Bardenhagen, 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, 2021.

[54] “Aerospace Motor — Axial Flux Electric Motor Technology”, *Evolito LTD*. [Online]. Available: https://evolito.aero/technology/. [Accessed: 10- Aug- 2022].

[55] “H3X — Electric Aircraft Propulsion”, *H3x.tech*. [Online]. Available: https://www.h3x.tech. [Accessed: 10- Aug- 2022].

[56] “Electric Powertrain Technology Systems”, *Helix*. [Online]. Available: https://ehelix.com/electric-powertrains/. [Accessed: 10- Aug- 2022].

[57] “APM-200 - Equipmake”, *Equipmake*. [Online]. Available: https://equipmake.co.uk/products/apm-200/. [Accessed: 10- Aug- 2022].

[58] “AMPERE-220”, *Equipmake*. [Online]. Available: https://equipmake.co.uk/products/ampere-220/. [Accessed: 10- Aug- 2022].

[59] “Integrated Motor — Controller: MAGiDRIVE™ - MAGicALL”, *MAG-icALL*. [Online]. Available: https://www.magicall.biz/products/integratedmotor-controller-magidrive/. [Accessed: 10- Aug- 2022].

[60] T. Lombardo, “Siemens Electric Aircraft Propulsion Unit: Inside the Digital Twin Design Strategy”, *Engineering.com*, 2018. [Online]. Available: https://www.engineering.com/story/siemens-electric-aircraft-propulsionunit-inside-the-digital-twin-design-strategy. [Accessed: 10- Aug- 2022].

[61] “Industry-Leading Products”, *magniX*. [Online]. Available: https://magnix.aero/services. [Accessed: 10- Aug- 2022].

[62] A. Dubois, M. Geest, J. Bevirt, R. Christie, N. Borer and S. Clarke, “Design of an Electric Propulsion System for SCEPTOR’s Outboard Nacelle”, in *16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C, 2016.

[63] “ENGINeUS™ Smart Electric Motors”, *Safran*. [Online]. Available: https://www.safran-group.com/products-services/engineustm. [Accessed: 10Aug- 2022].

[64] *Technical Data and Manual for EMRAX Motors / Generators*. Emrax, 2018.

[65] N. Zart, “The Pipistrel Alpha Electro, An Awesome 2-Seat Electric Trainer”, *CleanTechnica*, 2017. [Online]. Available: https://cleantechnica.com/2017/11/13/pipistrel-alpha-electro-awesome-2-seatelectric-trainer/. [Accessed: 10- Aug- 2022].

[66] D. Sigler, “MagniX, an Australian High-Power and Torque-Dense Motor”, Sustainable Skies, 2018. [Online]. Available: http://sustainableskies.org/magnixaustralian-high-power-torque-dense-motor/. [Accessed: 10- Aug- 2022].

[67] G.Oshin, “Magnomaticshigh performance motor for aircrafts”, *Linkedin*, 2022. [Online].Available :https://www.linkedin.com/feed/update/urn:li:activity:695666202530538700 8? updateEntityUrn=urnAli%3AfsfeedUpdate%3A%28V2%2Curn%3Ali%3Aactivity%3A69 56662025305387008%29. [Accessed: 10- Aug- 2022].

[68] C. Muller, “Opportunities and challenges of electric aircraft propulsion”, Brugg, 2017.

[69] F. Anton, “eAircraft: Hybrid-elektrische Antriebe fu¨r Luftfahrzeuge”, Potsdam, 2019.

[70] F. Anton, O. Otto, J. Hetz and T. Olbrechts, “Siemens eAircraft – Disrupting the way you will fly!”, 2018.

[71] “268 (200kW - 500Nm)”, *EMRAX*. [Online]. Available: https://emrax.com/emotors/emrax-268/. [Accessed: 10- Aug- 2022].

[72] “228 (109kW - 230Nm)”, *EMRAX*. [Online]. Available: https://emrax.com/emotors/emrax-228/. [Accessed: 10- Aug- 2022].

[73] M. Gos´alvez et al., “Green Flying Final Report”, Technical University Delft, 2018.

[74] M. Toll, “New axial flux electric motors pack more EV power in a smaller package”, *Electrek*, 2018. [Online]. Available: https://electrek.co/2018/05/03/axialflux-electric-motors-more-ev-power-smaller-package/. [Accessed: 10- Aug- 2022].

[75] McLaren, “McLaren - the power behind Formula E”, 2014.

[76] *P400 R Series E-Motors*. YASA, 2018.

[77] D. Sigler, "Siemens Makes a Big, Light Motor", *CAFE Foundation Blog*, 2015. [Online]. Available: http://cafe.foundation/blog/siemens-makes-big-light-motor2/. [Accessed: 11- Aug- 2022].

[78] DENSO, "DENSO, Honeywell Co-Develop E-Motor for Lilium's All-Electric Jet", 2022.

[79] J. Gonz´alez,"Quark: The Lightweight Electric Motor Capable of Generating Unprecedented Power", *Green Racing News*, 2022.[Online].Available: https://greenracingnews.com/quark-the-lightweight-electric-motorcapable-of-generating-unprecedented-power/. [Accessed: 10- Aug- 2022].

[80] "High performance motors: 17 kW/kg power density", SciMo. [Online]. Available: https://sci-mo.de/en/motors/Applications. [Accessed: 10- Aug- 2022].

[81] A. Datta, "Commercial Intra-City On-Demand Electric-VTOL", The Vertical Flight Society, 2022.

[82] J. Liu, W. Su, X. Tai, et.l. "Development of an inverter using hybrid SIC power module for EV/HEV applications", in *19th International Conference on Electrical Machines and Systems (ICEMS)*, Chiba, Japan, 2016.

[83] Mitsubishi Electric, "Mitsubishi Electric Develops World's Smallest SiC Inverter for HEVs", 2017.

[84] "Products - McLaren Applied", *Mclarenapplied*. [Online]. Available: https://www.mclarenapplied.com/products?categories=10. [Accessed: 10Aug- 2022].

[85] M. Hayes et al., "650V, 7mOhm SiC MOSFET Development for Dual-Side Sintered Power Modules in Electric Drive Vehicles", in *PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, Nuremberg, Germany., 2017.

[86] US Department of Energy, "FY2017 Electrification Annual Progress Report", 2017.

[87] Wolfspeed, "Cree to Invest $1 Billion to Expand SiC Capacity", 2019.

[88] S. Rogers, "Advanced Power Electronics and Electric Motors (APEEM) R&D Program Overview", Program AMR and Peer Evaluation Meeting, 2011.

[89] Advanced Propulsion Centre UK, "The Roadmap Report - Towards 2040: A Guide to Automotive Propulsion Technologies", Advanced Propulsion Centre UK.

[90] M. Guacci, D. Bortis and J. Kolar, “High-Efficiency Weight-Optimized Fault-Tolerant Modular Multi-Cell Three-Phase GaN Inverter for Next Generation Aerospace Applications”, in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, Portland, USA, 2019.

[91] D. Zhang, J. He, D. Pan, M. Dame, M. Schutten, “Development of Megawatt- Scale Medium-Voltage High Efficiency High Power Density Power Converters for Aircraft Hybrid-Electric Propulsion Systems”, in *AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, Cincinnati, OH, 2018. ISBN: 978-1-62410-572-2.

[92] “Electrical Power”, Geaviation. [Online]. Available: https://www.geaviation.com/commercial/systems/silicon-carbide. [Accessed: 10- Aug- 2022].

[93] R. Jansen, C. Bowman, A. Jankovsky, R. Dyson and J. Felder, “Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports”, in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, 2017.

[94] “HPI-450”, *Equipmake*. [Online]. Available: https://equipmake.co.uk/products/hpi-450/. [Accessed: 10- Aug- 2022].

[95] D. Zhang, J. He and D. Pan, “A Megawatt-Scale Medium-Voltage High-Efficiency High Power Density “SiC+Si” Hybrid Three-Level ANPC Inverter for Aircraft Hybrid-Electric Propulsion Systems”, *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 5971-5980, 2019. Available: 10.1109/tia.2019.2933513.

[96] S. Rogerson, “SiC DC-DC converter passes EV test”, *Vehicle Electronics*, 2014. [Online]. Available: https://vehicle-electronics.biz/content/sic-dc-dc-converterpasses-ev-test. [Accessed: 10- Aug- 2022].

[97] K Yamaguchi, K. Katsura, T. Yamada and Y. Sato, “High Power Density SiCBased Inverter with a Power Density of 70kW/liter or 50kW/kg”, *IEEJ Journal of Industry Applications*, vol. 8, no. 4, pp. 694-703, 2019. Available: 10.1541/iee-jjia.8.694.

[98] “Products”, *Drivetrain Innovation*. [Online]. Available: https://drivetraininnovation.com/products/. [Accessed: 10- Aug- 2022].

[99] “Inverter and Power Electronics”, *SciMo*. [Online]. Available: https://scimo.de/en/power-electronics/. [Accessed: 10- Aug- 2022].

[100] A. Pescod, “Future 50: Norfolk firm to transform electric vehicles with new inverter”, *Eastern Daily Press*, 2022. [Online]. Available: https://www.edp24.co.uk/news/business/equipmake-to-transform-electricvehicles-with-new-inverter-8743652. [Accessed: 10- Aug- 2022].

[101] W. Martinez, C. Cortes, L. Mun˜oz and M. Yamamoto, ”Design of a 200kW electric powertrain for a high performance electric vehicle”, *Ingenier´ıa e Investigaci´on*, vol. 36, no. 3, p. 66, 2016. Available: 10.15446/ing.investig.v36n3.53792.

[102] G. Calderon-Lopez., A. Forsyth, “High power density DC-DC converter with SiC MOSFETs for electric vehicles” in *7th IET International Conference on Power Electronics, Machines and Drives*, 2014. doi:10.1049/cp.2014.0463.

[103] “RedPrime DC-DC Converter 200kW, 1200V”, Zekalabs. [Online]. Available: https://www.zekalabs.com/products/non-isolated-high-power-converters/dc-dcconverter-200kw-1200v. [Accessed: 10- Aug- 2022].

[104] R. Bosshard and J. Kolar, “All-SiC 9.5 kW/dm3On-Board Power Electronics for 50 kW/85 kHz Automotive IPT System”, *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 1, pp. 419-431, 2017. Available: 10.1109/jestpe.2016.2624285.

[105] G. Su, C. White, Z. Liang, “Design and Evaluation of a 6.6 kW GaN Converter for Onboard Charger Applications” in *the 18th IEEE Workshop on Control and Modeling for Power Electronics*, Stanford, CA. 2017. doi:10.1109/COMPEL.2017.8013335.

[106] “High-Power Bidirectional DC/DC Converter for Hybrid-Electric Vehicle Applications”, *Advanced Power Electronics Corporation*. [Online]. Available: http://apecor.com/highpower.php. [Accessed: 10- Aug- 2022].

[107] R. Erickson, D. Maksimovic, K. Afridi, D. Jones, et.l. “A Disruptive Approach to Electric Vehicle Power Electronics Final Report”, 2017.

[108] A. Wienhausen, A. Sewergin, and R. Doncker, “Highly Integrated Two-Phase SiC Boost Converter with 3D-Printed Fluid Coolers and 3D-Printed Inductor Bobbins”, in *PCIM Europe 2018; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, Nuremberg, Germany, 2018.

[109] J. Schanen, A. Baraston, M. Delhommais, P. Zanchetta and D. Boroyevitch, "Sizing of power electronics EMC filters using design by optimization methodology", in *7th Power Electronics and Drive Systems Technologies Conference (PEDSTC)*, Tehran, Iran, 2016.

[110] M. Hartmann, "Ultra-Compact and Ultra-Efficient Three-Phase PWM Rectifier Systems for More Electric Aircraft," Ph.D. dissertation, ETH Zurich, 2011.

[111] "HMDL 1000VDC MCCB", *Eaton.*[Online]. Available: https://www.eaton.com/sg/en-us/catalog/electrical-circuit-protection/eatonhmdl-1000vdc-mccb.html [Accessed 14-No-2019].

[112] ABB, "ABB launches molded case circuit breakers for higher voltage solar power plants", 2018.

[113] Z. Shen, G. Sabui, Z. Miao and Z. Shuai, "Wide-Bandgap Solid-State Circuit Breakers for DC Power Systems: Device and Circuit Considerations", *IEEE Transactions on Electron Devices*, vol. 62, no. 2, pp. 294-300, 2015. Available: 10.1109/ted.2014.2384204.

[114] T. Sakuraba, R. Ouaida, S. Chen, and T. Chailloux, "Evaluation of Novel Hybrid Protection Based on Pyroswitch and Fuse Technologies", in *International Power Electronics Conference*, Niigata, Japan, 2018.

[115] Kopriv˘sek, M., "Advanced Solutions in Over-Current Protection of Hvdc Circuit of Battery-Powered Electric Vehicle", in PCIM Europe 2018, Nuremberg, Germany, 2018. ISBN: 978-3-8007- 4646-0.

[116] Lell, P., Volm, D., "Innovative Safety Concept to Shutdown Short Circuit Currents in Battery Systems up to 1000V Based on Ultrafast Pyrofuse Technology", in IEEE Holm Conference on Electrical Contacts, Albuquerque, NM, 2018. doi: 10.1109/HOLM.2018.8611656

[117] Bosch, "Explosions that save lives", [online]. Available: https://www.boschpresse.de/pressportal/de/en/explosions-that- save-lives-200641.html [retrieved 20 Mar. 2020]

[118] Kambham, T. R. C. R., "Pyro-Fuse Circuit", Taxas Instruments Incorporated, [online]. Available: http://www.freepatentsonline.com/y2019/0123542.html

[119] Mersen, “Current Limiting Device to Address DC Aeronautics Power Distribution Systems”, 2016.

[120] Safran, “Safran and Pyroalliance announce a partnership for emergency pyrotechnic electrical shutdown solutions for future aeronautics electrical networks”, 2021.

[121] “ARPA-E awards $30Mto 21 projects advance new class of high-performance power converters”, *Green Car Congress*, [online]. Available:: https://www.greencarcongress.com/2017/08/arpa-e-awards-30m-to-21-projectsadvance-new-class-of-high-performance-power-converters.html [Accessed 14-No2019].

[122] M. Terorde, F. Grumm, D. Schulz, H. Wattar, J. Lemke, “Implementation of a Solid-State Power Controller for High-Voltage DC Grids in Aircraft”, in *PESS Power and Energy Student Summit*, 2015.

[123] D. Molligoda, P. Chatterjee, C. Gajanayake, A. Gupta, and K. Tseng, “Review of design and challenges of DC SSPC in More Electric Aircraft”, in *2016 IEEE 2nd Annual Southern Power Electronics Conference (SPEC)*, Auckland, New Zealand, 2016. doi: 10.1109/SPEC.2016.7846117.

[124] KWx, “Solid-state 1kV DC breaker switch”, 2020.

[125] J. Adhikari, T. Yang, J. Zhang, M. Rashed, et al., “Thermal Analysis of High Power High Voltage DC Solid State Power Controller (SSPC) for Next Generation Civil Tilt Rotor-craft”, in *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Nottingham, UK, 2019. doi: 10.1109/ESARS-ITEC.2018.8607314

[126] W. Kong, “Review of DC Circuit Breakers for Submarine Applications”, Australian Government Department of Defense, Victoria, Australia, 2012.

[127] “SPDP50D375 datasheet”, *Datasheetspdf*. [Online]. Available: https://datasheetspdf.com/pdf-file/1385810/Sensitron/SPDP50D375/1. [Accessed: 11- Aug-2022]. 2cc8f361e8cad51efetype=Pterm=SSP-21116, accessed:Oct. 2019.

[128] “SSP-21116 Datasheet Preview”, *Datasheetarchive*. [Online]. Available: https://www.datasheetarchive.com/pdf/download.php?id=1e69c1b50e6211003ec 60b727efa0e619fa839type=Mterm=SSP21116. [Accessed: 11- Aug- 2022].

[129] "SPDP50D28-1 Datasheet", *Datasheetspdf*. [Online]. Available: https://datasheetspdf.com/datasheet/SPDP50D28-1.html. [Accessed: 11Aug- 2022].

[130] "MDSPC270M-50xL", *Hyjas*. [Online]. Available: http://www.hyjas.com/page12?product id=326product category=27. [Accessed: 11- Aug- 2022].

[131] *Short Form Catalogue Components Solutions*. Esterline Power Systems.

[132] M. Flynn et al., "Protection and Fault Management Strategy Maps for Future Electrical Propulsion Aircraft", *IEEE Transactions on Transportation Electrification*, 2019. Available: 10.1109/tte.2019.2940882.

[133] National Academies of Sciences, Engineering, and Medicine, *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC: The National Academies Press, 2016. doi:10.17226/23490