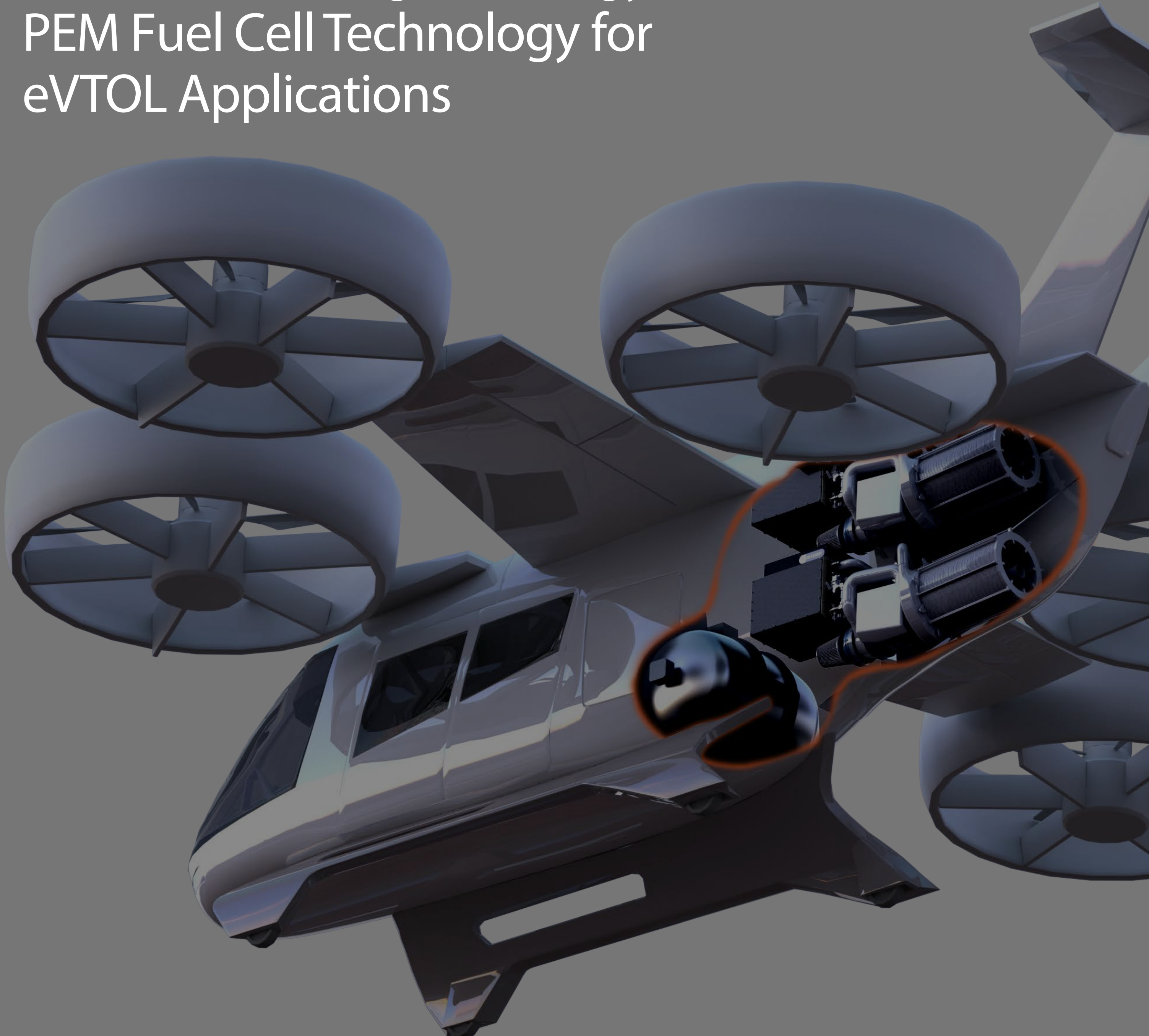
IE-FLIGHT

Benefits of Intelligent Energy's PEM Fuel Cell Technology for eVTOL Applications



Intelligent Energy®

Executive summary

As populations and cities continue to expand, there is an increasing demand on the existing infrastructure to transport both people and produce.

This white paper discusses the role of hydrogen fuel cells in the fast growing eVTOL market and how Intelligent Energy's (IE) technology can solve the challenges of heat dissipation during both flight and hover conditions, as well as in hot ambient environments. The paper describes the advantages of fuel cells and IE technology for improving the total cost of ownership when compared to pure battery powered options.

As populations and cities continue to expand, there is an increasing demand on the existing infrastructure to transport both people and produce. The rise of urban air mobility and in particular eVTOLs can help address meeting these transportation needs. With the application of hydrogen fuel cells as the electric power source, high efficiency alternatives to conventional combustion engine technology are possible too.

The global aircraft fleet is projected to grow to approximately 70,000 operating aircraft by 2050 and the new eVTOL market is projected to reach up to 161,000 over the same period according to Roland Berger and Rolls-Royce eVTOL market size report (1). There is an industry wide drive to de-carbonise the aerospace sector, and studies published by the UK's Aerospace Technology Institute FlyZero project have hydrogen fuel cells as being a central part of the zero-carbon emission solution (2).

For the eVTOL market, hydrogen fuel cells are a direct alternative power source to batteries and combustion engines, which have inherent mass and emissions challenges respectively.

Integrators currently working on conventional fuel cell powered eVTOL designs are challenged with the size of the fuel cell thermal management systems which are required to dissipate the low-grade heat generated by the PEM fuel cells. The heat co-generated alongside electrical power within the fuel cell requires continuous rejection to prevent fuel cell localised overheating and thermal degradation of the cell components. However, a large thermal management system leads to additional mass and drag penalties. This white paper outlines the smaller thermal management system use required with Intelligent Energy technology.

The benefits of PEM fuel cell technology for eVTOL aircraft and Intelligent Energy's proprietary technology in particular are covered. The modelling conducted within this white paper shows that with IE-FLIGHT fuel cell systems, a 4-passenger plus one pilot eVTOL aircraft is able to extend the range of the aircraft to be able to fly 645km from London to Frankfurt in a single flight, or alternatively fly 10 x 30km hops between hydrogen refuels, compared to a pure battery-electric eVTOL, requiring a re-charge using a 600kW fast charger after 3 x 30km hops.

A Total Cost of Ownership (TCO) analysis is also conducted within this paper which is underpinned by the comprehensive study from Argonne National Labs. The analysis concludes that a fuel cell hybrid tilt-rotor eVTOL is more economical to operate compared to a battery-electric tilt-rotor eVTOL, while simultaneously enabling more revenue potential through reduced downtime and enabling more long-range flight routes which a battery-electric aircraft cannot serve due to range limitations.

Fuel cell technology benefits for eVTOL applications

1. Significant increase in range compared to batteries

With a specific energy density of 120MJ/kg, hydrogen is the most energy dense fuel available besides nuclear fuel. Hydrogen far surpasses conventional jet fuel (48MJ/kg) and commercially utilised lithium based battery technologies (1MJ/kg), providing more energy per unit mass.

This characteristic is of course especially beneficial for aircraft where mass is a critical factor. By utilising hydrogen, fuel cell-powered aircraft can carry less fuel mass while storing a higher amount of usable energy, enabling longer flight durations without significantly increasing the aircraft's mass.

An IE-FLIGHT powered eVTOL will typically extend the flight time and range by two to five times, depending upon hydrogen storage cylinder size, compared to batteries.

Lithium-ion battery technology is a mature commercial sector. Technology improvements are edging towards theoretical and practical performance limits and battery technology investment is declining amongst a slowing global demand for electric vehicles in the automotive market (4).

At present there are approximately 300 private companies globally active in eVTOL development with a typical eVTOL aircraft range being 100-150 miles depending on the specific design configuration (5). A paper from Carnegie Mellon University (6)(Figure 1 below) illustrates the performance of current commercial battery technology and the battery performance requirements for varying eVTOL aircraft, in order to meet the specified range by the eVTOL manufacturer. Intelligent Energy has overlaid its IE-FLIGHT fuel cell systems with gaseous and liquid hydrogen fuel storage options as a comparison.

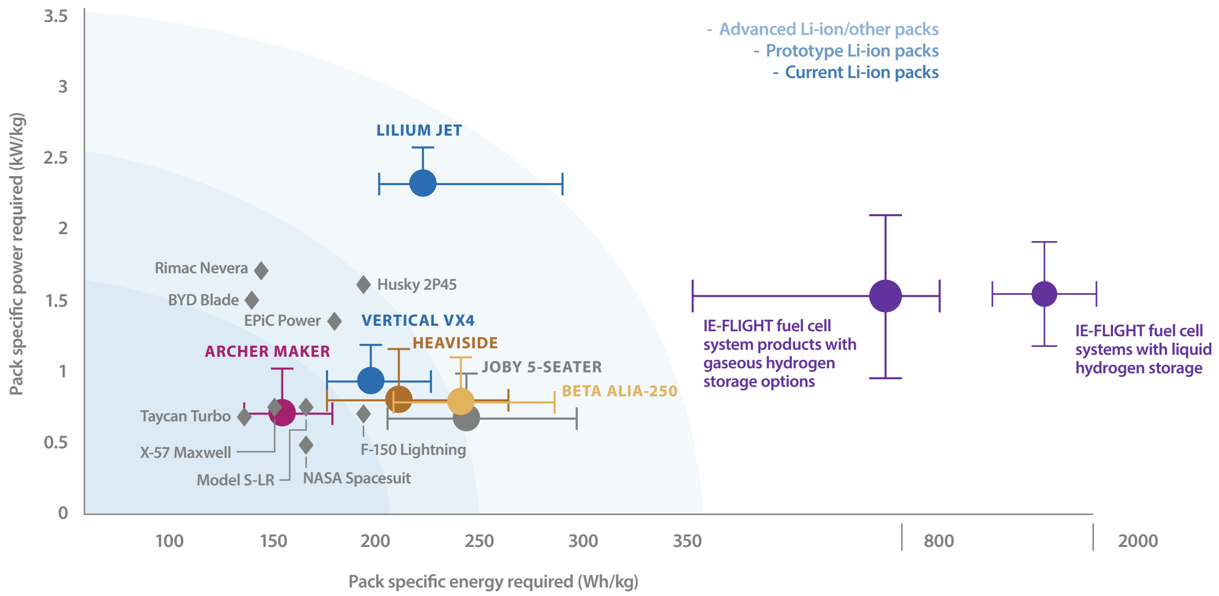


Figure 1 - IE-FLIGHT fuel cell systems performance with gaseous and liquid H2, overlayed by Intelligent Energy on to figure 2 from (6)

2. Refuelling Time and Operational Efficiency

Refuelling a hydrogen-powered aircraft is significantly faster than charging lithium-ion batteries, offering key operational efficiency benefits, especially for reducing eVTOL downtime when conducting regular flights between vertiports. This difference in refuelling or charging turnaround time is crucial for commercial operations where minimising ground time is essential for maximising flight schedules and asset profitability.

Hydrogen refuelling of a vehicle can take a matter of minutes (7). This is similar to conventional jet fuel refuelling as it involves pumping a gas or liquid into the aircraft tanks. In contrast, charging lithium-ion batteries for battery electric aircraft can take several hours depending on the battery capacity (size), and available local charging infrastructure. Certain battery chemistries can be charged faster, assuming there is the infrastructure to support it. However, this is not without compromise to the battery's performance characteristics (8), including reducing battery cycle lifespan, which increases TCO. This is illustrated in Figure 2 below where it is shown by Mathieu et al. (2021) that the speed in which a battery cell is charged is proportional to lowering the battery cell's lifespan.

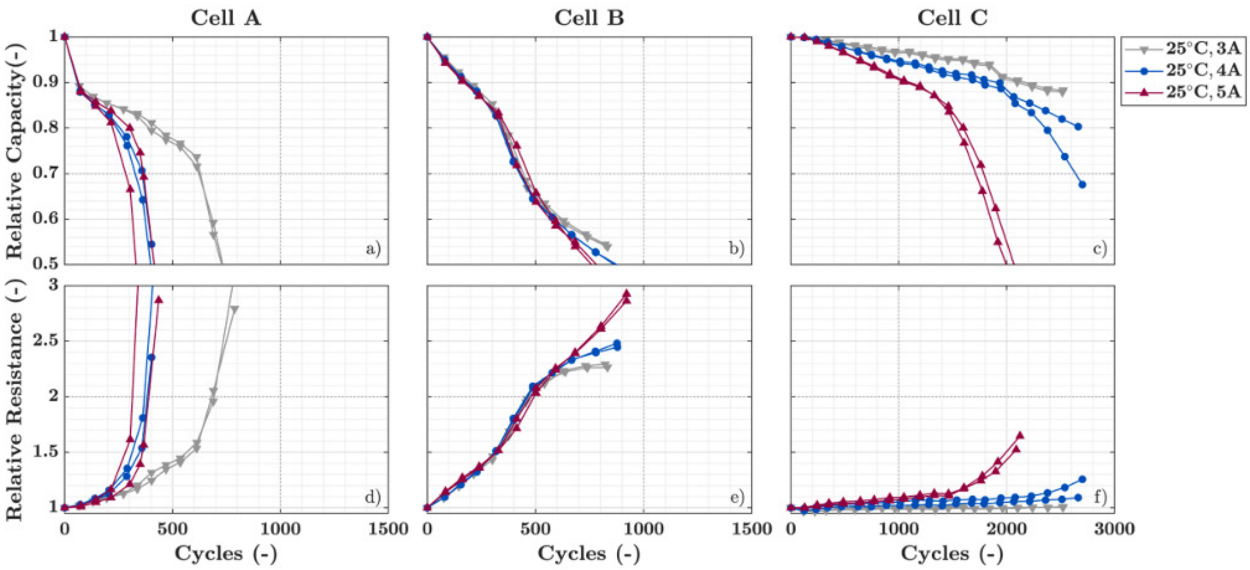


Figure 2 - Cell cycle life versus charge current for three different types of lithium-ion cells in production (8)

The faster refuelling process for hydrogen compared to recharging batteries reduces operational delays and associated labour costs, further improving profitability for high-frequency operations. Studies from Argonne National Laboratory (3) show that a key contributing factor to the more expensive TCO of battery powered eVTOL is the 16% loss in passenger miles per year due to the time needed for a full recharge, using a 600kW ultra-fast charger, after the battery state of charge drops below the allowed minimum (60% SoC) for dispatch (3).

3. Maximum performance in all weather conditions with fuel cells

It is widely known and understood that battery technology has significant performance degradation when operating in colder (slower kinetics of the electro-chemical reactions inside the cell) or hotter conditions (accelerated unwanted chemical reactions). When operating at -20°C, most batteries are only operable at 50% of their nominal rated capacity and have their C-rate reduced significantly at these cold temperatures, limiting the discharge current from the battery (9).

Data collected from real-world electric vehicles operation has shown that driving a battery-electric vehicle between 0°C to 15°C ambient air temperature has a 28% reduction in range when compared to operating in moderate ambient temperatures of 15°C to 25°C (10). When operating in hotter climates of around 40°C ambient air temperature, the cycle lifespan of batteries drops by approximately 40% (9).

IE-FLIGHT fuel cell technology offers rated performance over the operating temperature range without compromise to mission range or lifespan.

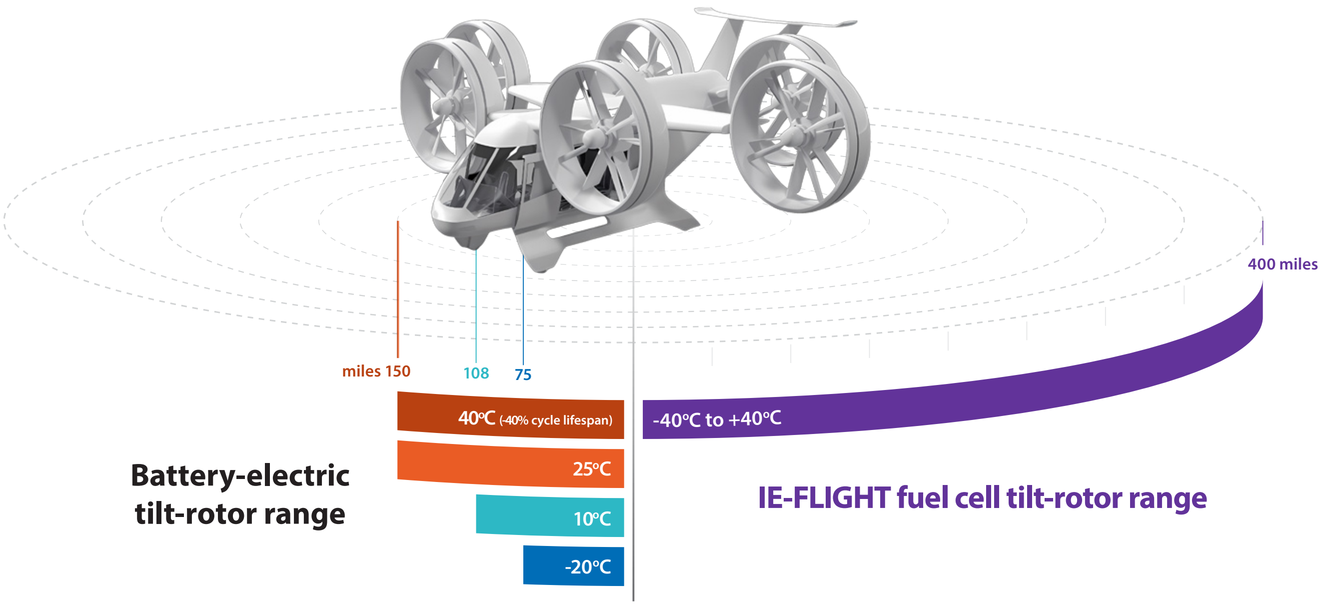


Figure 3 - Effect ambient temperature on eVTOL range, comparing pure battery to fuel cell electric power source

4. Total Cost of Ownership

The total cost of ownership (TCO) of IE-FLIGHT fuel cell powered aircraft presents significant benefits over battery-powered aircraft, driven by operational efficiency gains and improved long-term maintenance with IE-FLIGHT fuel cell technology.

Fuel cells offer higher energy density compared to lithium-ion batteries, allowing for lighter aircraft with greater range and payload capacity. This results in fewer refuelling stops and reduced downtime, improving aircraft commercial availability and utilisation rate.

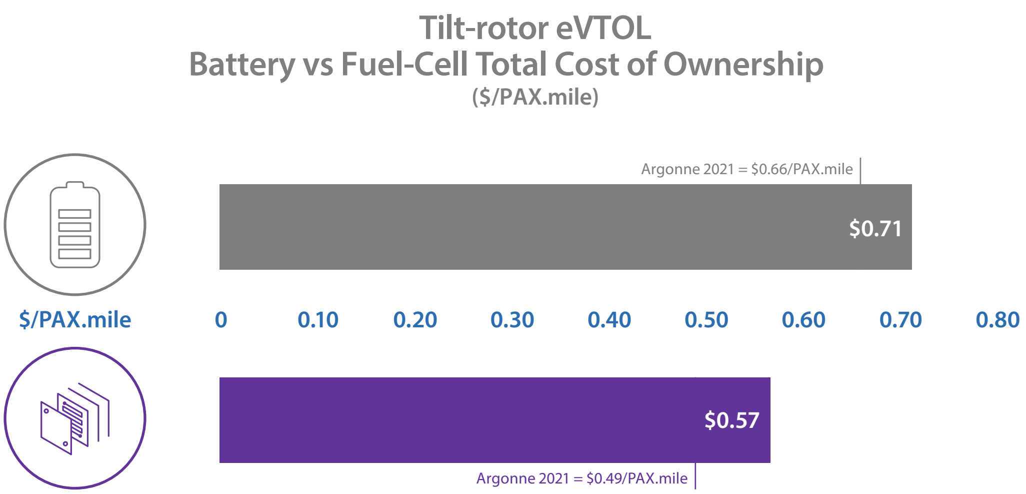
Over time, the longer lifespan of fuel cells, which degrade more slowly than batteries, leads to reduced replacement and maintenance costs. By contrast, batteries face issues such as thermally induced increased performance degradation when charging at high C-rates, leading to more frequent replacements, adding to lifecycle costs, and also increasing the risk of thermal-runaway (11).

As described in section 2, increased operational delays and additional labour expense to charge batteries, as shown in studies from the Argonne National Labs, show battery powered eVTOL TCO is more expensive, with a 16% loss in passenger miles per year (3). This study conducted a comprehensive analysis, comparing a pure battery-powered eVTOL and fuel cell / battery hybrid eVTOL aircraft. The TCO model has been reviewed and updated by IE to reflect 2024 costs (16.4% increase in inflation (12)) and target 2035 fuel cell system costs as published within the UK's Aerospace Technology Institute FlyZero report (13).

The model has also been updated to reflect reported minor improvements in battery charge cycles since the initial 2021 publication (14). The baseline model incorporated a battery pack life cycle of 300 charge cycles (with a range of 100-500 charge cycles given in the original study). This has now been increased by IE to 500 charge cycles for the purposes of the model comparison.

The results of the updated model show the TCO for a:

- fuel-cell powered eVTOL is $0.57/PAX.mile (Argonne 2021 = $0.49/PAX.mile),
- battery powered eVTOL is $0.71/PAX.mile (Argonne 2021 = $0.66/PAX.mile).



The studies highlight that the most sensitive TCO parameter for fuel cell powered eVTOLs is specific power density, as this determines the Maximum Take-Off Weight (MTOW) of the vehicle, which impacts airframe capital costs and liquid hydrogen (LH2) fuel consumption costs. Argonne have calculated that by improving the fuel cell system specific power density from 858W/kg to 2000W/kg, this could reduce the TCO by 24%. IE-FLIGHT technology enables fuel cell system power density to surpass 2000W/kg in the near future and thus realise this TCO benefit.

As hydrogen production scales and becomes cheaper, the fuel cost advantage for fuel cell-powered aircraft consequently improves. The US Department of Energy (DoE) is forecasting hydrogen to cost $1 per kg by 2031 (15), and is investing billions of dollars in technology to enable this target (16). This target is also being helped through federal tax credits, with Plug Power claiming to already be producing green hydrogen for close to $2/kg (17).

Assuming a $2-5/kg price, this would equate to costs for a 5-PAX eVTOL flying from London to Paris, a 225mile (360km) journey, of approximately:

- $38-$95 in hydrogen refuelling for the fuel cell powered craft, compared to,
- $68-$114 in electricity costs ($0.15-$0.25c/kWh) to recharge a sufficiently large battery pack.

5. Supply chain and recyclability benefits of fuel cells

Recycling is a critical component in the lifecycle of the chosen power source for eVTOL applications and recycling of both PEM fuel cells and lithium-ion batteries offers significant economic and environmental benefits.

Fuel cells can offer significant recyclability advantages over batteries, which should also be considered in the context of eVTOL applications. Lithium-ion batteries have complex chemistries resulting in hard-to-recycle, or more energy intensive processes, to reclaim materials such as cobalt, nickel and manganese. It should also be noted that lithium-ion batteries vary sufficiently in both the use of specific chemistries and format of cells, such that it becomes difficult to standardise the recycling process across suppliers; a challenge currently facing the industry. Furthermore, the design of the battery involving multi-layers within the structure and components complicates any efficient automated recycling process.

It has been quoted that just 3% of a battery pack can be economically recycled, and with batteries expecting to deliver 9,500 flight cycles per year within the eVTOL business case, frequent battery pack replacements will be required. A more recyclable solution with higher recycling efficiencies should be targeted. PEM fuel cells are primarily composed of commercial grade ferrous alloys, carbon, fluorinated polymers and electro catalysts such as platinum. Platinum, for example, is highly reusable and its recovery from fuel cells is well-established, reducing the environmental impact over time.

IE-FLIGHT technology for eVTOLs

Intelligent Energy has been developing fuel cell stack technology specifically for the aerospace market since 2020 and in July 2024, the IE-FLIGHT fuel cell system product line was launched.

Underlying IE patented cooling technology involves the injection and evaporation of water on the fuel cell stack, which is the most thermally effective way to remove heat from the fuel cell.

Compared to liquid-cooled fuel cell systems, the IE-FLIGHT product line offers the following advantages:

1. Simpler construction of IE technology and lower cost design

An evaporatively cooled (EC) fuel cell is a simpler construction with fewer components than a liquid cooled fuel cell.

In a liquid cooled (LC) cell, heat is removed via liquid cooling channels captive between two separator plates, with reactant channels on the outer faces of each plate. Therefore, two separator plates are required within each cell, providing sealed compartments for 3 separate fluids passing across the whole cell area when stacked up into a fuel cell stack. These separator plates require significant clamping force and perhaps localised welding to reduce inter facial electrical contact resistance.

In an EC cell, a single separator plate is used, featuring channels for both the cathode and anode reactants on opposite sides. Localised features are included for direct water injection, excluding need for an additional whole cell area cooling compartment like inside a liquid cooled cell and substantially reducing the welding requirement. Thus, resulting in reduced electrical contact resistance and lower mass, beneficial to overall power plant weight. In addition, a stack of EC cells features a small cell pitch, aiding overall volume package. Figure 4 summarises the overall benefits.

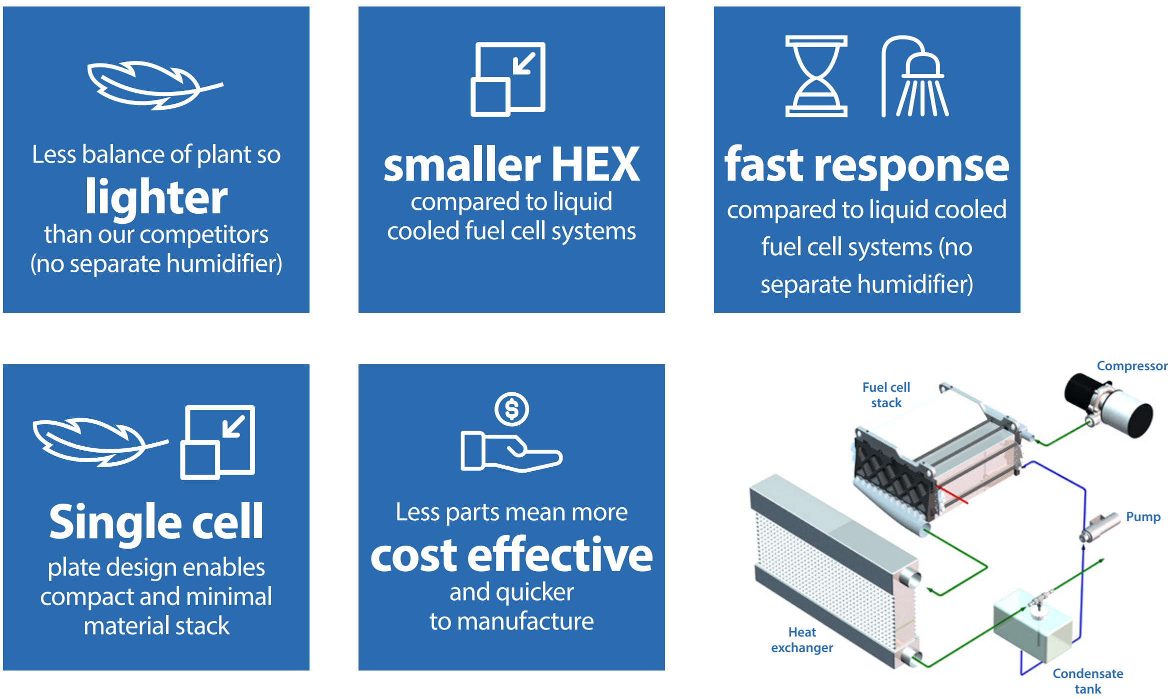


Figure 4 - Core benefits of EC technology

In the construction of an EC fuel cell system, over two thirds of the components are the same as for a LC fuel cell system, as shown in Figure 5 below. This results in a common supply chain and the ability for Intelligent Energy to leverage the benefits of production volume and cost down in line with the rest of the fuel cell industry.

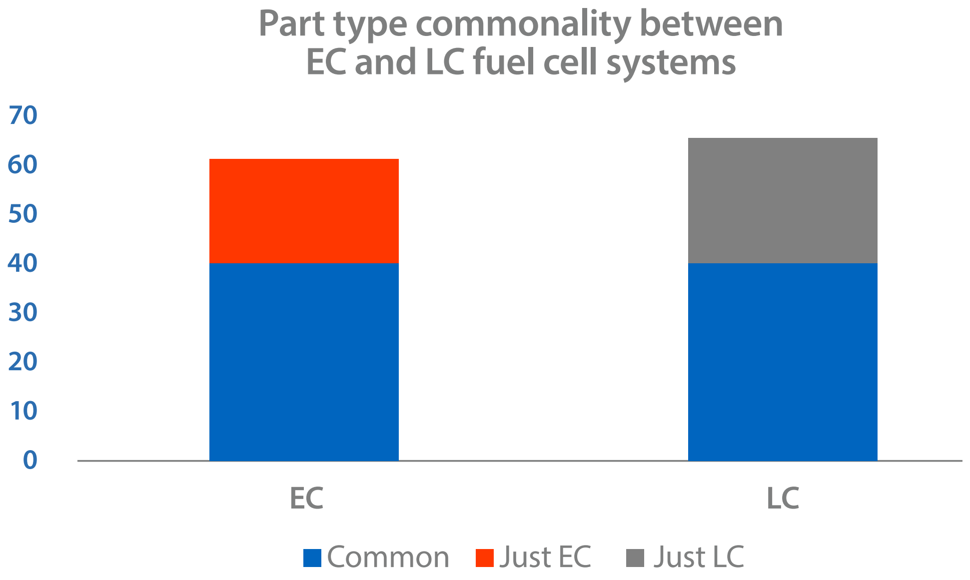


Figure 5 - Sub-system component count comparison between evaporatively cooled and liquid cooled fuel cell system

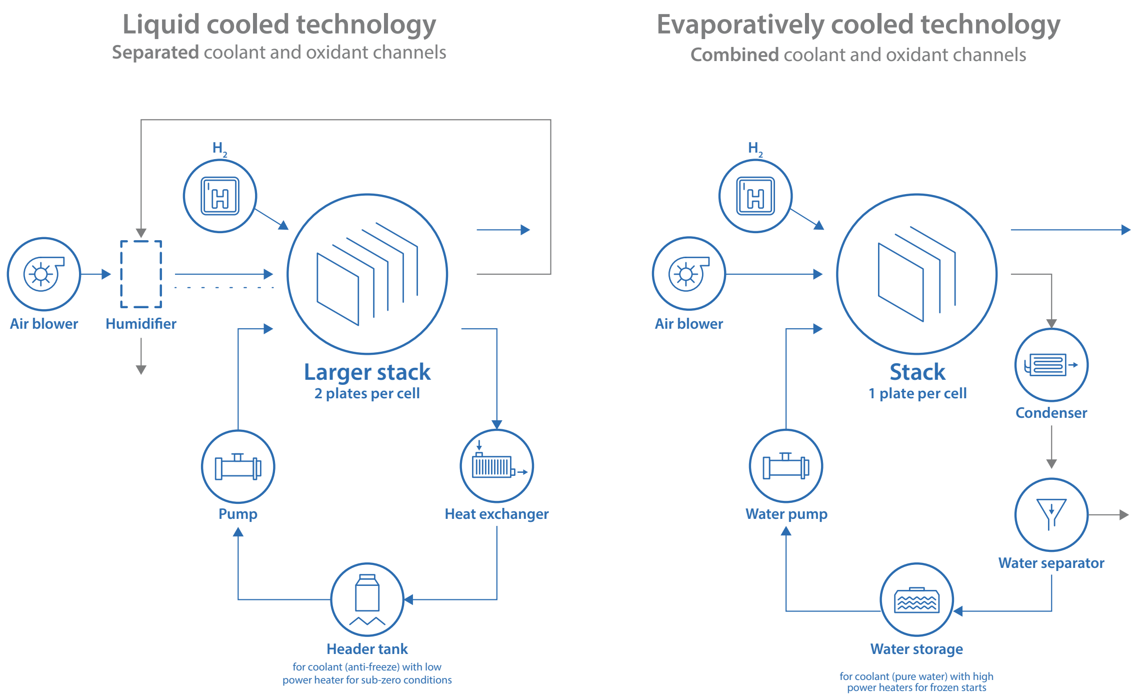


Figure 6 - Single cooling and humidification loop in EC system versus two separate loops required in LC system

2. Fast transient response reduces battery sizing for peak loads

The transient response of an electrical drivetrain system refers to its ability to react to changes in input conditions, such as throttle commands and load variations. Therefore, fuel cell transient response is a critical parameter to consider in eVTOL electrical drivetrain systems, influencing performance, stability, efficiency, and safety. Understanding this response is essential for optimising overall system design performance, reliability and ensuring safety. Figure 6 presents a comparison of LC and EC cathode circuits with their differing coolant strategies.

EC fuel cells utilise direct water injection for cell cooling & humidification, shown on the right, and exhibit a superior transient response when compared to traditional LC fuel cell systems shown on the left. Enhanced response is attributed to the direct humidification process occurring inside the EC fuel cell, as opposed to transport lag associated with external humidifiers in LC systems reliant on vapour transfer from exhaust gases.

In an LC system, on a fast transient demand the cell voltage inside the cell will temporarily diminish, limiting power draw as the inlet reactant gas in the cathode dries out due to the external humidifier losing input vapour from the cathode exhaust. In addition, the lower cell voltage liberates increased heat loss at the cell which is rejected into the adjacent liquid coolant, reducing transient fuel efficiency.

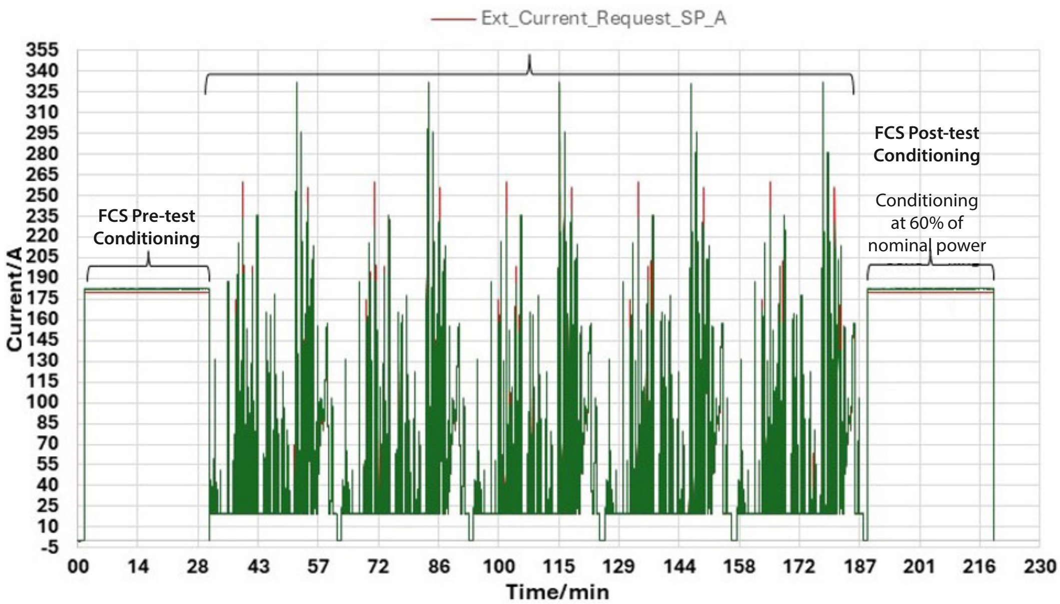


Figure 7 - Test data from a transient response test of an EC fuel cell system

Given the fast inherent response of liquid pumps for injecting water in EC during positive transient ramp in demand, the cell is readily humidified through water injection. Therefore, cell voltage is stable, reducing in an expected way with increased current draw. The rate of change in power draw is purely limited by the rate at which the compressor can introduce cathode reaction air. Thus, the compressor ramp-up speed serves as the key aspect of the fuel cell's capacity to deliver power to the drivetrain rapidly without any complication from external humidification of gases. Given stability in cell voltage, transient response and instantaneous fuel efficiency is improved.

This inherent ability of EC fuel cells to achieve rapid transient response enables their use as a primary power source, thereby reducing the required size of the battery in eVTOL aircraft. This approach allows the fuel cell to handle a significant portion of peak power demands, in contrast to traditional LC systems that rely heavily on large batteries to manage startup and transient current change. Consequently, the integration of an EC fuel cell system can lead to more efficient energy management and weight savings in the overall power system design.

The EC architecture shown on the right of Figure 6 is used in existing IE products. Figure 7 presents data to illustrate the performance of a recent IE-DRIVE™ HD product undergoing a transient load test sequence, designed to simulate extreme operating conditions where the fuel cell is the primary power source. Initially, the fuel cell undergoes a standard pre-test conditioning phase, followed by a series of duty cycle load peaks ranging from 0 to 85kW (net) and 100kW (gross), repeated for five cycles. The results reveal a ramp-up speed of 60kW/s and above, in contrast to the average ramp-up speed of 20kW/s typically achieved by standard LC technologies.

This significant difference underscores the enhanced responsiveness and dynamic performance provided by EC fuel cell systems under transient loading conditions. Intelligent Energy expects further improvements in the systems transient response realising >80kW/s in the IE-FLIGHT product line.

The integration of an EC fuel cell system significantly enhances the performance, stability, efficiency, and safety of electric drivetrains in applications. Fuel cell stability during transient conditions is crucial as it allows for controlled operation and mitigates oscillations or instabilities. Furthermore, the efficiency of electrical drivetrains is closely tied to transient response, with quick adjustments to input commands minimising energy losses during dynamic operations. This is is essential for maximising range and energy consumption in eVTOL applications. An optimised transient response is integral to safety mechanisms, enabling prompt and effective system reactions in emergency situations, thereby enhancing overall eVTOL safety.

3. Full power through mission cycle, including hover with no ram air

During vertical take-off, ram air cooling of any heat producing system in an eVTOL propulsion system is not available. Therefore, heat soak occurs into any cooling loop, assuming no forced cooling.

In LC fuel cell systems, typically a special low electrical conductivity coolant , based on a water ethylene glycol mixture, may be pumped through the coolant channels inside the fuel cell stack, as shown on the left of Figure 6. Heat is absorbed into the coolant at each cell as electrical power is drawn from the stack. Without any forced or ram air cooling at the air-cooled heat exchanger (radiator), the coolant will warm up and the cell temperature will climb.

Depending on time in hover, ambient temperature and starting temperature for the coolant, the temperature may reach such a level that the electrochemical performance of the cell is impacted. This may be through both local temperature and reduction in incoming humidity of reactants, increasing proton conduction resistance, resulting in a drop in cell voltage. If more current is drawn to maintain a constant electrical power level, the problem will be exacerbated, with more heat produced and associated increase in coolant temperature. There will be increased degradation in the cell, impacting resultant life. Any continued operation will lead to further voltage derating and the power draw by the aircraft electrical system must be reduced to recover cell performance.

Hybridisation with batteries helps but increases the overall mass of components in the system. Worst case, the battery capacity may be sized for full hover power and time requirements, whilst the LC fuel cell is operated at zero or very low power until ram air cooling through horizontal flight motion can be ensured to reject the cell heat absorbed into the coolant. Resultant battery size may be significant.

In an EC fuel cell system, there is a liquid to gas phase change where the injected water evaporates inside the cell. This injected water provides humidification to the incoming cathode reactant air and also absorbs heat through vapourisation as current is drawn from the cell. During the same hover conditions described for the LC case above, the air-cooled condenser in an EC system may not be rejecting heat, given a lack of ram air cooling. In this scenario, the water level in the tank will start to decrease as vapour is lost to the exhaust from the hot-side outlet of the condenser. However, the same level of water injection flow rate can continue into the cells. The cell temperature will climb very slowly as power continues to be drawn, with water temperature rising and increasing the sensible heat entering the cells. The rate of rise will be much slower than in the LC case, as water continues to be evaporated at the same rate and absorb heat of reaction. Given the humidity in the reactants are maintained and heat continues to be rejected effectively inside the cell, the cell voltage remains high and electrical power supply continues efficiently.

If we consider a 300kW net output from the fuel cell system – then at end of life, calculations can show the steady state thermal rejection will be around 324kW. If we assume an LC system containing 25litres of water ethylene glycol coolant starts at 15degC, and assuming all of the heat is absorbed into the coolant with no heat rejection to surroundings or fabric of the rest of the fuel cell system, the coolant will reach 75degC in around 16s.

In an EC system, if we consider it starts with only 8litres of deionised water in the tank, the tank liquid volume would drop to around 2litres after 16s of constant 300kW net power with no heat loss at the condenser, whilst still maintaining appropriate humidification and heat rejection at the cell. In subsequent level flight, ram air cooling of the condenser would increase heat rejection and sufficient condensate could be recovered to replenish the liquid level inside the tank.

4. Smaller heat exchanger, lower drag through high temperature rejection

Market ready PEM fuel cells with power dense and durable membranes operate at cell temperatures around 75 to 80degC. Inside an LC system, the convective and conductive heat transfer path across the separator plates between cells, results in a temperature drop from the cell electrodes to liquid coolant. Therefore, the hot-side inlet temperature to the heat exchanger in an LC system will be lower than the cell temperature, around 70 to 75degC.

In comparison, within an EC system the temperature difference between cell temperature and hot-side radiator inlet temperature is reduced. This is because the water injection results in a more direct, predominantly convective heat flux directly into the cathode exhaust which acts as the thermal conduit to take heat away from the cells. Given the high thermal convection rates of phase changing flows occurring in the EC system cathode flow path, it has been shown that for the same power and cold-side flow conditions, the frontal area of the EC heat exchanger (condenser) is around 30% smaller than a LC heat exchanger (radiator) (18).

In addition, Intelligent Energy's EC technology can be augmented to raise the heat rejection temperature from the system, independent from the cell temperature. The left of Figure 8 presents a lower temperature (LT) EC solution, as exists in current IE-DRIVE product line. On the right of Figure 8 is the latest higher temperature (HT) architecture being developed for the IE-FLIGHT product line and wider EC applications in future IE products. By pressurising the cathode exhaust between fuel cell stack and condenser, the heat rejection temperature from the system increases whilst maintaining the same LT conditions inside the fuel cell for the best durability and performance from market ready components.

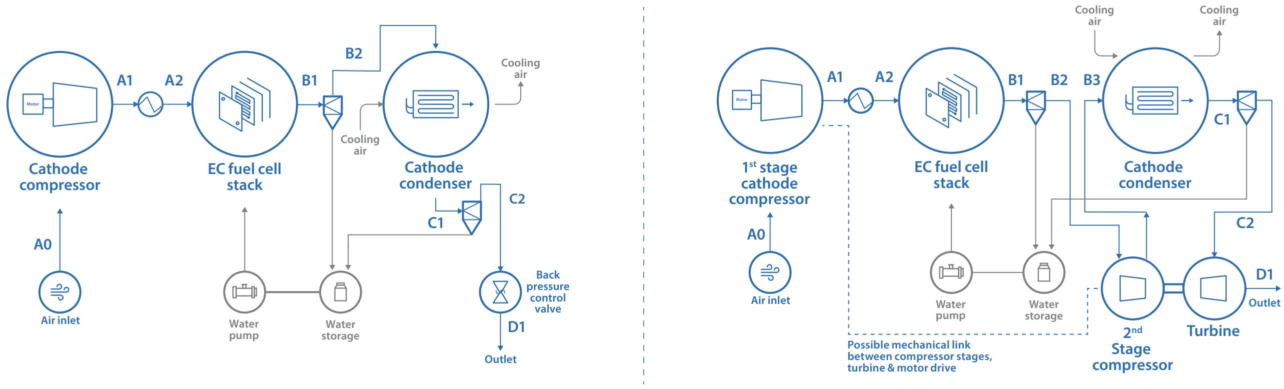


Figure 8 - Comparison between Intelligent Energy evaporatively cooled LT-PEM solution (left) and Intelligent Energy's high temperature operation system (right) to enable a much smaller condenser

The EC-HT architecture raises thermal effectiveness through increasing the temperature delta across the heat exchanger, from hot-side to cold-side. The resulting raised temperature drives a reduction in the air-cooled heat exchanger size and hence will reduce the balance of plant (BoP) mass and consequently eVTOL aircraft drag.

For more detailed information on Intelligent Energy's HT technology and operation, please refer to Intelligent Energy's IE-FLIGHT High-Temperature Operation White paper (19).

As part of the full development of IE-FLIGHT product line, IE have collated a range of requirements from customers developing future zero emission aircraft to form a directional market requirements document. It is evident that outside air temperature for the lower altitude environment, with unpressurised cabin consistent with eVTOL applications, may vary from -60degC to +55degC. This upper temperature is only 20degC below the optimum LT PEM cell temperature, resulting in significantly sized heat exchangers if a LT-LC architecture is used in future hydrogen fuel cell powered eVTOLs.

The EC-HT system architecture raises this temperature difference. For example, the hot-side inlet temperature to the condenser can be raised to increase thermal effectiveness when the vehicle is operating in a hot ambient condition, e.g., 55degC at near sea level by running the 2nd stage compressor harder to raise the downstream pressure and resultant temperature, e.g., 97degC hot-side inlet temperature. This may be typical in Gulf states or SW USA, especially on a sun-soaked concrete apron or vertiport.

If the vehicle is operated on a day more represented by International Standard Atmosphere (ISA), e.g. -5degC at 10000ft, the 2nd stage compressor may be off and the condenser runs at a lower temperature close to the cell at 75degC. In this way, efficiency improves as temperature reduces towards ISA as the parasitic power in BoP is reduced.

This variation in hot-side pressure and temperature changes the sizing case for the air-cooled heat exchanger. In a LT-LC system, the radiator would need to be sized for the hottest conditions likely for the range of markets in which the eVTOL aircraft may be operated. Therefore, this increased frontal area device would always be present on the aircraft, imparting additional drag.

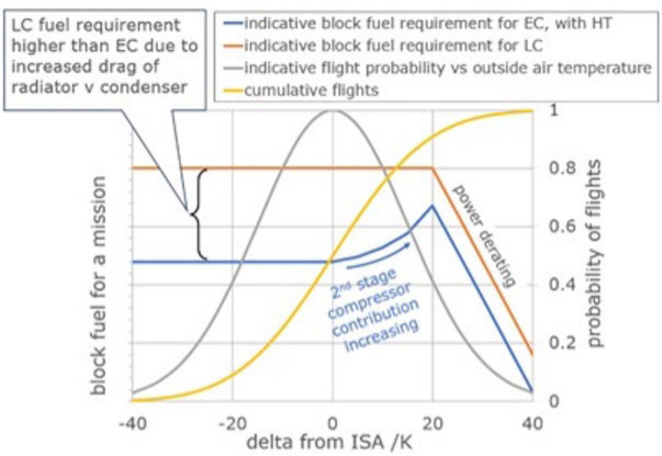


Figure 9 - Example of potential improvement in aircraft fuel use with EC-HT compared to LC

With the EC-HT architecture from Intelligent Energy, the condenser can be sized and operating conditions adapted to ensure sufficient water is recovered through condensation, without sizing with LT architecture restrictions at the hottest ambient temperature. Trade studies are underway at IE to understand this sizing point further, with significant size reductions anticipated for the IE EC-HT heat exchanger as part of this design study compared to an LT-LC heat exchanger.

The benefit of this is shown conceptually in Figure 9. A probability density function of flights against outside air temperature difference from ISA is illustrated, where increased 2nd stage compression occurs towards the higher temperatures to ensure heat rejection from the smaller heat exchanger in EC-HT. The higher block fuel consumption for the mission in the LC case is due to the larger heat exchanger that is required onboard the vehicle, which creates additional drag. At the highest air temperatures, some compromised use by the operators may be tolerated, e.g., lower climb rate, less time in hover etc. The numbers shown in the graph are indicative – the point at which derating occurs is dependent on the design and be determined in conjunction with the customer.

Based on fleet operation across the global temperature range, the majority of flights will benefit from EC-HT technology.

Concept eVTOL case study

In this worked example, a 4-passenger plus one pilot ducted tiltrotor eVTOL aircraft, based on the Bell Nexus 6HX concept design shown in Figure 10 below, was modeled. This compares latest electric aircraft Electric Power Systems EPiC 2.0 Energy batteries (20), said to be available in 2025, with an IE-FLIGHT fuel cell solution with liquid hydrogen storage. The flight characteristics of the Bell Nexus 6HX were computed by Politecnico di Milano and used for this model (21).

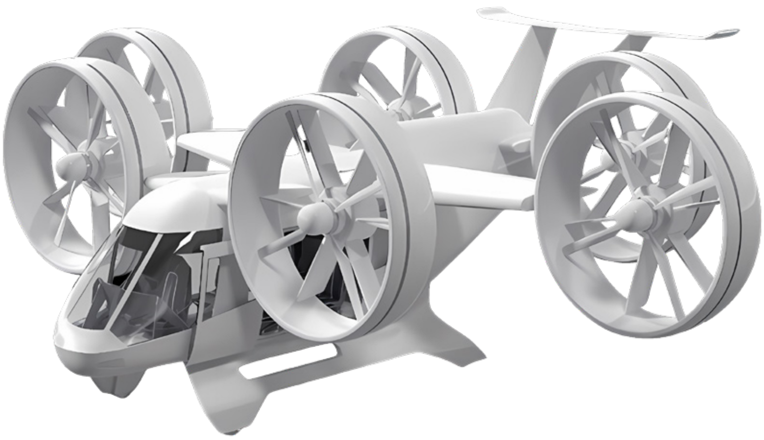


Figure 10 – Conceptual 4 passengers plus one pilot eVTOL aircraft

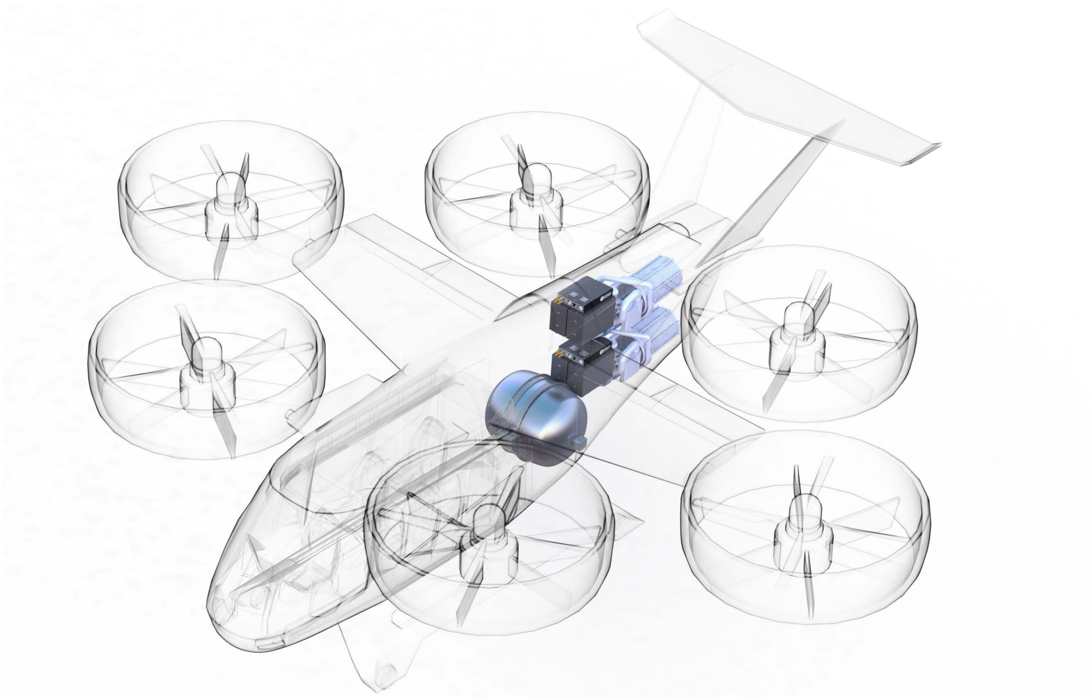


Figure 11 – Depiction of 2 x IE-FLIGHT 300 (F300) fuel cell systems with LH2 cylinder mounted in the tail

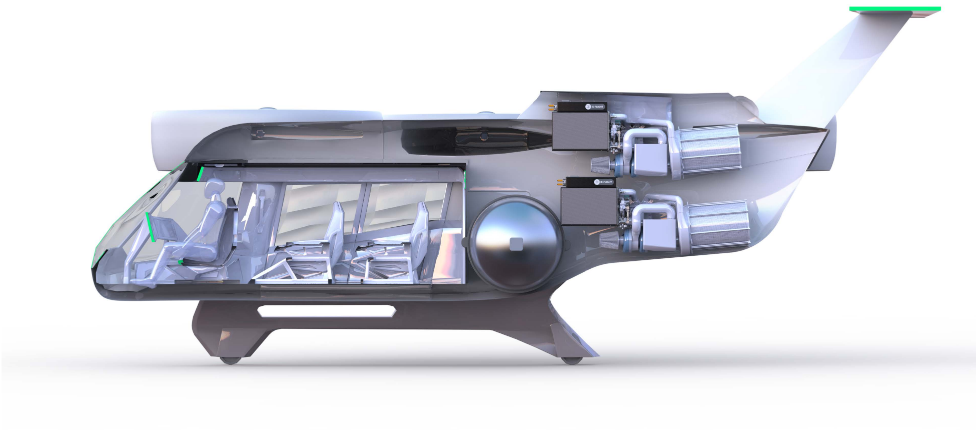


Figure 12 – Side view of depiction of 2 x F300 fuel cell systems with LH2 cylinder mounted in the tail

Using an IE-FLIGHT fuel cell solution, it has been assumed that the powertrain incorporates 2 x IE-FLIGHT 300 (F300) fuel cell systems (19) which are able to deliver the full power that the air vehicle needs during all-stages of flight, in contrast to a LC fuel cell system which relies more on the hybrid batteries. Conceptual layouts of 2 x F300 fuel cell systems with liquid hydrogen storage are shown in Figure 11 and Figure 12.

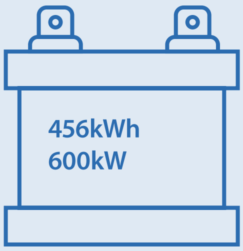
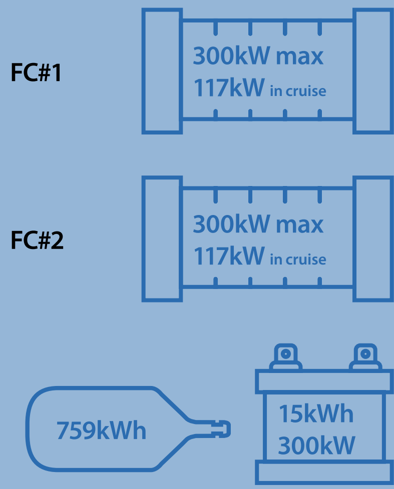
The computed power-profile for the Bell Nexus 6HX eVTOL is shown below in Table 1, from (21).

Flight condition	Power requirement (kW)
Take-off/Hover	663
Climb	515
Cruise	234
Descent	133
Hover/Landing	663

Table 1 – Conceptual eVTOL power requirements throughout various stages of flight

Additionally, the hybrid battery, initially used to turn the F300 fuel cell systems on, is sized in the unlikely event of 1 x F300 fuel cell failure - ensuring sufficient capacity in the hybrid battery to provide 300kW, in addition to the functioning 300kW fuel cell system for an emergency landing procedure.

Case study results

Configuration	**Battery only**	**2x IE-FLIGHT Fuel Cell Systems**
Technology		
Range(miles/ km)	150/241	625/1000
Battery/ FCS Mass (kg)	2,073	710
Volume (L)	1,825	900
30km trips on single refuel	3	10
Refuelling time (mins)	46 (ultra-fast 600kW charger)	12
Air pollution (NOx)@POU (g/kg fuel)	0	0
Operating hours until Battery/ FC replacement *	608	>8,000 hours

* Operating hours based on 500 charge cycles, based on the upper range estimate within Argonne National Labs study (3)

Key findings from the model

- To achieve the 150-mile range with the 5-seater Bell Nexus H6 concept design, the battery weight represents over two thirds of the weight of the aircraft.
- In order to extend the range of the battery-electric version of the eVTOL aircraft by 1.5x, the mass of the battery pack more than doubles due to diminishing returns from adding more batteries to the vehicle to extend the range which increases vehicle size and weight.
- In contrast, due to specific energy density benefits of LH2, adding just over 1% of vehicle weight in LH2 fuel would double the range of the aircraft between refuels.

Conclusion

Intelligent Energy's IE-FLIGHT fuel cell system's unique evaporatively cooled design contributes to a simplified, lightweight construction and enhanced power stability, which together reduce costs and improves performance consistency.

This case study demonstrates that an IE-FLIGHT-powered eVTOL can achieve extended range and reduced refuelling times, promising a transformative impact on urban air mobility. These advancements underscore IE's role in supporting the aerospace sector's decarbonisation efforts, positioning hydrogen-powered eVTOLs as a practical, scalable solution for sustainable air transport.

In summary, Intelligent Energy's innovative fuel cell technology offers substantial benefits for eVTOL applications, addressing key challenges faced by battery and combustion-based solutions. By leveraging hydrogen fuel cells, IE-FLIGHT technology enables significant improvements compared to batteries in three main areas:

1) Extending aircraft range and unlocking flight routes not possible with battery power aircraft.
    - Fly London to Paris (225 miles) or London to Frankfurt (400 miles).
2) Total cost of ownership and profitability through operational refuelling efficiency gains
    - Increase number of passenger miles per year by 19% with fuel cell eVTOLs compared to batteries, due to faster refuelling times.
3) Operating across diverse environmental conditions without performance reduction
    - Unlike batteries, fuel cells do not suffer from range reduction, when the temperature drops below 15°C, or a reduction in lifespan when operating on the high end of the operating temperature envelope.

Appendix

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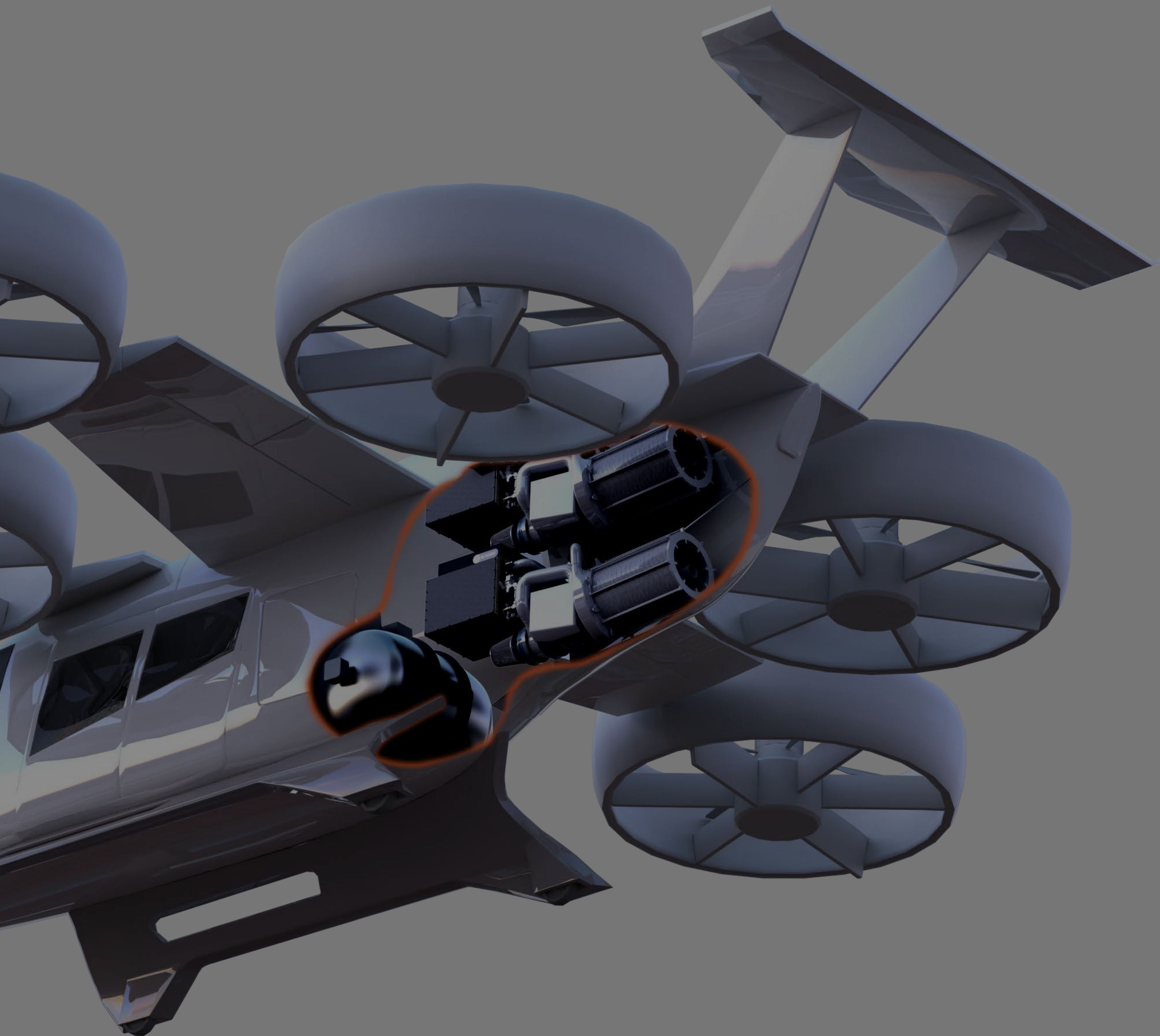

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