

Article

Application of Hybrid-Electric Propulsion to ‘Very Light Jet’ Business Aircraft

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Abstract

The following paper investigates the feasibility of hybrid-electric propulsion (HEP) for a very light jet (VLJ) business aircraft based on predictions of battery performance for the 15-year timeframe to 2040. Given the unique requirements of a range of between 1100 and 2200 km (600 and 1200 nmi) and a cruise speed of around Mach 0.65, this paper utilizes a time-stepping simulation to determine range for a baseline aerodynamic model over combinations of energy hybridization ratios and battery specific energy densities of $H_E \in [0.0, 0.25]$ and $e_{\text{bat}} \in [400, 1250]$ Wh/kg for series and parallel architectures. The paper also analyzes fuel and battery energy consumption, battery weight and volume, and finally a typical mission of 1111 km (600 nmi). The results of the paper find that the parallel architecture is better suited to application on very light jets, as it enables a greater maximum range of 1394 km (754 nmi) with a mild energy hybridization of 5% and a battery specific energy density of 1250 Wh/kg for a fixed maximum takeoff weight. Over a typical 1111 km (600 nmi) mission, fuel savings with a parallel architecture are 96 kg (212 lbs) compared to a conventional turbofan, or 7.1% of the total fuel load. Consequently, it is recommended that a hybrid-electric very light jet utilize a mild-hybrid parallel architecture of around 5% energy hybridization and batteries of at least 1250 Wh/kg.

Keywords: hybrid-electric aircraft; business aircraft; conceptual design; hybrid architectures; range estimation

1. Introduction

The business and general aviation industries have pledged to a reduction in carbon emissions in accordance with similar efforts across the broader aviation industry. While global business aviation operations constitute a mere 0.04% of CO₂ emissions caused by human activity, the Business Aviation Commitment on Climate Change (BACCC) has set out a target of a 50% reduction in carbon dioxide emissions by 2050 [1,2] relative to 2005 levels. Building on the pledges of the BACCC, industry bodies including the General Aviation Manufacturers Association (GAMA), National Business Aviation Association (NBAA), and the International Business Aviation Council (IBAC) aim to increase fuel efficiency by 2% annually up to 2030 [3].

While overall emission reductions are currently being achieved through the increased availability and broader adoption of Sustainable Aviation Fuels (SAFs) through the industry, the path towards improvements in fuel consumption efficiency relies on continuous technological advances. In addition to advancements in engine thermodynamic performance, a potential solution to reducing fuel consumption is through the use of electrified propulsion technologies such as hybrid-electric and fully electric propulsion architectures.



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The proliferation of such fully electric in the automotive industry has been a catalyst for similar developments in aviation. Concepts for aerial vehicles with frequent, short-range operations are reaching increasing levels of technological maturity at Technological Readiness Levels (TRLs) of 6-7 [4,5]. A number of these urban air mobility vehicles, eVTOLs, short-range aerial taxis and light general aviation aircraft are even undergoing various stages of certification with regulatory bodies such as the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) [6].

However, despite the significant advances in the adoption of electric propulsion architectures in the aviation industry, the limitations of the specific energy density of current battery technology make fully electric concepts for heavier, longer-range aircraft an as-yet unrealized objective. Even assuming an optimistic improvement in specific energy density of 7% annually, batteries would take over 50 years to match the energy density of Jet A-1 fuel [7,8]. Consequently, an approach combining the energy density of jet fuel with the advantages offered by electrified architectures in a hybrid-electric propulsion (HEP) scheme offers the most practicable solution for the next generation of business aircraft.

The potential application of HEP architectures is currently being studied and implemented for a variety of aircraft with large operating fleets. In the case of the aforementioned short-range air mobility concepts, HEP offers pathways to new businesses and concepts of operation (ConOps). For commercial aviation, incremental improvements in fuel efficiency for regional aircraft through hybrid-electric propulsion offer a path towards meeting the broader aviation industry's emissions targets. As a result, significant investments are being made by start-ups, large aircraft manufacturers, and research establishments into studying the feasibility of these concepts.

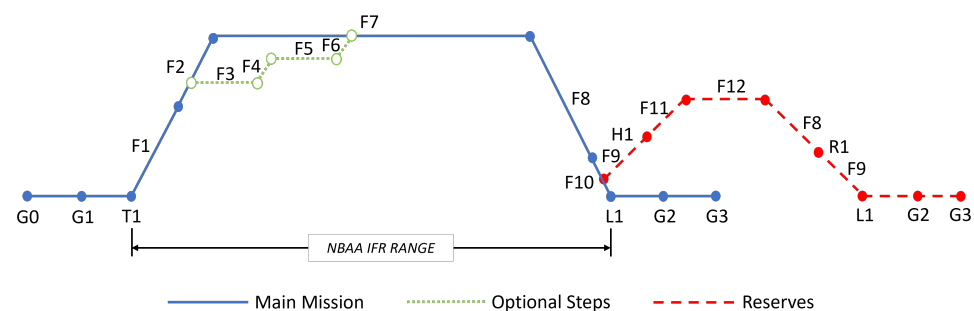
However, the widespread focus on the applicability of HEP to short-range and regional concepts leaves a major gap in research for aircraft fulfilling other ConOps. In particular, published material on HEP applications to business aviation aircraft is woefully lacking. Given the concept espoused in business aircraft design of carrying a limited number of passengers on non-scheduled services, over a long range compared to aircraft size, at relatively high speed, findings from other design types do not necessarily translate.

Among the various classes of business aviation jet aircraft, a summary of which is presented in Table 1, a large majority of currently active business aircraft are those that can seat six passengers and on average fly less than 1852 km (1000 nmi) [9]. In the decade between 2015 and 2024, approximately 1350 VLJs were delivered, or about 20% of total business jet deliveries [10]. The purpose of this paper is as a follow-on to [11] with the aim of providing a first step in filling the research gap for very light jet (VLJ) type aircraft. While the methodology adopted in [11] is broadly applicable to other aircraft types, VLJs are constrained by different considerations and ConOps compared to large-cabin jet aircraft. The small size, and frequent short-range missions undertaken by VLJ-type aircraft impose unique challenges, especially in terms of energy consumption and aircraft weight distribution.

The typical flight profile for a very light jet is presented in Figure 1, and is based on the NBAA IFR Range and Aviation Week's Business & Commercial Aircraft (BCA) profiles [12]. Descriptions of the individual stages of the profile are provided in Table 2. The rules allow for up to two optional 2000 ft increments to reduce fuel burn. The stepped climb is utilized to allow the aircraft to reduce weight through fuel burn before climbing to the optimum cruise altitude. It must be noted that this is a standard ideal range methodology, and actual flight profiles are dependent on a number of factors, including airspace, ATC, and weather.

Table 1. A generic classification of business jet aircraft sizes, as presented in [11].

Jet Size Class	MTOW [kg (lbs)]	Avg. NBAA IFR Range [km (nmi)]	Pax. Seats [#]
Very Light Jets	<5670 (12,500)	1852 (1000)	4–6
Light Jets	≈9072 (20,000)	3704 (2000)	5–6
Midsized Jets	≈13,608 (30,000)	4630 (2500)	7–8
Super-Midsized Jets	≈18,144 (40,000)	5556 (3000)	8–10
Large-Cabin Jets	≈36,287 (80,000)	8334 (4500)	10–18
Ultra Long-Range Jets	>41,957 (92,500)	12,038 (6500)	12–20

**Figure 1.** Typical NBAA cruise mission profile for a very light business jet. Descriptions of the phases are provided below in Table 2.**Table 2.** Descriptions for a typical NBAA IFR range profile.

Phase	Phase Name	Phase Description	Approximate Values
G0	Engine Start	Engine start	Approx. 5 min
G1	Taxi	Ramp to rwy	Approx. 10 min
T1	Takeoff	Roll to airborne	From brake release to 50 ft
F1	Initial Climb	Climb to departure alt	To between 2500 ft and 4500 ft
F2	Climb	Climb to cruise alt	To approx. 37,000 ft
F3	Initial Cruise	Optional cruise lvl	Depends on aircraft
F4	Step Climb 1	1st alt increment	2000 ft increment
F5	Intermediate Cruise	Optional cruise lvl	Depends on aircraft
F6	Step Climb 2	2nd alt increment	2000 ft increment
F7	Final Cruise	Cruise climb and cruise	37,000 ft to 45,000 ft
F8	Descent	Descent to apch fix	Descent @ 3000 fpm
F9	Approach	Descent to threshold	Std IAP to 50 ft
L1	Landing	Touchdown to full stop	50 ft to full stop
G2	Taxi	Taxi to ramp	Approx. 5 min
G3	Engine Shutoff	Engine shutoff	-
F10	Missed Approach	Missed apch procedure	Depends on airport
H1	Hold	Hold for clearance	5 min hold
F11	Alternate Climb	Climb to alternate cruise	Between 8000 ft and 16,000 ft
F12	Alternate Cruise	Cruise to alternate	Cruise 185 km (100 nmi)
R1	Reserves	VFR reserves	30 min at 5000 ft

For the above flight profile, the majority of VLJs have maximum cruise speeds between Mach 0.60 and Mach 0.70. Maximum range with four passengers for current very light jets averages 2037 km (1100 nmi). Table 3 presents a comparison of current and recent VLJs.

Table 3. Comparison of range and maximum cruise performance for common VLJs. MTOW is also provided as reference [12–14].

Aircraft Model	Max. TO Weight [kg (lbs)]	4 Pax. Max. Range [km (nmi)]	Max. Cruise [Mach (KTAS)]
Cessna CE-510	3920 (8645)	1783 (963)	0.63 (339)
Cessna CE-525	4853 (10,700)	2191 (1183)	0.71 (401)
Cirrus SF50	2721 (6000)	1151 (622)	0.53 (305)
Eclipse EA-500	2721 (6000)	1528 (825)	0.64 (369)
Embraer EMB-500	4854 (10,703)	2022 (1092)	0.70 (406)
Honda HA-420	5034 (11,100)	1972 (1065)	0.72 (419)

The significant VLJ shipments and continued growth of this segment of business aviation make research into the feasibility of hybridization imperative. The constraints imposed by the small size and comparatively low weight of VLJs necessitate a dedicated examination, separate from other business jet classes. This paper aims to provide the first published research to determine the following:

1. The corresponding range is achievable for a VLJ from a given degree of energy hybridization for series and parallel hybrid-electric architectures under fixed Maximum Takeoff Weight (MTOW) assumptions.
2. Estimated fuel and emission reduction for a typical mission.
3. An optimal architecture for a potential first-generation hybrid-electric VLJ.

2. Background

In general terms, electrified aircraft propulsion (EAP) can be categorized into three distinct branches based on energy source and powertrain architecture: turboelectric, hybrid-electric, and fully electric. For turboelectric systems, all the energy is derived from a fuel source such as 100LL AvGas or Jet-A. Fully electric systems are powered by energy stored in batteries, or other electrical energy storage devices. Hybrid-electric systems are a combination of the turboelectric and full-electric schemes, in that they store and utilize energy from fuel and electrical energy sources, typically Jet A and batteries. On HEP systems, the energy may be used from storage sources individually, or simultaneously, depending on the power requirement for a given flight phase [5,15,16].

Within hybrid-electric propulsion systems, there are three primary architectural classifications: series, parallel, and series/parallel. Each of the configurations offers different advantages but also certain drawbacks. In this paper, the primary architectures of interest are the series and parallel schemes.

2.1. Series Architectures

The series HEP architecture is characterized by completely electric thrust generation. As is seen in Figure 2, the sequence of converting energy into thrust is sequential and linear. The process begins with fuel energy converted to electrical power via a turbogenerator, which is architecturally an electrical generator connected to a turboshaft via gearing. Electrical power from the generator is transformed by the power converter to an appropriate electrical current and voltage condition for the electric motor or to recharge the battery. The power converter also converts electrical power from the battery to the appropriate condition for the electric motor. The electrical motor then converts the electrical power

into mechanical power to be used by the thrust-generating fan or propulsor [5,17]. The energy to thrust conversion on the series drivetrain can thus be divided into three distinct paths—fuel to shaft, battery to shaft, and shaft to thrust [18]. Table 4 provides the efficiency factors for each path.

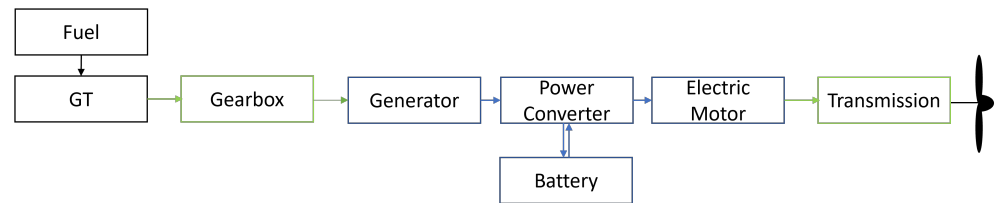


Figure 2. Simplified diagram of a series architecture. Black arrows represent fuel paths, blue arrows electric paths, and green arrows mechanical paths [11].

Table 4. Drivetrain efficiency paths for a series architecture [11,18]. Subscripts are as follows: tg—turbogenerator, pc—power converter, em—electric motor, gb—gearbox, and p—propulsor fan/propeller.

Drivetrain Path	Series
Fuel to Shaft, η_1	$\eta_{tg}\eta_{pc}\eta_{em}$
Battery to Shaft, η_2	$\eta_{pc}\eta_{em}$
Shaft to Thrust, η_3	$\eta_{gb}\eta_p$

The advantage of transmitting power electrically, as in a series system, is that it allows for decoupling of the turbogenerator and propulsor. The decoupling enables a distributed architecture to be used. However, the conversion of mechanical energy to electrical, and back to mechanical also introduces certain inefficiency, as seen in Table 4. The additional steps and components also add to the overall weight of the system [5,16], as demonstrated subsequently.

2.2. Parallel Architectures

In a parallel architecture, thrust is produced by the summation of mechanical power directly from the engine, as well as from the electrical motor. This is achieved by coupling the electric motor to the propulsor or low-spool shaft of the turbofan engine with a transmission gearbox. An accessory generator on the turbofan engine provides electricity to power the electric motor, or to recharge the batteries. The electricity produced by the accessory generator is appropriately conditioned by the power converter. Figure 3 illustrates the parallel HEP system. Similar to the series system, the energy to thrust path for a parallel system can also be split into three distinct elements. The paths and corresponding efficiency factors are presented in Table 5.

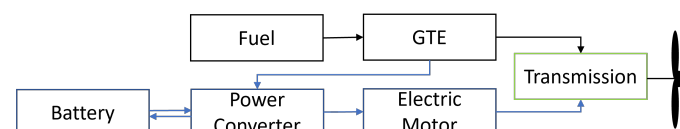


Figure 3. Simplified diagram of a parallel architecture. Black arrows represent fuel paths, blue arrows electric paths, and green arrows mechanical paths [11].

Table 5. Drivetrain efficiency paths for a series architecture [11,18]. Subscripts are as follows: tf—turbofan, pc—power converter, em—electric motor, gb—gearbox, and p—propulsor fan/propeller.

Drivetrain Path	Parallel
Fuel to Shaft, η_1	η_{tf}
Battery to Shaft, η_2	$\eta_{pc}\eta_{em}\eta_{gb}$
Shaft to Thrust, η_3	η_p

Due to the ability to generate thrust from the turbofan and electric motor in conjunction or independently, the parallel system offers operational flexibility [15–18]. Nonetheless, the gearbox coupling adds complexity to the system [4]. Additionally, while lighter than series schemes, parallel architectures are still relatively heavier than conventional turbofans [5].

2.3. Electrical Components

Based on the schematic diagrams for the series and parallel architectures, it becomes evident that the efficiency and weight of the electrical components play a significant role in the feasibility of applying hybrid-electric propulsion to very light jets. In practical application, electrical systems of 1 to 3 kV class are required [5]. Table 6 presents the predicted efficiency and specific power for electrical components in the 15-year timeframe.

Table 6. Drivetrain efficiencies and specific power for electrical components of a HEP architecture.

Component	Efficiency	Sp. Power [kW/kg]
Turbogenerator, η_{tg}	0.49 [19,20]	13.0–15 [21–23]
Power Converter, η_{pc}	0.99 [5,24]	12.0–20.0 [5,24,25]
Electric Motor, η_{em}	0.98 [4,26–28]	9.0–16 [5,16,29,30]

2.4. Battery Technology

While batteries have specific energy densities an order of magnitude lower than Jet A fuel, they represent the most promising near-term technological solution for electrical energy storage on a future HEP VLJ aircraft. This is due to the high technological readiness and increasingly widespread adoption for short-range electric aircraft. Batteries also exhibit reasonable performance in terms of specific power, volumetric energy density and comparatively long cycle lives [31–33]. Table 7 presents the predicted cell-level performance within the next 15 years for some of the promising battery technologies.

From Table 7, it becomes evident that there is a wide range of predictions for battery-specific energy density over the next 15 years. While Li-air and Li-S offer the potential for significantly superior energy performance compared to Li-ion batteries, factors including future cycle life and production readiness are to be determined. Consequently, it is imperative to investigate the range of specific energy densities from 400 Wh/kg to 1250 Wh/kg.

Table 7. Approximate predictions of best performance for battery cells in the next 15 years.

Energy Storage Type	Specific Energy [Wh/kg]		Vol. Energy Density [Wh/L]	Cycle Life [#]
	Current	Future	Current	Current
Jet A-1	11,950		9500	
Lead-acid	50 [34]		50–100 [34]	1800 [34]
Ni-Cd	60 [34]		75–150 [34]	3000 [34]
NiMH	80 [35]		300 [36]	2000 [36]
Li-Po	130–200 [34]		250 [34]	1000 [34]
Li-ion	200–250 [34]	400 [31]	200–300 [34]	3000 [31]
Li-air	400–800 [34]	750–1250 [33,37,38]	180–250 [39]	550 [33]
Li-S	200–700 [34]	500–1250 [31,40]	300–450 [33]	300 [33]

3. Methodology

3.1. Baseline Aerodynamic Model

The methodology of this paper is based on that presented in [11] with the appropriate modifications for a VLJ aircraft. The first step in the process is to define the performance of a conventional turbofan baseline aircraft model, to which the series and parallel HEP configurations may be compared. Using the twin-engine aircraft presented in Table 3, general weight information for the aircraft class was established as an approximate composite average of the larger VLJs provided in Table 3, namely the CE-525, HA-420, and EMB-500. The resulting weights are presented in Table 8. Additional specifications and parameters required for the simulation are presented in Table 9 using information from manufacturer specification data sheets and [12,41], averaged over combinations of the three representative aircraft. Powerplant values are based around a Williams FJ44-1, which is utilized on numerous VLJs and other light jets.

Table 8. Weights for a generalized baseline very light jet class aircraft.

Weight Parameter	Weight [kg (lbs)]
Maximum Takeoff	4850 (10,700)
Operating Empty (2 Crew)	3100 (6850)
Useful Load	1725 (3800)
Max. Fuel	1500 (3300)
Max. Payload	675 (1500)
Available Fuel with 4 Pax.	1350 (3000)

Table 9. Other specifications for a baseline VLJ.

Parameter	Value
Single Engine SL Static Thrust [kN (lbf)]	8.90 (2000)
Cruise TSFC [g/kN-s (lbs/lbf-hr)]	12.32 (0.435)
Bypass Ratio	3.3
Max. Ceiling [ft]	41,000
Mach Max. Operating at Ceiling	0.71
Cabin Volume [m ³ (ft ³)]	5.70 (200)
Baggage Volume [m ³ (ft ³)]	1.55 (54.6)

3.2. Turbofan Baseline Performance Simulation

The previously developed MATLAB 2018a performance simulation consists of multiple distinct segments that enable range and energy consumption to be determined. These phases comprise a takeoff over a 50 ft obstacle, a V_Y climb to a given cruise altitude at the maximum rate of climb, cruise at an assigned Mach number, and a steady descent at a rate to an altitude of 5000 ft. This main mission block is followed by a reserve block, which includes a missed approach and climb; cruise of 185 km (100 nmi) at best economy cruise at an altitude of 10,000 ft; and, finally, steady descent to landing. The reserve mission also retains energy for the required 30 min of holding time.

The simulation is based on quasi-steady-state assumptions to determine the aircraft weight using a forward Euler time-stepping computational method. For every sequential one-second increment of time, the simulation recalculates aircraft lift, drag, velocity and weight based upon a starting weight. From these calculated parameters and the governing equations of motion, horizontal position and altitude are determined for every point in time. The equations are substantially derived from McCormick's Aerodynamics, Aeronautics and Flight Mechanics [42]. Fuel and energy consumption, and consequently weight, are determined using the thrust production at a given time point.

For the takeoff and climb phase, the maximum rate of climb was determined across the range of flyable velocities from stall speed V_S to V_{MO} . The stall speed was determined based on assumed maximum coefficient of lift $C_{L_{max}} = 1.7$. V_{MO} was assumed to be the true airspeed equivalent of Mach 0.73, based on the sample aircraft. For each velocity, C_L was computed based on instantaneous aircraft weight. Thrust was held at a constant 90% of maximum available at any given altitude for the climb phase. Upon reaching the predetermined cruising altitude of 37,000 ft, thrust was set to equal the drag produced at a velocity of Mach 0.65. During descent, the simulation modulated thrust to maintain a constant rate of descent of 3000 ft per minute to 5000 ft.

3.3. Drag Buildup

Aerodynamic drag for the baseline aircraft model simulation comprises contributions from induced, profile and wave drag. Induced drag was calculated at each instant based on aircraft weight and velocity with an assumed Oswald's span efficiency factor of $e_0 = 0.80$. Zero-lift drag was calculated using the geometry-based semi-turbulent empirical estimations developed by [43]. Table 10 presents the geometric parameters used in the zero-lift drag calculations. Drag effects from leakage and protuberance were assumed to be an additional 5% to the zero-lift drag. Wave drag was determined based on a Mach drag-divergence of $M_{DD} = 0.75$ from the McDonnell method [43–45]. An additional 0.0003 counts of drag were added to the total drag account for trim effects [46].

Table 10. Geometric values for a aerodynamic model used in the computation of induced and profile drag.

Wings	
Wing Ref. Area, S_{ref} [m^2 (ft^2)]	22.29 (240)
Wing Wet. Area, S_{wet} [m^2 (ft^2)]	32.51 (350)
Mean Wing Chord, C_{avg} [m (ft)]	1.64 (5.39)
Chordwise Max. Thickness, x/c	0.50
Thickness to Chord Ratio, t/c	0.120
Max.-Thick. Line Sweep, α_m [$^\circ$]	7
Wing L.E. Sweep, α_{LE} [$^\circ$]	4
Wingspan [m (ft)]	14.41 (47.25)

Table 10. Cont.

Wings	
Aspect ratio, AR	9.30
Horizontal Stabilizer	
H. Stab. Wet. Area, S_{wet} [m^2 (ft^2)]	7.99 (86)
Mean H. Stab. Chord, C_{avg} [m (ft)]	1.19 (3.89)
Chordwise Max. Thick., x/c	0.50
Thickness to Chord Ratio, t/c	0.095
H. Stab. L.E. Sweep, α_{LE} [$^\circ$]	20
Vertical Stabilizer	
V. Stab. Wet. Area, S_{wet} [m^2 (ft^2)]	5.21 (56)
Mean V. Stab. Chord, C_{avg} [m (ft)]	1.55 (5.07)
Chordwise Max. Thick., x/c	0.50
Thickness to Chord Ratio, t/c	0.10
Max.-Thick. Line Sweep, α_m [$^\circ$]	25
Fuselage	
Fuselage Wet. Area, S_{wet} [m^2 (ft^2)]	65.07 (700)
Length, L [m (ft)]	12.99 (42.6)
Diameter, d [m (ft)]	1.58 (5.2)
Single-Engine Nacelle	
Nacelle Wet. Area, S_{wet} [m^2 (ft^2)]	6.51 (70)
Length, L [m (ft)]	1.68 (5.5)
Diameter, d [m (ft)]	0.52 (1.7)

3.4. Power Required and Turbofan Power Available

With the determination of drag for a given weight, velocity and altitude, the power required curves for the aerodynamic model are established. The power required curves are presented in Figure 4. Thrust available for the engine was determined using the equation presented in Equation (1), which corrects for altitude and Mach effects. A moderate throttle ratio (TR) common for smaller high bypass ratio engines, was used, such that $TR = 1.05$. The throttle ratio describes the maximum turbine inlet temperature (TIT) at the operating altitude condition compared to the maximum TIT at sea level. For business jets, engines are typically optimized for maximizing efficiency at cruise-level conditions. The calculated available power has been overlaid onto the required power curves in Figure 4. The difference between the required and available power dictates the rate of climb, and the performance ceilings.

$$T_a = T_{a,SL} \delta_o \left[1 - 0.49 \sqrt{M_\infty} \frac{3(\theta_0 - TR)}{1.5 + M_\infty} \right] \quad (1)$$

The determination of available propulsive power for the turbofan enables sizing of equivalent hybrid-electric architectures. Three points in the turbofan power available envelope are of importance— V_S and V_H at sea level, and V_H at the ceiling. V_S represents the stall speed of the aircraft, while V_H represents the maximum speed at maximum continuous power. The sizing values of the delivered propulsive power are presented in Table 11. From the table, and Figure 4, the difference between the available power and required power also demonstrates the ability for One Engine Inoperative capabilities.

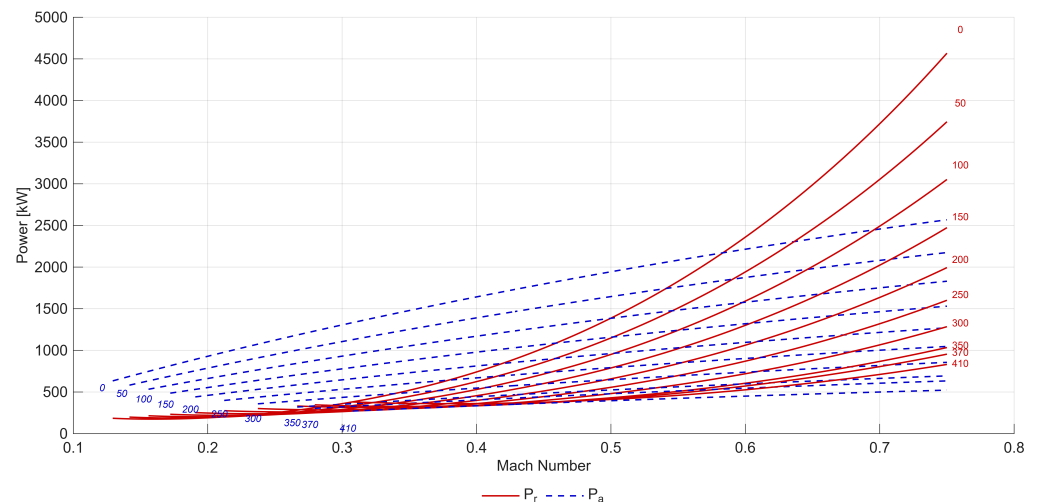


Figure 4. Power required and power available for the VLJ model. Altitudes are provided in $\times 100$ ft levels.

Table 11. Critical single-engine propulsive power available conditions.

Flight Condition	Power [kW (hp)]	Thrust [kN (lbf)]
Sea Level at V_S	403 (540)	8.93 (2008)
Sea Level at V_H	1280 (1716)	4.06 (913)
Ceiling at V_H	340 (455)	1.62 (364)

3.5. Turbofan Weight

In order to ascertain the additional weight imposed by the series and parallel architectures, the baseline turbofan weight must be established. This was determined from the average thrust-to-weight ratio for engines utilized on this class of aircraft, including the Pratt & Whitney Canada PW617, GE Honda HF 120, and Williams FJ33 and FJ44 engines, which average 0.0493 kN/kg (5.03 lbf/lb). Based on this average, an 8.90 kN (2000 lbf) engine can be expected to weigh approximately 180.44 kg (397.87 lbs) dry. In order to estimate the wet engine weight, an additional 5% was added to the dry weight. Consequently, total wet engine weight was found to be 189.46 kg (417.76 lbs).

3.6. Hybrid-Electric Drivetrain Sizing

Utilizing the calculated single-engine propulsive power of 2219 kW, the series and parallel architectures can be sized. Since the propulsive power was determined based on delivered thrust, the preceding components on the drivetrain must be enlarged to account for losses in the energy path. The efficiency losses for the series architecture are provided by Table 4. Table 5 provides the efficiency for the parallel drivetrain. Once the power ratings for the individual components are determined, weights are obtained by dividing by the specific power. The predicted efficiencies and specific powers of the electrical components are available in Table 6. Additionally, the propeller gearbox was assumed to have an efficiency of 0.99 and specific power of 100.0 kW/kg, and the combining transmission gearbox an efficiency of 0.99 and specific power of 50.0 kW/kg [47,48]. Propulsor efficiency was taken to have an efficiency of 0.85 and specific power of 13.0 kW/kg [5,20,49]. To account for wet weight, turbomachinery weight was multiplied by 1.05 on account of lubricants and accessory pads. The electric motor weight was increased by 3% as they require lubricants as well.

The total weight for the series architecture was found to be 384 kg (846 lbs). The power and weights for individual components of the series drivetrain are presented in Table 12. Given the multitude of components in a series system, the individual weights are based on optimistic trends for the predicted specific power spectrum.

Table 12. Weight estimate of a serial architecture hybrid-electric propulsion system.

Component	Power [kW (hp)]	Weight [kg (lbs)]
Propulsor Fan	1280 (1716)	42.66 (94.10)
Propeller Gearbox	1505 (2019)	15.06 (33.21)
Electric Motor	1521 (2039)	104.45 (230.31)
Power Converter	1552 (2081)	103.48 (228.16)
Turbogenerator	1567 (2102)	117.57 (259.28)
Total Weight	-	384 (846)

Similarly for the parallel architecture, Table 13 presents the power and weight at the drivetrain component level, for a total weight of 214 kg (473 lbs). The parallel sizing was predicated upon a power hybridization (motor power ratio) of 25%, where the motor provides 25% of total installed power capability. This power ratio was found to provide reasonable fuel savings in other studies [20,50–54]. Since electric motors have lower specific powers than turbofan engines, capping the motor at 25% enables hybridization without adding excessive weight to the power plant installation. While increasing power hybridization results in superior overall powertrain propulsive efficiency, it also comes at the cost of added system weight. The turbofan was proportionally scaled to deliver the remaining 75% of propulsive power at sea level V_{MO} , rather than using the less conservative method by [43].

Table 13. Weight estimate of a parallel architecture hybrid-electric propulsion system.

Component	Power [kW (hp)]	Weight [kg (lbs)]
Propulsor Fan Addition	429 (575)	14.30 (31.53)
Transmission Gearbox	505 (676)	38.83 (85.60)
Electric Motor	509 (684)	35.00 (77.20)
Power Converter	520 (698)	37.16 (81.94)
Turbofan	1280 (1716)	149.21 (328.27)
Total Weight	-	274 (604)

3.7. Hybrid-Electric Simulation

Having determined the weights of the series and parallel HEP systems, it becomes possible to determine the new 4-passenger fuel weight for the very light jet model such that the aircraft retains an MTOW of 4852 kg (10,700 lbs). The weight deltas between the turbofan configuration and the HEP architectures are presented in Table 14.

Table 14. Weight modifications to the available energy weight for two power plants.

Architecture	Weight [kg (lbs)]	Δ Weight [kg (lbs)]	Energy Weight [kg (lbs)]
Turbofan	379 (836)	0	1350 (3000)
Series	768 (1692)	−389 (−858)	961 (2119)
Parallel	548 (1208)	−169 (−372)	1181 (2604)

The developed simulation was then modified to utilize the new energy weights for the series and parallel hybrid-electric propulsion systems. For both HEP architectures,

energy consumption was configured to prioritize depletion of fuel over batteries. This enables a greater reduction in aircraft weight earlier in flight, improving overall range. Consequently, for the series architecture, the climb and cruise phases were biased towards energy draw from the turbogenerator before battery energy. For the parallel scheme, thrust was developed through the simultaneous use of the turbofan and electric motor, as the electric motor is not sufficiently powerful for individual operation. The HEP reserve mission fuel allocation of approximately 272 kg (600 lbs) was also modified to include a proportion of battery equivalent no greater than the 4-passenger energy weight hybridization ratio.

To account for the broad range of predicted battery-specific energy densities, the simulation was swept across a range of $e_{\text{bat}} \in [400, 1250]$ Wh/kg. Energy hybridization ratios considered ranged from $H_E \in [0.0, 0.25]$ in increments of 0.01, where H_E is the ratio of energy stored in batteries to the total stored energy such that $H_E = \frac{E_{\text{bat}}}{E_{\text{bat}} + E_{\text{fuel}}}$. For each specific energy density combination, total energy weight was fixed to 911 kg (2008 lbs) for the series HEP and 1134 kg (2634 lbs) for the parallel configuration.

3.8. Validation of Simulation

Finally, in order to verify the applicability of the developed time-stepping point-mass simulation for a very light jet, the turbofan methodology was evaluated using known geometric and weight parameters for the Cessna CE-525 aircraft. The Cessna CE-525 has an MTOW of 4853 kg (10,700 lbs) and an Operating Empty Weight (OEW) of 3170 kg (6990 lbs), values relatively similar to the representative baseline. A comparison of the simulated results for the CE-525 is presented against a combination of brochure data from [13,55] and the AFM [56].

As is seen in Table 15, the simulation methodology provides performance values sufficiently close to published data for the CE-525. The accuracy is in the same order of magnitude as the validation provided in [11] for a large-cabin jet. Even though the developed methodology does not account for transitions between flight phases, such as between takeoff and climb, or climb to cruise, the transition periods are relatively short compared to the overall mission. As a result, the methodology is adequate to provide a first-order analysis of hybridized aircraft performance.

Table 15. Validation of simulation methodology for energy consumption and range parameters.

Parameter	Simulation	Brochure/AFM	% Difference
Climb Time to FL370 [min]	18.6	18	3.3%
4-Pax. Range [km (nmi)]	2134 (1152)	2191 (1183)	4.8%
Block Fuel [kg (lbs)]	5072 (2300)	5186 (2352)	2.3%

4. Results and Discussion

4.1. Range

The results of the simulation parametric sweep over the array of battery-specific energy density and hybridization ratios for the series and parallel are presented as contour plots in Figure 5 for the series architecture and Figure 6 for a parallel scheme. As expected, increasing hybridization substantially reduces mission range. While increasing battery energy helps recover some of the lost range, the gradient of the contours demonstrates that range is overall more sensitive to the hybridization ratio. This is because hybridization displaces more fuel energy with battery energy than is gained by increasing specific energy density, which at 1250 Wh/kg is still about a tenth that of Jet A at 11,950 Wh/kg. Tables 16 and 17 respectively provide the ranges for the series and parallel HEP architectures for a variety of hybridization and energy density ratios.

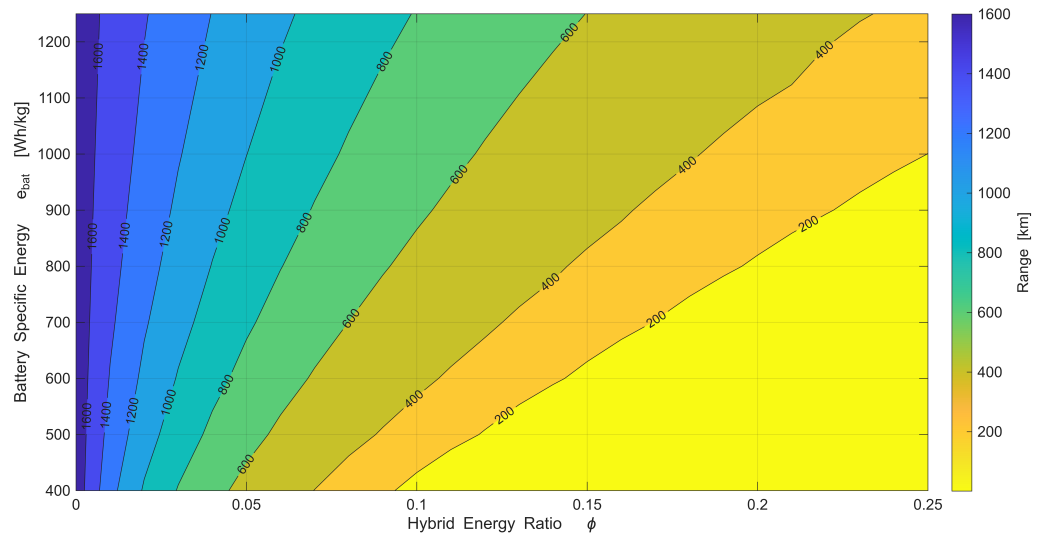


Figure 5. Parametric contour plot for range against hybridization ratio and battery specific energy density for the series configuration.

Table 16. Range for combinations of hybridization ratio and specific energy density for a series HEP architecture.

Hybrid. Ratio	Range [km (nmi)]			
	400 Wh/kg	800 Wh/kg	1000 Wh/kg	1250 Wh/kg
0.025	883 (477)	1194 (645)	1278 (690)	1354 (732)
0.050	546 (295)	891 (481)	1002 (541)	1116 (603)
0.100	131 (71)	561 (303)	674 (364)	793 (428)
0.150	0 (0)	384 (207)	485 (262)	598 (323)
0.200	0 (0)	174 (94)	366 (198)	467 (252)
0.250	0 (0)	0 (0)	198 (107)	372 (201)

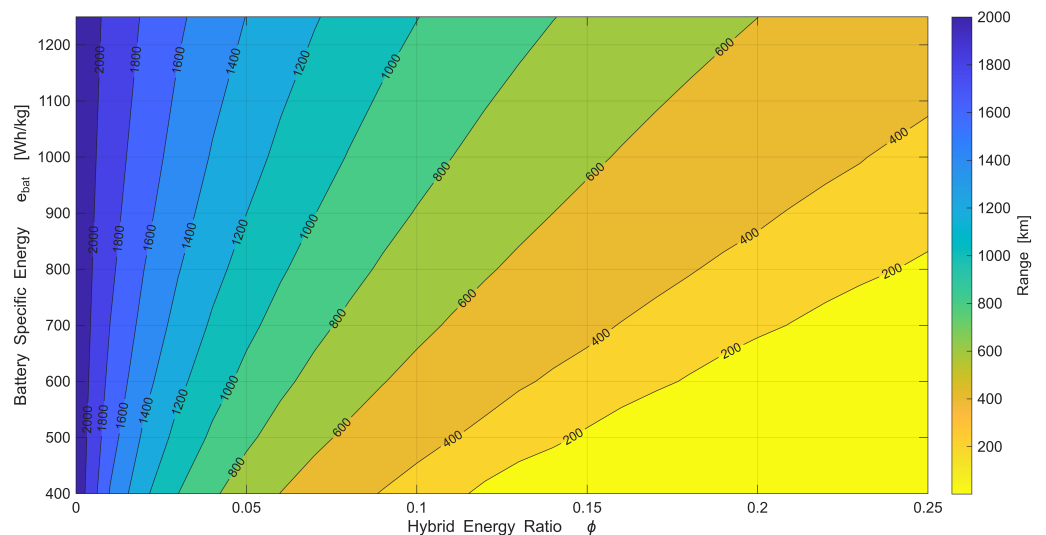


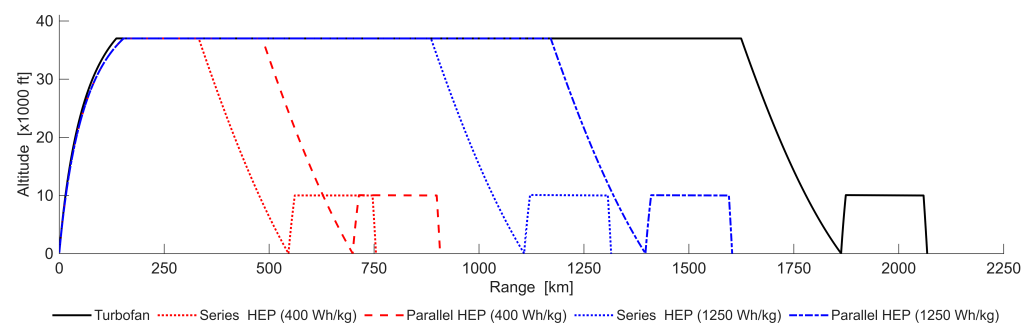
Figure 6. Parametric contour plot for range against hybridization ratio and battery specific energy density for the parallel configuration.

Table 17. Range for combinations of hybridization ratio and specific energy density for a parallel HEP architecture.

Hybrid. Ratio	Range [km (nmi)]			
	400 Wh/kg	800 Wh/kg	1000 Wh/kg	1250 Wh/kg
0.025	1118 (604)	1504 (812)	1611 (870)	1706 (921)
0.050	698 (377)	1127 (609)	1265 (683)	1397 (754)
0.100	337 (182)	718 (388)	860 (464)	1003 (542)
0.150	0 (0)	496 (268)	624 (337)	763 (412)
0.200	0 (0)	365 (197)	472 (255)	600 (324)
0.250	0 (0)	154 (83)	366 (198)	483 (261)

Based on the contour plots and tables, it becomes evident that battery-specific energy densities of less than 400 Wh/kg are insufficient for a hybridized VLJs with practical range. While 800 Wh/kg batteries are more promising, substantial range is only achievable with hybridization ratios of less than 5%, a value below which hybridization is very marginal even for a mild-hybrid concept. Batteries of between 1 kWh/kg and 1.25 kWh/kg demonstrate superior potential for feasible HEP very light business jets with meaningful degrees of hybridization.

Figure 7 compares the ranges for the series and parallel architectures at a 5% hybridization against the turbofan baseline for the most conservative $e_{\text{bat}} = 400$ Wh/kg and most optimistic $e_{\text{bat}} = 1250$ Wh/kg predictions for battery specific energy. As is seen in the figure, the turbofan aerodynamic model has a 4-passenger range of 1863 km (1006 nmi), which is within the typical flight range of twin-engine very light jet aircraft such as those listed in Table 3. With 1250 Wh/kg batteries, the series architecture has a range of 1116 km (603 nmi) and the parallel scheme a range of (1397) 754 nmi. While neither hybrid architecture reaches the typical maximum range of twin-engine VLJs with four passengers, the parallel scheme's range is superior to single-engine VLJs like the Cirrus SF50's. The 754 nmi range of the parallel system is also 94% the range of the Eclipse EA-500 series, the shortest-range twin-engine VLJ.

**Figure 7.** Series and parallel HEP architectures at $H_E = 0.05$ compared with turbofan mission profile.

4.2. Fuel and Battery Consumption

In order to determine whether the fuel-saving purpose of hybridization is accomplished, the fuel consumption of the series and hybrid configurations must also be examined. Figures 8 and 9 present the mission-average fuel burn and battery consumption per distance of range.

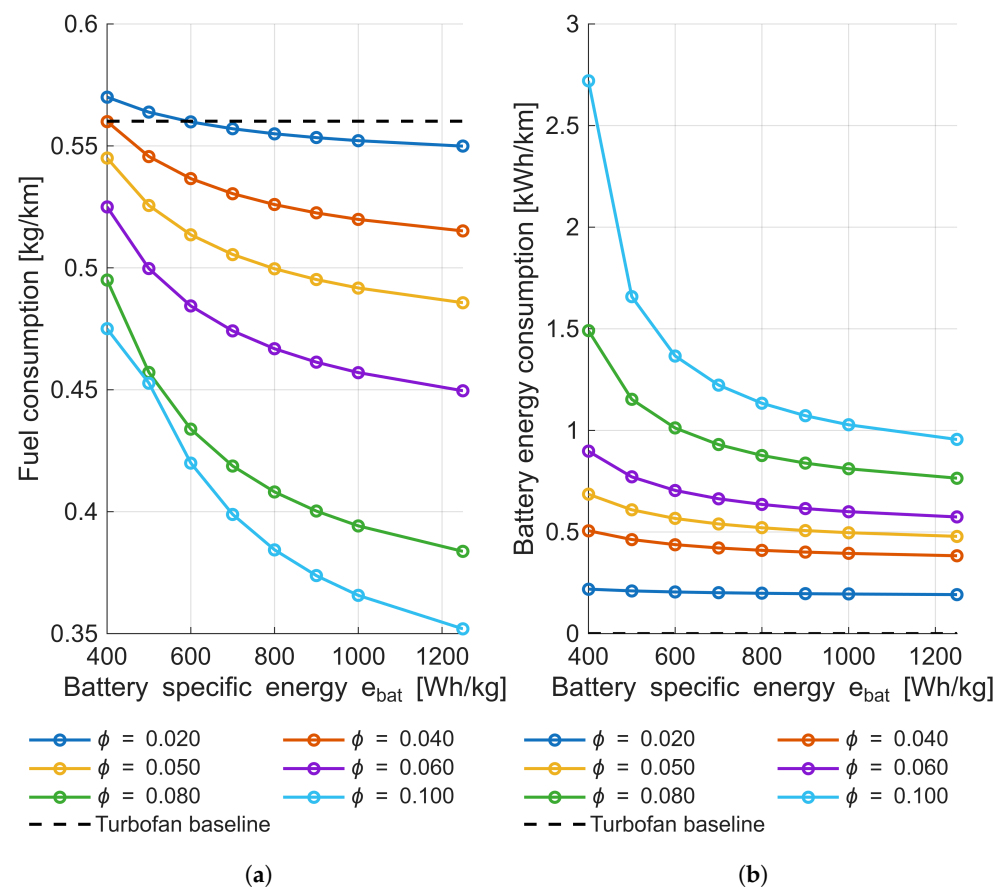


Figure 8. Series architecture fuel and battery energy consumption per km of range against specific energy density. (a) Fuel consumption for various hybridization ratios; the dashed black line is the baseline turbofan model. (b) Battery consumption for various hybridization ratios.

As seen in the figures, increasing the hybridization ratio enables a significant reduction in fuel burn and a commensurate increase in battery energy consumption. This occurs due to the increasing replacement of fuel energy with battery energy. Fuel consumption similarly decreases with increasing battery specific energy, as more battery energy is carried for a given energy weight. However, the fuel burn improvement per unit range is substantially less drastic than for hybridization ratio variation. Consequently, HEP architectures with low specific energies of up to 400 Wh/kg and low hybridization of less than 5% burn more fuel for a fixed distance than the turbofan configuration because of the increased aircraft empty weight. However, mild hybridization ratios of 5% to 10% combined with high specific energy density of 1000 Wh/kg to 1250 Wh/kg can reduce fuel burn substantially for fixed distances within the range capabilities of the particular hybridization and specific energy density combination.

4.3. Battery Weight and Volume Distribution

Among the primary challenges of hybridization of a very light business jet aircraft are accommodation for batteries in terms of weight and volume. VLJs have small relatively small, weight and balance margins to remain within stability limits. Tables 18 and 19, respectively, provide the weights and volumes for series and parallel architectures with varying levels of hybridization with 1250 Wh/kg batteries. The batteries were assumed to have a volumetric energy density of 360 Wh/L.

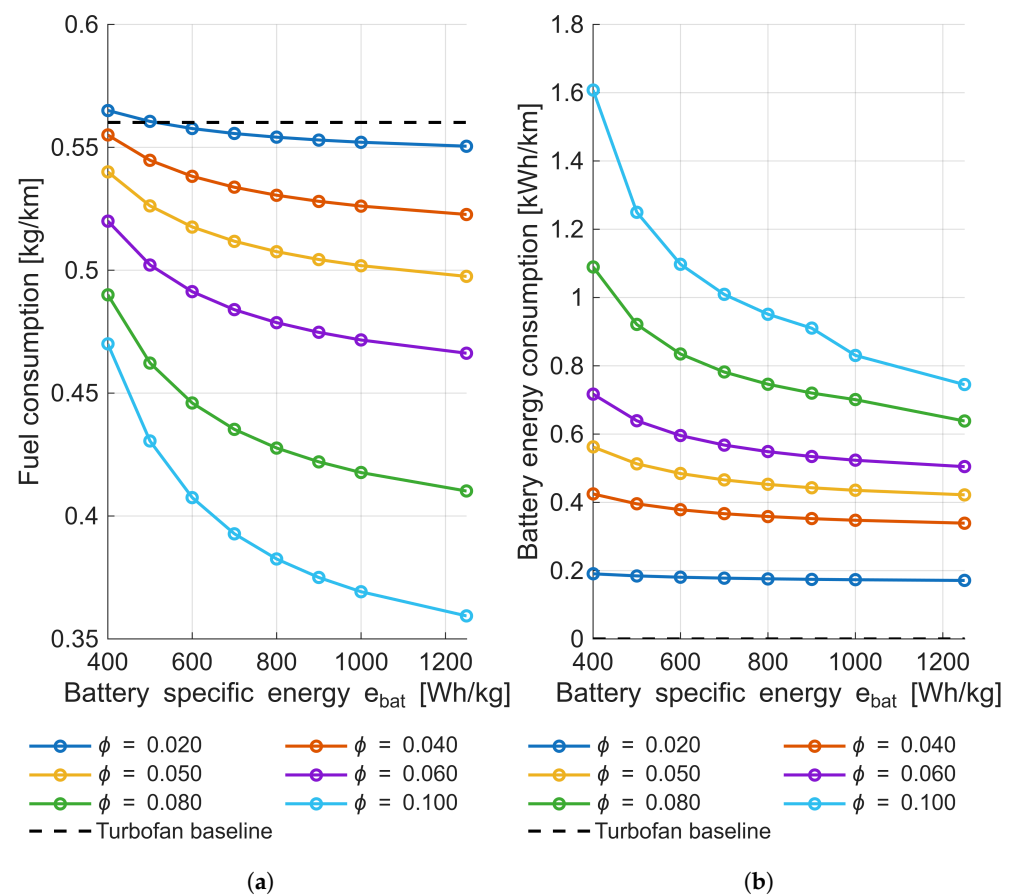


Figure 9. Parallel architecture fuel and battery energy consumption per km of range against specific energy density. (a) Fuel consumption for various hybridization ratios; the dashed black line is the baseline turbofan model. (b) Battery consumption for various hybridization ratios.

Table 18. Weights and volumes for 1250 Wh/kg batteries on the series architecture VLJ model.

Hybrid. Ratio	Weight [kg (lbs)]	Volume [L (ft ³)]
0.025	204 (449)	1559 (55)
0.050	346 (763)	2647 (94)
0.100	527 (1162)	4036 (142)
0.150	639 (1408)	4890 (173)
0.200	714 (1575)	5469 (193)
0.250	769 (1695)	5887 (208)

Table 19. Weights and volumes for 1250 Wh/kg batteries on the parallel architecture VLJ model.

Hybrid. Ratio	Weight [kg (lbs)]	Volume [L (ft ³)]
0.025	241 (531)	1842 (65)
0.050	408 (901)	3129 (110)
0.100	623 (1374)	4769 (168)
0.150	755 (1664)	5779 (204)
0.200	844 (1861)	6463 (228)
0.250	909 (2003)	6957 (245)

As is seen from the tables, batteries comprise a substantial weight and volume, even at mild hybridization ratios of around 5%. Figure 10 illustrates a representative VLJ

aircraft with three baggage storage areas—forward, cabin, and aft. Space available is on the order of 850 L (30 ft³), 283 L (10 ft³) and 1133 L (40 ft³), respectively, for the baggage compartments, in addition to space made available in the wings by replaced fuel storage volumes. Aircraft CG limits are +31.8 mm (+1.5") forward and +152.4 mm (+6") aft of empty CG. In a series configuration, battery weight must be distributed further forward than in a parallel configuration on account of the heavier powertrain. While both series and parallel configurations can be volumetrically accommodated within the representative CG margins, the greater weight of the series power plant results in an aft-heavy aircraft, even with both crew seats occupied. The distribution of batteries around the aircraft would also necessitate appropriate structural modifications to support additional weight. The relatively constant weight and volume of batteries also reduces the ability to modulate aircraft trim through fuel consumption, potentially requiring greater use of control surfaces to maintain pitch attitude, increasing aerodynamic drag in the process. Despite the challenges, it is worth noting that the fixed mass of batteries also offers potential advantages in terms of reducing wing bending and thus wingbox structural weight when batteries are accommodated in the wings [57].

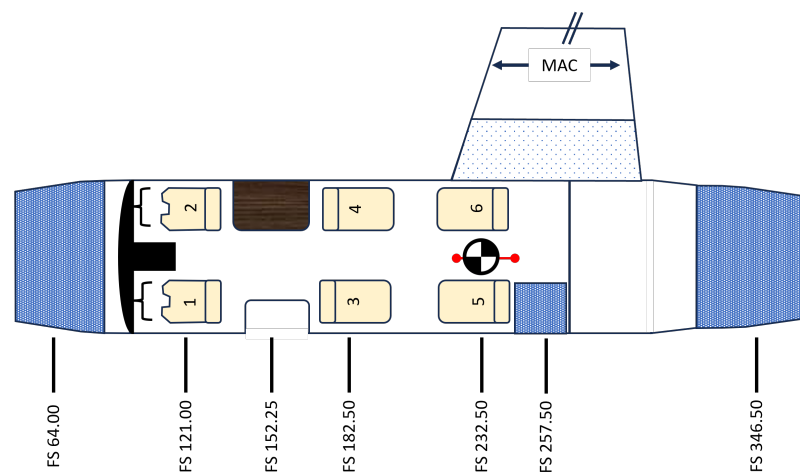


Figure 10. Representative illustration of available space on a VLJ. Baggage compartments are crosshatched in blue. The dotted area in the wing depicts the space made available in the wing by the displacement of fuel.

4.4. Typical Mission

Based on a mild hybridization ratio of 5% and the best-case battery-specific energy of 1250 Wh/kg, an exemplary 1100 km (600 nmi) mission at MTOW can be examined. This range encompasses the great circle distances for routes such as New York City–Charlotte, NC; Miami, FL–Atlanta, GA; Seattle, WA–San Francisco, CA; or London–Berlin. Figure 11 and Table 20 present the fuel and battery energy consumption for the turbofan, serial and parallel configurations.

The turbofan model consumed approximately 655 kg (1444 lbs) over the mission, while the series and parallel architectures consumed 580 kg (1279 lbs) and 559 kg (1233 lbs), respectively. In addition to fuel consumption, the series scheme utilized 492 kWh of battery energy. In contrast, the parallel HEP configuration utilized 446 kWh of battery energy. Overall fuel savings for the mission are 75 kg (165 lbs) and 96 kg (212 lbs) for the respective series and parallel hybrid architectures. Despite the relatively small overall savings, these savings represent fuel burn reductions of 11.5% and 14.65% against the turbofan baseline.

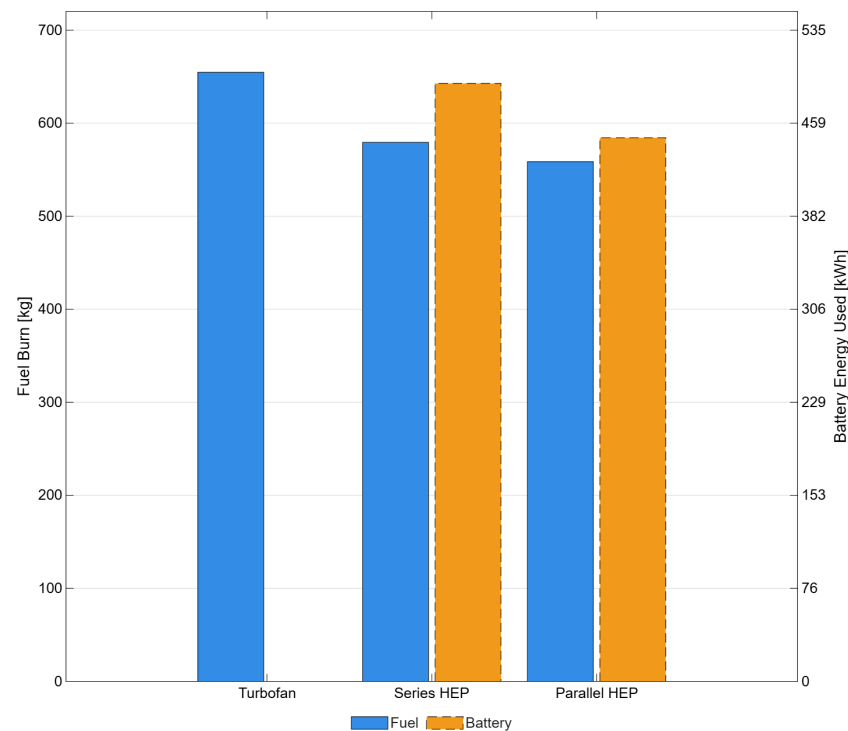


Figure 11. Fuel and battery energy consumption over a 1100 km (600 nmi) mission at aircraft MTOW. The blue bars correspond to fuel consumption, whilst the orange bars with dashed outlines correspond to battery energy consumption.

Table 20. Energy consumption for a 1,100 km (600 nmi) Mission with $H_E = 0.05$ and $e_{\text{bat}} = 1250 \text{ Wh/kg}$.

Parameter	Turbofan	Series	Parallel
Fuel Mass Consumption [kg (lbs)]	655 (1444)	580 (1279)	559 (1233)
Fuel Energy Consumption [kWh]	7827	6931	6680
Battery Energy Consumption [kWh]	-	492	446
Total Energy Consumption [kWh]	7827	7423	7126
Energy SAR [km/kWh (nmi/kWh)]	0.142 (0.077)	0.150 (0.081)	0.156 (0.084)

The fuel savings equate to a reduction in typical mission emissions of approximately 101 kg (224 lbs) of CO_2 for the series system and 197 kg (435 lbs) for the parallel system from fuel sources, based on an average 3.775 weight ratio of CO_2 emissions per unit of Jet A, and a US average of 0.367 kg (0.81 lbs) of CO_2 per kWh of electricity generation.

The typical mission analysis also confirms that a mild hybridization of around 5% is about the lowest ratio warranted on a VLJ. When used for propulsion purposes, lower energy hybridization ratios provide diminishing returns in terms of fuel burn reduction while incurring losses from added power plant weight and fixed battery weight.

5. Conclusions

The results and analysis of the simulation demonstrate and confirm the conceptual feasibility of hybrid-electric propulsion for very light jets, albeit with reduced ranges compared to typical aircraft of the class. While the representative aerodynamic model was able to achieve a four-passenger NBAA IFR range of 1863 km (1006 nmi), the series and parallel HEP architectures with a mild hybridization ratio of 5% were limited to 1116 km (603 nmi) and 1397 km (754 nmi), respectively, under the same conditions with the optimistic battery prediction of 1250 Wh/kg by 2040. While sub-one-thousand nautical mile ranges are shorter than twin-engined aircraft of the VLJ class, the series range is

comparable to the 622 nmi range of the single-engine Cirrus SF50. The parallel architecture enables superior range over the SF50. This demonstrates that a hybridized twin-engine VLJ still retains adequate performance within the current aircraft class bounds.

The better overall range of the parallel hybrid-electric architecture is a result of incurring a smaller weight penalty than for the series, thereby leaving more weight available for energy storage for a similar maximum takeoff weight. The lower empty aircraft weight for the parallel configuration also enables superior fuel savings. For a 1100 km (600 nmi) mission at $H_E = 0.05$ and $e_{\text{bat}} = 1250$ Wh/kg, the parallel system reduces fuel consumption by approximately 14.7% relative to the turbofan baseline, while the series configuration yields a reduction of about 11.5%. These gains in fuel efficiency are accompanied by slight reductions in total mission energy on account of the superior overall efficiency of hybrid-electric powerplants. As a result, VLJs utilizing mildly hybridized parallel architectures in conjunction with Sustainable Aviation Fuels (SAFs) would enable significant reductions in emissions.

The parallel configuration also has advantages over the series architecture in terms of technological readiness and implementation. Since parallel systems retain sizable turbofans, smaller and less powerful electrical components are required, lending to easier integration within the pylon-nacelle structure. Less powerful motors and power electronics are likely to be technologically ready for use sooner than more powerful systems with higher specific powers.

Apart from providing the requisite performance to fulfill ConOps in terms of performance, a mild hybridization ratio also enables the hybrid aircraft to operate in areas with limited charging infrastructure. VLJs frequently operate routes between airport pairs with limited flight services, which may or may not have on-ground charging infrastructure.

Based on these findings, it is recommended that the development of a future hybrid-electric VLJ utilize a parallel architecture with mild hybridization of around 5%. Additionally, it is recommended that the minimum battery-specific energy required for a feasible HEP very light jet business aircraft be at least 1250 Wh/kg.

Nonetheless, it should also be emphasized that this is a top-level study of the feasibility of hybrid-electric very light jet business aircraft in terms of performance based on optimistic battery predictions. Nominal predictions based on historical trends indicate substantially lower battery-specific energy densities at below 1000 Wh/kg. Recurrent maintenance costs and aircraft availability are also concerns for hybrid-electric aircraft, as battery packs would need replacement after reaching a certain minimum performance. As a result, while hybrid-electric VLJs may be feasible from a ConOps standpoint, they may not be economically viable. Finally, certification pathways and industry standards still need to be defined prior to or during the development of any potential hybrid-electric VLJ aircraft.

6. Future Research, Work and Opportunities

Numerous other considerations must also be examined in detail before a manufacturer could consider an engineering program. While this paper utilizes the best available predictions for power plant weight and component efficiency, future performance of constituent hybrid-electric components may not reach predicted levels. As a result, it would certainly be worthwhile to perform sensitivity studies for the less-developed and heavier components. Other factors such as structural integration, and battery and power plant thermal requirements are also critical for determining the potential for undertaking a hybrid-electric VLJ project. Market studies and the consultation of VLJ owners and operators would also be necessary to determine the demand for a hybridized VLJ and the impact on operational impacts due to reduced aircraft availability when charging batteries on the ground.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
AFM	Airplane Flight Manual
ALT	Altitude
APCH	Approach
ATC	Air Traffic Control
BPR	Bypass Ratio
DC	Direct Current
ESAR	Energy Specific Air Range
FADEC	Full Authority Digital Engine Controller
GAMA	General Aviation Manufacturers Association
HEP	Hybrid-Electric Propulsion
IBAC	International Business Aviation Council
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
LVL	Level
MTOW	Maximum Takeoff Weight
NBAA	National Business Aviation Association
PAX	Passenger
RWY	Runway
SP	Specific Power
TSFC	Thrust-Specific Fuel Consumption
TR	Throttle Ratio
VLJ	Very Light Jet

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