Characteristics of Electric Propulsion Systems

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1 Energy Storage Systems

In traditional propulsion systems, kerosene or other liquid fuel fuel is combusted with atmospheric oxygen in a piston engine or gas turbine, which then provide shaft power to drive the thrust-producing propeller or fan directly or via a gearbox. In newer electric-drive concepts, the source energy comes from either a battery or fuel cell in the form of electrical power, which is then used by an electric motor and associated electronics to drives the propeller or fan. Figure 1 compares the overall efficiency trends of these different propulsion systems.

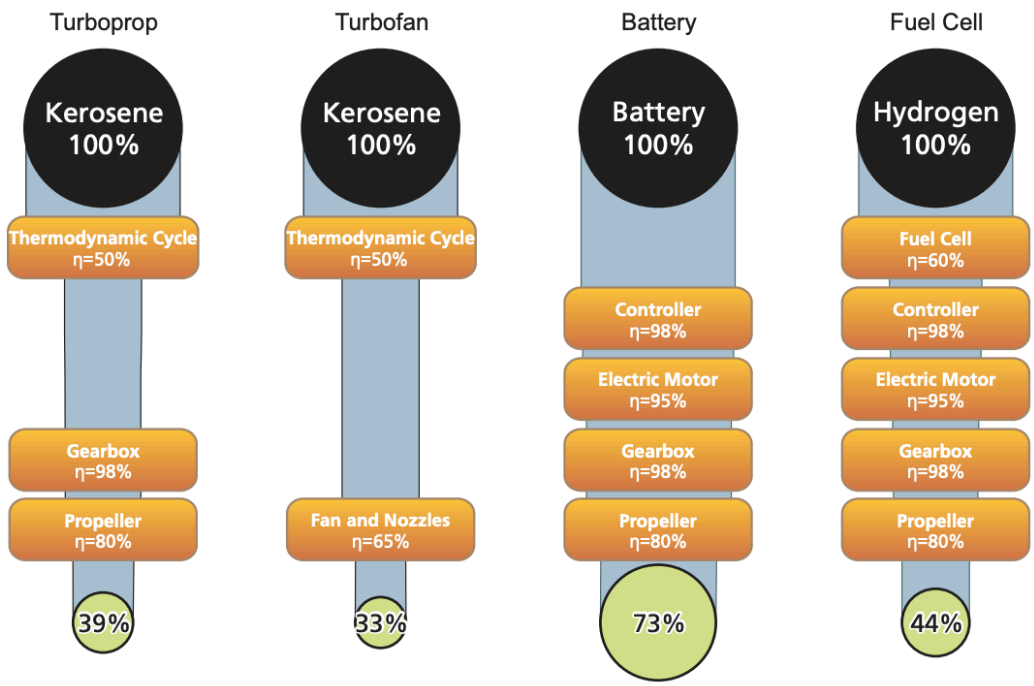


Figure 1: Comparison of propulsion system overall efficiencies

In an actual aircraft application one must also consider the volume and mass specific energy characteristics of different energy storage systems. Although Figure 1 states that battery-based electric systems are more efficient, Figure 2 shows that current battery technology provides roughly $\frac{1}{60}$'th of Kerosene's mass specific energy, which severely limits the possible cruise range of battery-powered aircraft. Figure 2 also shows that while hydrogen's specific energy is very large, even larger than the kerosene, in the form of gas at achievable pressures its energy per volume content is poor, and thus it requires large (and heavy) tanks which adversely impact aircraft performance and thus negate most if not all of the hydrogen's low weight.

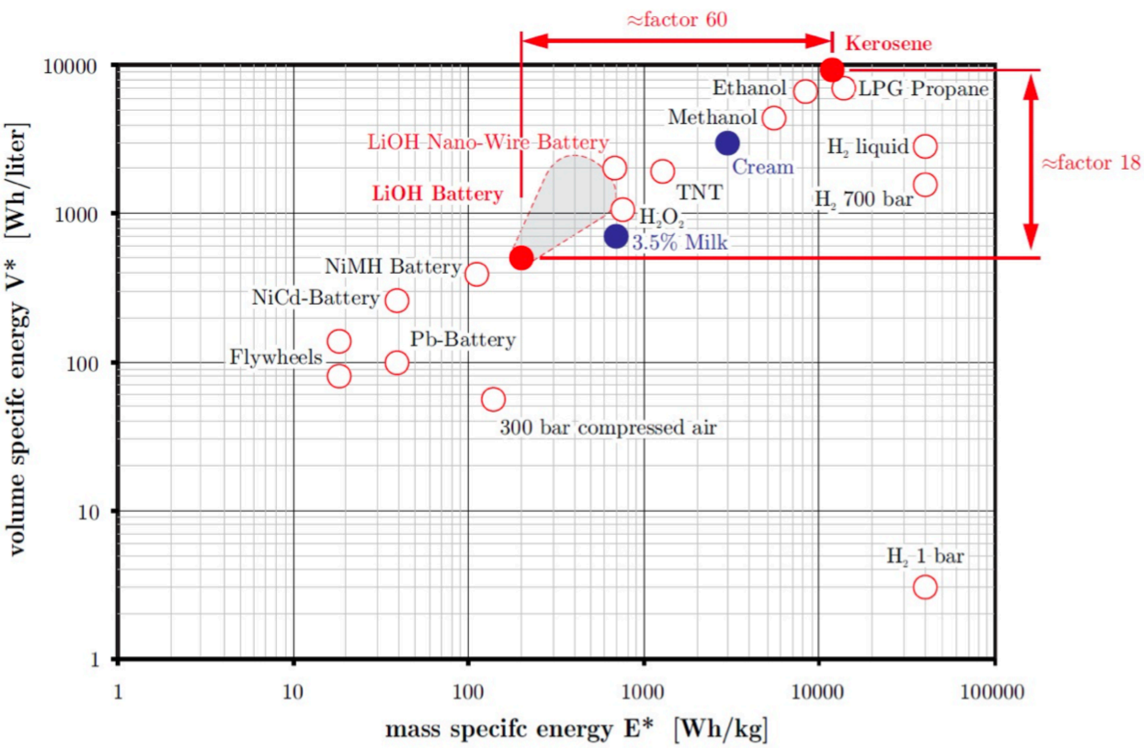


Figure 2: Volume and mass specific energy characteristics of different energy storage systems

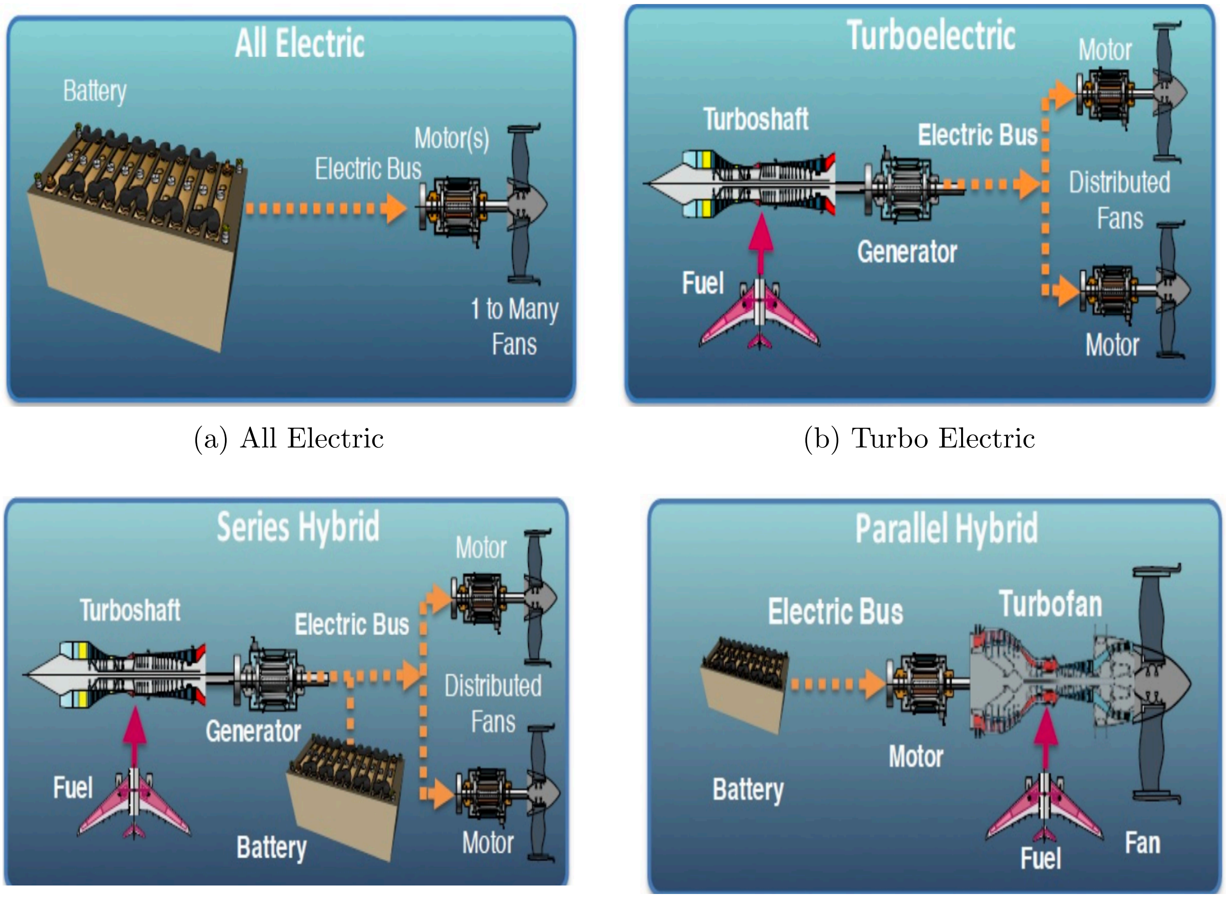
2 Electric-Drive Propulsion Systems

Figure 3 shows various all-electric or hybrid distributed electric propulsion concepts which have been explored and developed for aircraft applications.

Different aircraft types and missions naturally lend themselves best to the various propulsion systems. For example, all-electric aircrafts tend to be single/2-seater short-range aircraft such as Pipistrel, or eVTOLs which are designed for low-noise urban mobility type missions. Turbo-electric aircraft use combustible fuel for energy storage but electric power to drive the propulsion system. On the other hand, hybrid/electrical concepts are considered for long-range transport aircraft. In series hybrid propulsion configuration, electrical power is supplied by the two sources and combined at an electrical bus. It provides burst power for e.g. takeoff, also power back-up as redundancy. In the parallel-hybrid propulsion configuration, the engine provides power to the propulsion system during cruise, while the batteries are used for extra burst power when needed, such as during takeoff and climb. The fuel engine might also recharge the batteries during cruise so the aircraft requires only liquid refuelling (and not ground recharging) for normal service.

The series hybrid/electric propulsion system naturally enable the use of many small propellers or fans along the wing, which can be used for blown lift in Electric Short Takeoff or Landing (eSTOL) aircraft. Many small propellers can also be made inherently quieter than fewer larger propellers.

Figure 4 diagrams the "degree of hybridization" of hybrid/electric configurations. It also provides a guideline for the maximum amount of stored energy as compared to energy extracted



(a) All Electric

(b) Turbo Electric

(c) Series Hybrid

(d) Parallel Hybrid

Figure 3: Comparison of Alternative Electric-Drive Propulsion Systems

by the motor.

In summary, propulsion system selection and sizing depends on mission performance and efficiency requirements, namely weight, continuous rated power, (torque and rotational speed (RPM)) voltage (or current) at nominal and One-Engine-Inoperative (OEI) cases as well as cost. Specific power along with the specific energy presented in Figure 2 is typically used as a performance metric. However, in some situations cost might be the most critical decision parameter. For example, turbo-shaft engines are expensive. Although a single turbo-shaft engine can provide the same power of multiple-electric motors, from OEI case, cost of maintenance and replacement, distributed electric motors can be preferable. The pros and cons of the all-electric versus hybrid systems are listed in Table 1.

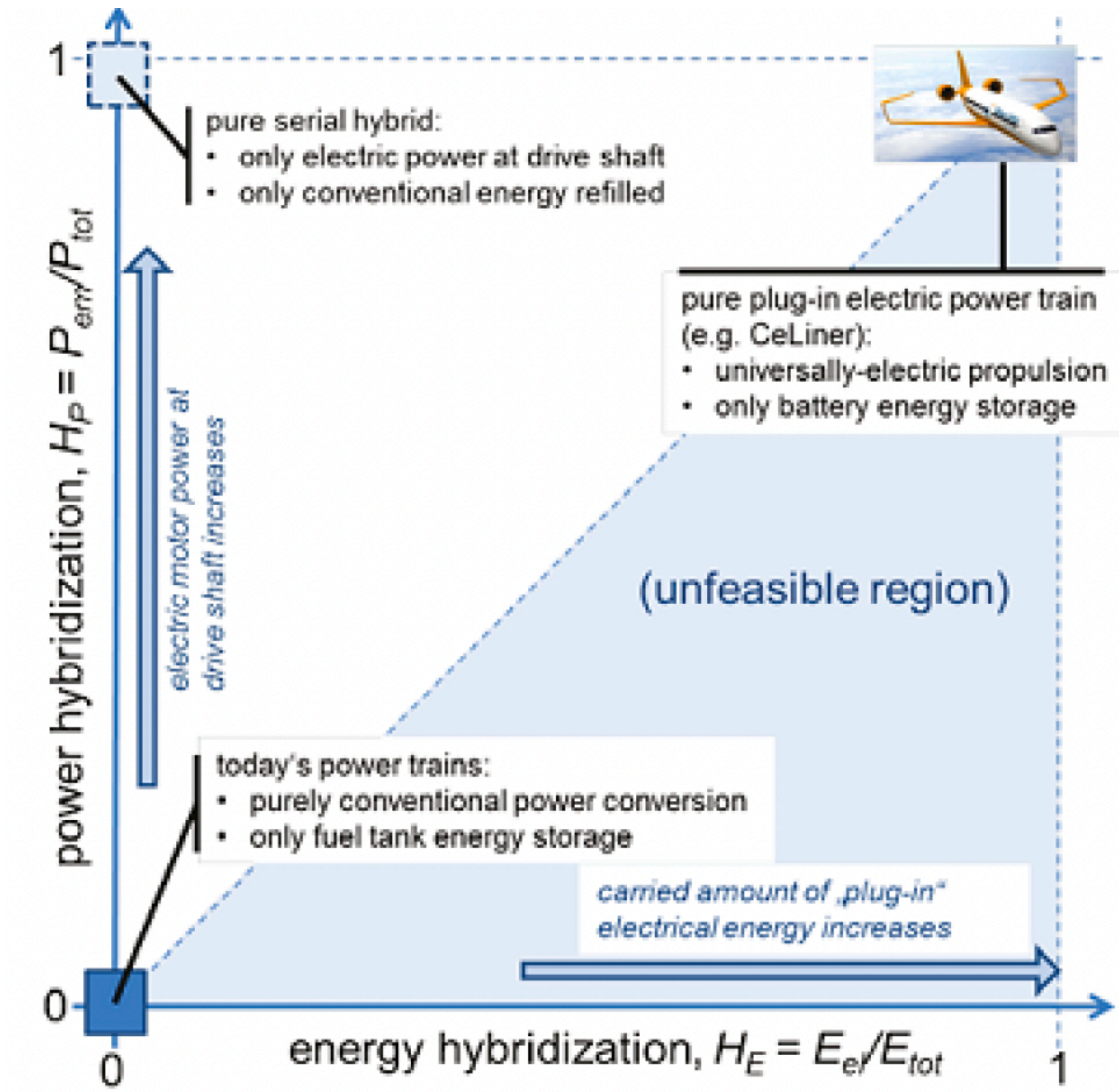


Figure 4: Degree of Hybridization

Table 1: Pros and Cons of Different Propulsion Architectures (HTS means High Temperature Superconductors)

HEP configuration	Advantages	Disadvantages
Turbo-electric	• Does not depend on advances of energy storage technologies • High design freedom for propulsion-aircraft integration	• High weight and low efficiency • Gas turbine engine is sized for peak power conditions • Depend on advances in HTS material technology
Series	• Decoupled engine can run at optimal RPM throughout mission • High design freedom for propulsion-aircraft integration • Power split between conventional and electrical power source is adjustable in flight • Batteries can be re-charged in-flight	• High weight and low efficiency • Need a generator • Could depend on advances in HTS material technology
Parallel	• No need for a generator makes it lighter • Fewer energy conversions, more efficient • Power split between conventional and electrical power source is adjustable in flight • Engine could be down-sized to provide only average continuous power	• Could need a complex gearbox • Power split is changes are restricted due to risk of engine off-design operation • Engine is not decoupled from thrust and cannot run at optimal RPM • Mostly limited to conventional configurations for engine-aircraft integration
Series-Parallel	• Better design freedom when compared to parallel configuration • Batteries can be re-charged in-flight	• Extra generator increases weight • Complex control strategy • Engine not fully decoupled from propeller
Partial turbo-electric	• Does not depend on advances of energy storage technologies • Good design freedom for electric motors-aircraft integration	• Depending on degree of hybridization could be heavy and inefficient • Gas turbine engine is not decoupled from thrust generation

3 Propulsion System Comparison Metrics

Quantitative comparisons of possible propulsion systems are typically performed using the following metrics:

- **energy specific air range** quantifies the distance which can be flown. per unit of energy
- **payload fuel energy efficiency** Breguet range equation is used to define payload fuel efficiency in terms of range, payload weight, and mission fuel weight.
- **weight**
- **cost**
- **noise level**

4 All-Electric Motor Propulsion System Sizing

Figure 5 shows the weight breakdown of different types of Vertical Takeoff/Landing (VTOL) aircraft. Clearly the large weight fraction for energy storage in the form of batteries plays an important role in the design selection for the all-electric aircraft.

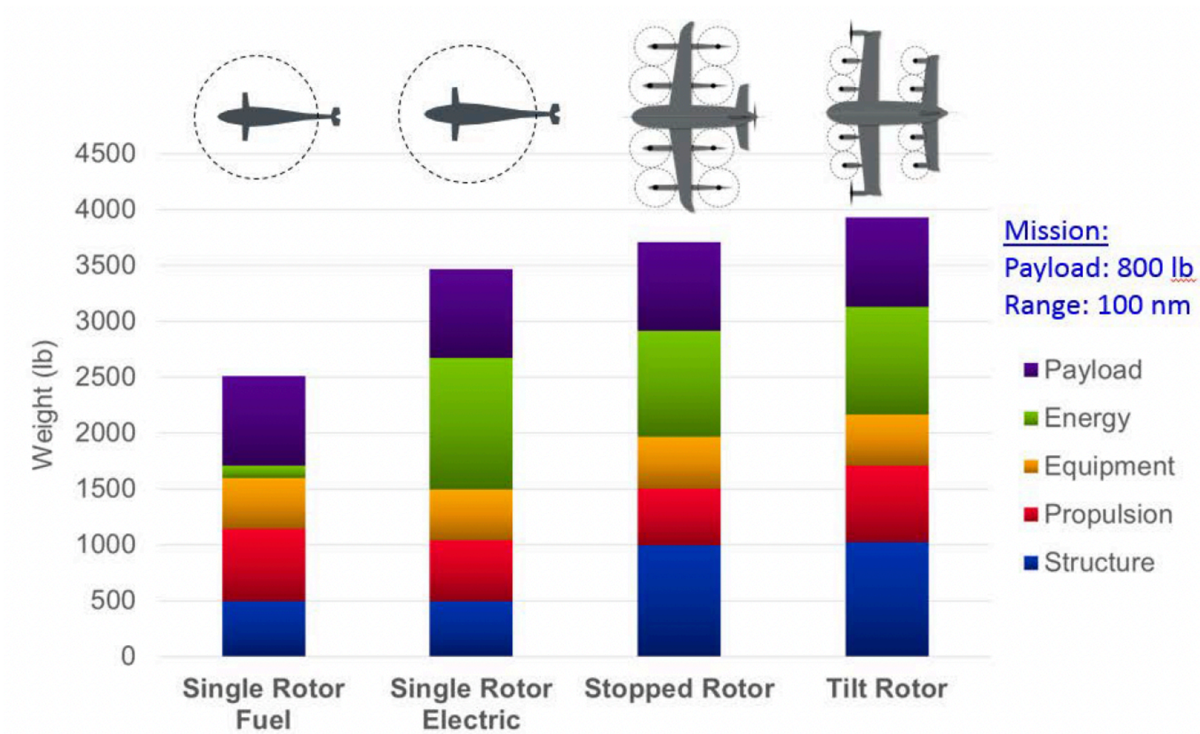


Figure 5: Weight breakdown for fueled and all-electric distributed propulsion system

The block diagram in Figure 6 shows the main elements of an existing high voltage (HV) all-electric battery energy management system. In an aircraft, an additional low voltage (LV) system, fed by the same batteries, would also be used to drive control surface actuation servos, lighting, accessories, and instruments.

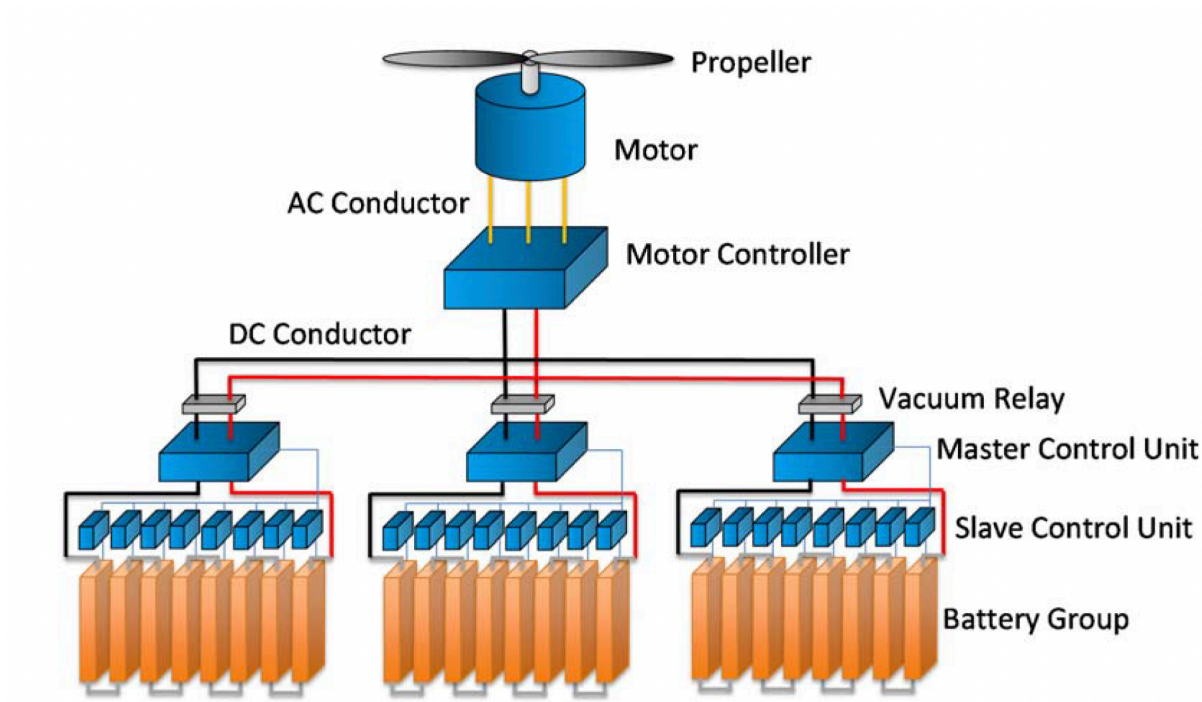


Figure 6: Pipistrel "Taurus" propulsion system schematic

Figure 6 shows only one motor and propeller, which is what's used in the Taurus Pipstrel. In a distributed electric propulsion system, several motors would typically be powered from a common HV power bus, although the actual current draw and corresponding torque of each motor, and hence its thrust, can typically be individually controlled. Separate battery packs each with its individual power bus can also be used to provide redundancy, which in turn increases flight safety.

5 Electric Motor Weight Estimation

The torque of an electric motor is directly related to the motor current and magnetic field strength, and hence to the amount of copper, magnets, and iron, which form the bulk of the motor weight. Hence, the weight of electric motors of similar configuration tends to scale mainly with the maximum or steady-state motor torque. The correlation is shown in Figure 7 on the right. The power P and torque Q are trivially related by $P = Q\Omega$, where Ω the motor rotation speed. So if Ω is limited by the motor's strength against rotor burst, motors with similar architectures and similar materials will also have their power proportional to their weight, as shown in Figure 7 on the left. However, if the motor speed must be reduced by other considerations such as the propeller structure or propeller noise, then the power output will also decrease. In this case, estimation of the motor weight based on the torque will be more reliable.

Once the propeller design engineer determines torque and speed requirements, a custom motor design or off-the-shelf options can be evaluated. Motor manufacturers typically provide continuous rated power and torque curves such as the one shown in Figure 8. For good

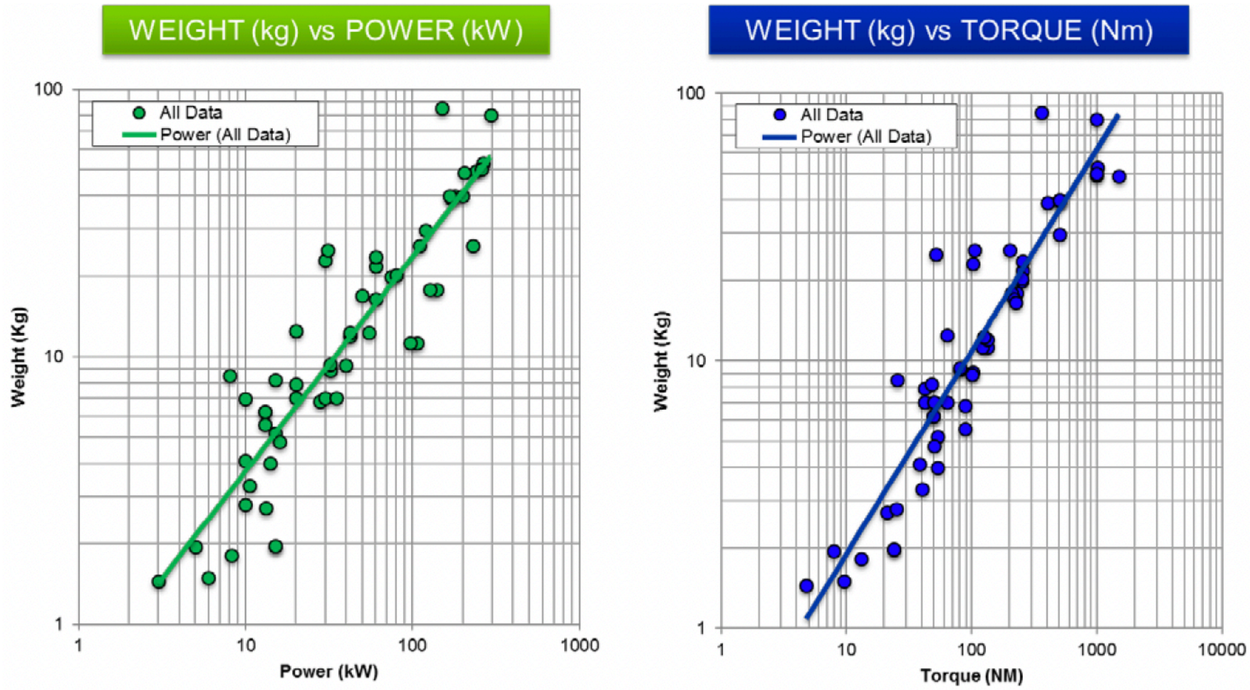


Figure 7: Motor weight correlation with power and torque

overall system efficiency the motor and propeller will ideally both operate close to their respective efficiency peaks. This is rarely possible for all power or torque levels and at all airspeeds. The two most common methods of bringing the efficiency peaks closer together are gearing, or variable pitch, or both. However, these inevitably increase weight, cost, and mechanical complexity, so the best solution requires some system-level analysis.

In peak-power demand situations such as OEI, thermal limits play an important factor for reaching maximum power of an elecrtic motor. Liquid-cooling systems are typically more effective than the alternative air-cooling systems for electric motors, but also heavier and more complex. Air-cooling systems are preferred for smaller motors and widely used in eVTOL applications. For high-rpm, low-torque operations, liquid-cooling is used. Engine selection must also consider the cooling system requirements.

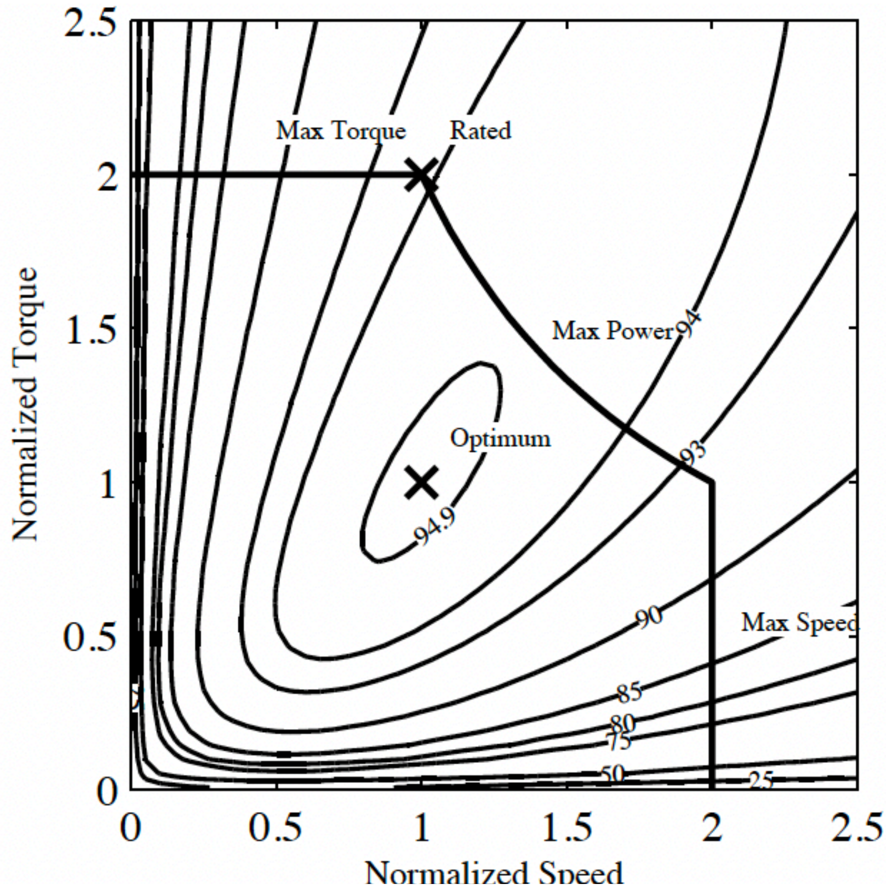


Figure 8: Typical electric motor normalized torque vs speed diagram

6 Battery Weight Estimation

In all-electric aircraft, power is provided by a battery pack, which is an assembly of battery cells. Even though the battery technology is growing fast, at today's standards lithium-based cell systems provide the most viable solution to all-electric propulsion. Specific energy [Wh/kg] and specific power [W/kg] are important metrics for sizing the battery pack. Typical lithium-based batteries have approximately 200 [Wh/kg] as presented in Figure 9.

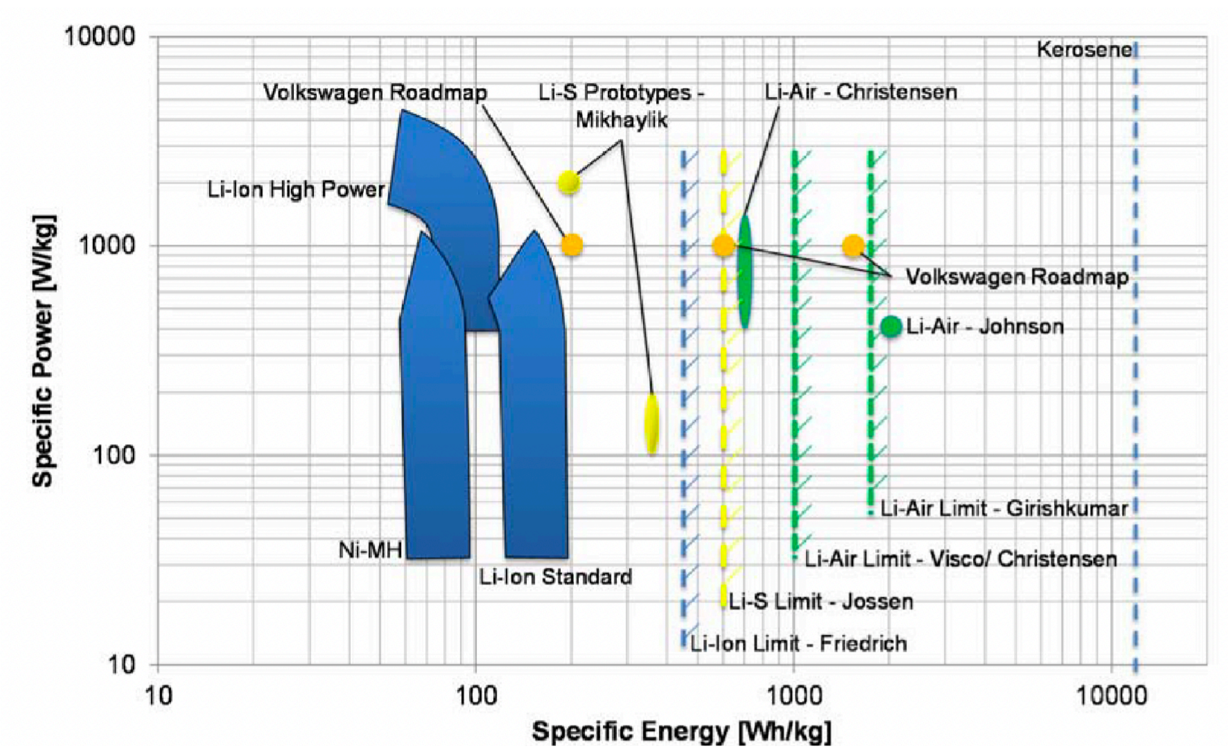


Figure 9: Specific Energy and Specific Power of Batteries

Another weight contributing element for batteries are cooling, insulation materials, battery management systems and wiring. As a crude approximation, one can use a literature information based on weight fractions. Battery management system (BMS) monitors the state-of-charge (SOC), which reflects the percentage of the remaining charge relative to the cell's rated capacity. The cell voltage shows a moderate decline with proceeding discharge, and a sudden decline as the discharge proceeds further. Figure 11 presents a battery cell the voltage drop as an all-electric aircraft during a typical mission. As seen from the Figure, the voltage drop can be dramatic when the depth of discharge reaches 85%. As the battery discharges the chemical reaction causes increase in temperature (approximately from 25deg Celcius to 50-60deg Celcius). Both voltage drop, and temperature rise causes OEI case at the end of the flight mission as one of the most critical sizing consideration. Depending on the mission and regulations, there could be a minimum reserve energy requirement which is typically provided by 20-mins reserve.

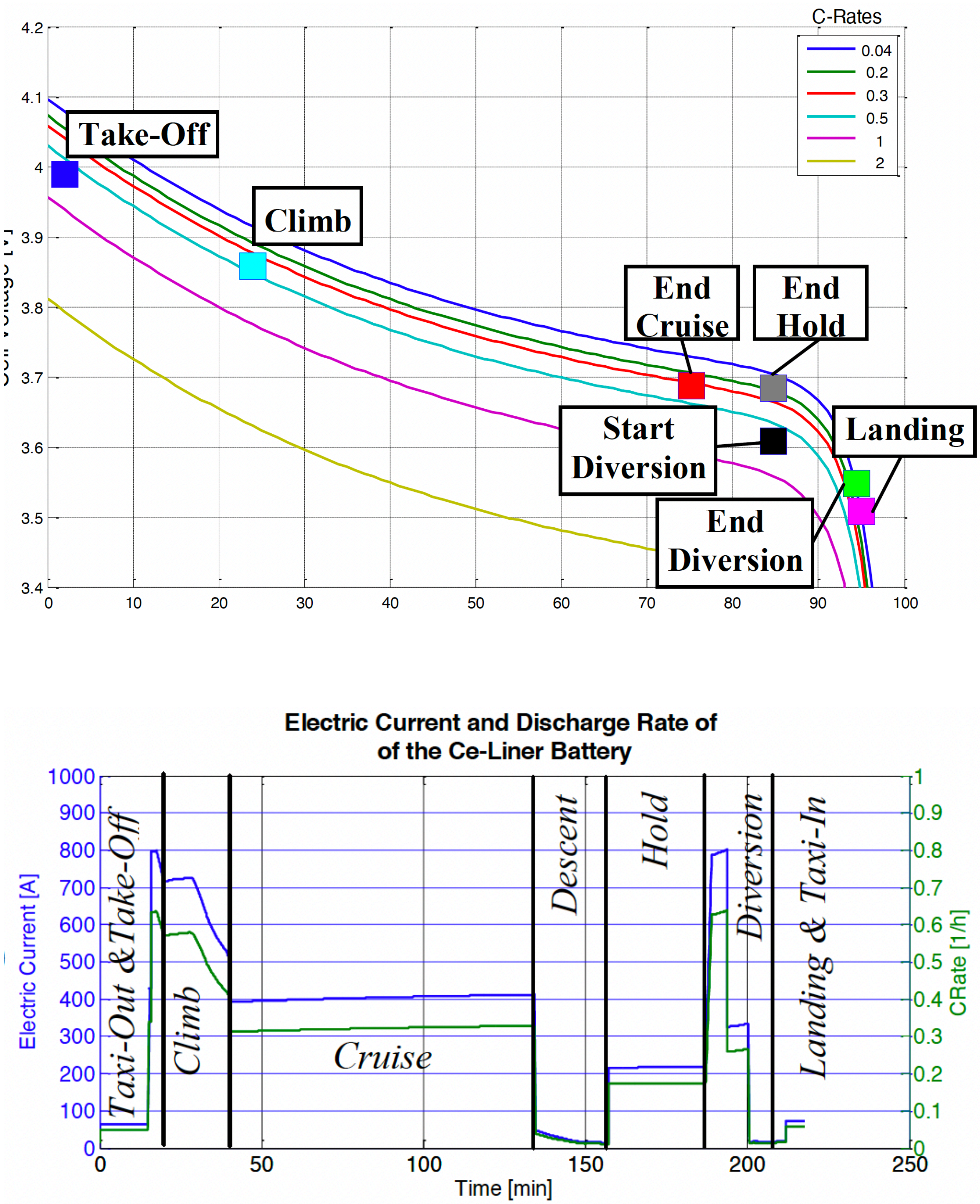


Figure 10: Discharge and current demand characteristic of a battery cell during a typical mission (DOC = 1-SOC)

C-rate defines the rate of discharge of a battery cell, and it expresses the discharge current relative to the current required to discharge the cell in one hour. So for example, a 100 Ah battery, being discharged at 5C, outputs 500 Amps in 0.2 hours.

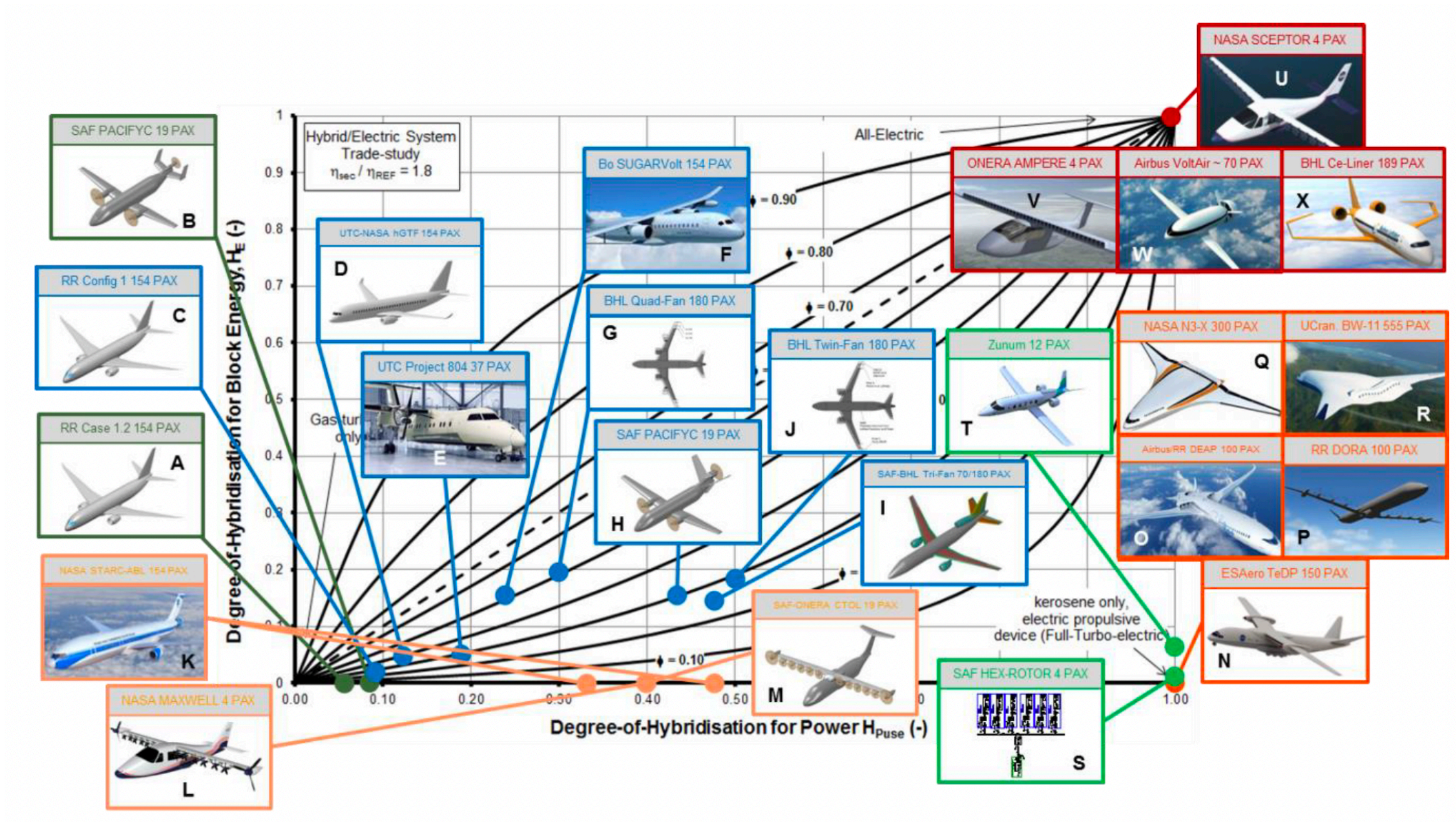


Figure 11: Recent aircraft designs with different degree of hybridization

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